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REVIEW

On the Evolution of Symbols and Prediction Models

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Abstract
The ability of predicting upcoming events or conditions in advance offers substantial selective advantage to living beings. The most successful systematic tool for fairly reliable prognoses is the use of dynamical causal models in combination with memorised experience. Surprisingly, causality is a fundamental but rather controversially disputed concept. For both models and memory, symbol processing is requisite. Symbols are a necessary and sufficient attribute of life from its very beginning; the process of their evolutionary emergence was discovered by Julian Huxley a century ago. In behavioural biology, this universal symmetry-breaking kinetic phase transition became known as ritualisation. Symbol use for predicting future dynamical processes has culminated in the unprecedented complexity of mental models used in science and technology, coining the historical ascent of modern humans. Observation and measurement transform structural information of physical exchange processes into symbolic information from which state quantities are derived by means of mental models. However, phylogenetically inherited models such as naïve realism do not necessarily explain the sophisticated insights revealed by modern experiments with, say, entangled quantum states. It is suggested to carefully distinguish observed exchange quantities from predicted unobservable state quantities, and physical reality from mental models thereof.

Keywords Prediction · Symbols · Models · Ritualisation · Causality · Evolution

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1. Introduction

Ultimately, all languages and sciences have their very roots in the Darwinian evolution. Commonly, biophysics is concerned with physical processes taking place in biological systems (Romanovsky et al., 1975; Volkenshtein, 1978; Glaser, 2012). An alternative aspect of the interaction between physics and biology, however, is the effect which biological evolution had and still has on the development of physics, in particular on the physical understanding of the world. Healing the formerly lingering conflict between Clausius' law of growing entropy (Clausius, 1876) and Darwin's law of natural selection (Darwin, 1859), physics of self-organisation and evolution (Prigogine et al., 1972; Ebeling & Feistel, 1982, 2018; Feistel & Ebeling, 2011; Eigen, 2013) was inspired seminally by Ilya Prigogine (1969), Manfred Eigen (1971) and Hermann Haken (1973) half a century ago, and constitutes a prominent example for the fruitful impact of biology on physics.

Another such pivotal attempt has recently been undertaken by Donald Hoffman (2020) in his book "The Case Against Reality", intending to explain "how evolution hid the truth from our eyes" by recalling the pre-Darwinian philosophical scepticism of Plato, David Hume (1967) or Immanuel Kant (1956) from a modern biological perspective. "Evolution by natural selection agrees: spacetime and objects are not fundamental."[1] Our familiar physical picture of the world with its things and colours is a construct of the human mind which in turn was built and tailored in the course of varying stringent demands of Darwinian evolution. Largely consistent with such an approach, but looking also beyond a mere focus on just human evolution, in this paper the fundamental role of symbols and models is reviewed. This role has systematically been growing and advancing along with the biological, social and scientific evolution from the origin of life up to the challenges in recent physical science.

In physics and biophysics, modern dynamical models describe symbolically, mostly in the form of differential equations, the temporal change of quantities of interest, usually known as »order parameters« or »state variables« of a system under consideration (Fisher, 1930; Volterra, 1931; Wilson & Bossert, 1973; Haken, 1973, 1977; Hirsch & Smale, 1974). Those equations permit predictions for the future values of those quantities derived from conditions prevailing at present or in the recent past. In the words of Max Born: „Mathematically, the law of causality is expressed by the fact that physical quantities obey differential equations of a certain kind. … The causal law of classical physics implies that the knowledge of the state of a closed system at some point of time determines its behaviour for all of its future."[2]

However, causal dynamical models are much more general tools than just evolution equations of theoretical physics. When we intend to throw a ball into a distant basket, our mind imagines the expected trajectory of the flying ball, and from our memory the information is recalled of which muscles at which strength and time need

[1] Hoffman et al. (2023): p. 1.

[2] Born (1966): p. 7. Quoted text: " Mathematisch drückt sich das [Kausalgesetz] dadurch aus, daß die physikalischen Größen Differentialgleichungen von bestimmtem Typus genügen. … Daß die Kenntnis des Zustandes … in einem Augenblick den Ablauf eines abgeschlossenen Systems für alle Zukunft determiniert; das ist die Fassung, die das Kausalgesetz in der [klassischen] Physik annimmt."

to be activated to achieve this. We do this without solving a differential equation, but none the less, as in the case of physical equations, we also exploit neural symbols to perform this. "When the hand moves, so does the spirit."[3]

"Brains are … essentially prediction machines."[4] Our nervous system is permanently predicting and correcting expected results of our intended activities; before we move our head or turn our eyes, the related change of the image at our retina is estimated so that the world around us remains virtually unchanged to us. Our internal prediction model eliminates in advance the motion of the observer from that of the observed. In situations when such predictions fail we feel uncomfortable like seasick. Our predictions are derived from previous experience by the use of suitable *mental models*, be they conscious or not. "Experience consists of perspectives belonging to sensation, and of conclusions which are merely a business of understanding."[5] Assumingly, many animals make similar predictions when they move, chase or flee, even though they cannot tell us about that. "Macaque monkeys are capable of implementing a causal inference strategy with a level of sophistication that is comparable to humans."[6]

> "Mental models are personal, internal representations of external reality that people use to interact with the world around them. They are constructed by individuals based on their unique life experiences, perceptions, and understandings of the world. Mental models are used to reason and make decisions and can be the basis of individual behaviors. They provide the mechanism through which new information is filtered and stored."[7] "Mental modelling arose out of a pre-existing capacity to use simulations of motor actions to anticipate the consequences of the actions. As the capacity developed, elements of the simulations could be changed, and the consequences of these changes could be 'thought through' consciously."[8]

Human consciousness is still a scientific mystery (Krauss & Maier, 2020). From the perspective of its assumed symbolic information processing, consciousness may be considered as a composite mental model, consisting of an evolutionarily advantageous subset of all mental models that are functioning in an individual brain, and being designed for comprehensive cooperative prediction processes and related rational decisions. As far as consciousness is operating on the basis of neuronal carriers of symbolic information, its functioning may in principle be transferred to other physical carriers of the same information, whether or not this may be technically possible or ethically eligible. Hypothetically, Turing's universality principle, stating

[3] Buddha (2015), p. 68: Quoted text: „Wenn sich die Hand bewegt, dann bewegt sich der Geist entsprechend.".

[4] Clark (2013): p. 181.

[5] Kant (2016): p. 52. Quoted text: „Erfahrung besteht aus Anschauungen, die der Sinnlichkeit angehören, und aus Urteilen, die lediglich ein Geschäfte des Verstandes sind.".

[6] Sarafyazd and Jazayeri (2019): p. 7.

[7] Jones et al. (2011): p. 1

[8] Stewart (2022): p. 1.

that information processing of discrete symbols can be performed by digital computers of any physical kind, may apply similarly also in this case. “This special property of digital computers, that they can mimic any discrete state machine, is described by saying that they are *universal* machines.”[9] It is understood that “a digital computer is … a general symbol-processing device, capable of performing any well-defined process for the manipulation and transformation of information.”[10]

Dynamical models typically appear in two distinct modes; they are first set up at »design time« and later executed at »run time«, as we know such models from implementing numerical algorithms on a computer. In the case of physics, famous such »model designers« were Isaac Newton, Albert Einstein or Erwin Schrödinger who discovered novel »natural laws« and formulated those symbolically as differential equations. At »run time«, they derived measurable predictions for the motion of planets or the light spectra of hydrogen. Because “understanding as complicated a fabric as the human apparatus of thinking demands the construction of models”[11], as an antecedent of today’s »artificial intelligence«, Steinbuch’s (1961) classical »Lernmatrix« model (Kämmerer, 1974: p. 251), combines an initial »Lernphase« (training phase) at »design time« with a subsequent »Kannphase« (skilled phase) at »run time«. We experience similar operation modes from ourselves; when learning to swim or to drive a car, we initially control our moves consciously and arduously at »design time« but do it automatically and easily later at »run time«, as soon as the required mental model is implemented and usable as a predictor for what we intend to achieve. Understanding the evolution of such models requires related but different explanations for their two different operational modes.

Since the earliest days of life, perception has always been “an implicit preparation to respond.”[12] For an organism, any perception is futile as long as there is no ability for reacting to it. The need for prediction, and accordingly, for appropriate models, is much older than the existence of humans or smart animals. As soon as an organism has developed a capability of freely performing and controlling certain own activities, that is, degrees of freedom beyond its merely passive physical response to external forces, it needs to decide how and when to execute or to suspend such an activity. This decision is beneficially based on expectations of whether or not this activity will result in selective advantages in the future. Any biological behaviour, including human activities, is organised by such kind of decisions. Accordingly, symbols, models and successful behaviour can be assumed to have emerged by Darwinian coevolution; none of them may have existed on its own without the other two.

Quite fundamentally, biological survival as we know it requires sophisticated biochemical networks which are maintained and reproduced under the control of the genetic information. In this wider sense, by exploiting previous experience of successful survival of forerunners in the past, inherited genetic information constitutes a prediction model, a recipe telling the offspring what to do in order to stay alive und

[9] Turing (1950): p. 441.

[10] Feigenbaum and Feldman (1963), as quoted by Vater (2011): p. 43.

[11] Steinbuch (1961): p. VI. Quoted text: “Das Verständnis solch komplizierter Gebilde wie des menschlichen Denkapparates muß über den Entwurf von Modellen erarbeitet werden.”

[12] Baccarini (2013): p. 230.

multiply. In this case, »design time« of the model is the Darwinian evolution of all previous ancestors, while its »run time« is the current existence and performance in a living organism. The success of this self-design process of accumulating experience depends on environmental continuity; changes of the outside world must proceed slower than the genetic adaption process of a species. This condition is violated when sudden natural catastrophes happen, or when humans severely affect the terrestrial ecosystem by technical means in accelerating manner.

Relying on a certain predictability of the world around, the relevance of this fundamental »continuity principle of life«, which is required to hold for the success of any kind of prediction model, extends from the survival of first organisms up to the validity of scientific theories. In biology, offspring tries to repeat parental success. In experimental physics, repeatability is an indispensable validity criterion. Actually, as discussed in Sect. 8, the virtually irresolvable conundrum of the »Einstein-Planck paradox« serves as an example for the way the interpretation of physical experiments may be hampered by the conveyed mental model of naïve realism (Sect. 3). Historically acquired physical state models of continuous fields and waves unexpectedly failed in explaining an observed random exchange of discrete energy quanta. In 1905, Einstein had suggested light quanta as particles flying indivisibly through space, while Planck in 1907 restricted the quantum effects to processes of emission and absorption only, assuming light to be a spreading electromagnetic wave in between. "It will need much heavier arms to rock the so very firmly founded building of the electromagnetic theory of light."[13] "With respect to the theory of light quanta, the phenomenon of interference of light mounts up to an enormous difficulty."[14] Since this statement of Planck in 1920, subsequent experimental results have ever deepened this mystery of the light's very nature between its birth and death. We do not (yet) possess a comprehensive and consistent mental model for this state of matter. Successful models based on experience of the past fail in their extrapolation to explain novel physical observations. "'Our intuitions are terrible sometimes,' [Eleanor Knox] says. They 'evolved on the African savanna interacting with macro objects and macro fluids and biological animals' and tend not to transfer to the world of quantum mechanics."[15]

What all the biological models have in common is the requisite duplicate use of symbols, on the one hand for recording the individual experience by a suitable memory medium, on the other hand for processing those stored data in combination with most recent, instantaneous sensual input. We know a similar situation of computers containing memory devices that feed a certain group of bits, symbolically representing something, into a digital processor which returns a manipulated, transformed group of bits. This raises the question of how symbols and models, as fragile and dangerous as they are, could have come into robust biological existence by self-organisation of non-symbolic matter. The emergence of symbols at »design time« is

[13] Planck (1958): Vol. II, p. 243, as quoted by Hermann (2022): p. 43, "Da bedarf es denn doch noch schwereren Geschützes, um das nachgerade sehr stark fundierte Gebäude der elektromagnetischen Lichttheorie ins Wanken zu bringen."

[14] Planck (2018): p. 18. Quoted text: „Die Erscheinung der Interferenz des Lichts türmt sich … der Lichtquantentheorie gegenüber als ungeheure Schwierigkeit auf.".

[15] Becker (2022): p. 31.

a symmetry-breaking kinetic phase transition known as *ritualisation*. Ritualisation processes can indeed be detected throughout the history of life, from its very origin up to processes in the modern human society. In turn, at »run time«, symbols, as conventionally specified before, are produced from the world's structural information as a result of *symbolisation*, i.e., of a perception process known as *observation*, including, as a special case, human metrological observations in the form of *measurement*.

The subjective impression that by means of our eyes and fingers we possess the ability of observing physical states such as the world around us, is an extremely useful deception. What our senses actually are capable of detecting are only physical exchange processes of the world outside with our sensory cells which convert incoming structural information into symbolic information to be processed by the neural system. Physical states, as they appear to us, are actually merely images, generated by genetically inherited mental models from the exchange fluxes perceived by our senses. Hence, observable physical exchange quantities (reality) and unobservable physical state quantities (model) are not the same and should carefully be distinguished.

Humans extended the use of symbols to previously unseen diversity and complexity. Using certain symbols is so easy and natural to us that we hardly become aware of them. "Our own ease of understanding speech belies its underlying complexity."[16] Mostly by meticulously introspecting their own thoughts and imaginations, philosophers such as Plato, Hume, Kant, Leibniz or Hegel described their varied beliefs of how humans recognise and understand the world. However, introspection is a restricted tool because "the brain can never become conscious of itself."[17]

Especially Max Planck had always tried to detect the "absolute" in the laws of Nature. "We may always start only from the relative. All our measurements are of relative nature. The material of the instruments we are working with depends on the location where it was dug, their construction depends on the skill of the technician who invented them, their use depends on the specific purpose which the experimenter intends to achieve. It is the hidden absolute, the generally valid, the invariant which needs to be discovered from all those data."[18] It was in particular Albert Einstein who ingeniously derived his theories of relativity by rigorously distinguishing mathematical properties of the observer from those of the observed. Still, yet, confusing quantum paradoxes like »Schrödinger's Cat« (Sect. 8) suggest that the epistemological discrimination between human inherited mental models, that is, the apparently so evident »common sense«, and hard facts like unequivocal measurement results, appears only insufficiently well accomplished. However, »common sense« is a poorly defined concept. "Appealing to [common sense] is nothing but referring to the judge-

[16] Lewicki (2010): p. 821.

[17] Donald (2008): p. 192.

[18] Planck (1958): Vol. II, p. 359, as quoted by Hermann, A. (2022): p. 27, „Ausgehen können wir immer nur vom Relativen. Alle unsere Messungen sind relativer Art. Das Material der Instrumente, mit denen wir arbeiten, ist bedingt durch den Fundort, von dem es stammt, ihre Konstruktion ist bedingt durch die Geschicklichkeit des Technikers, der sie ersonnen hat, ihre Handhabung ist bedingt durch die speziellen Zwecke, die der Experimentator damit erreichen will. Aus all diesen Daten gilt es das Absolute, Allgemeingültige, Invariante herauszufinden, was in ihnen steckt.".

ment of the crowd; an applauding which makes the philosopher blush while it lets the popular joker triumph and be defiant."[19]

The ancient self-organisation of symbols by the first living beings has created a long trace up to contemporary dynamical models of humans. Modern science and its causal dynamical prediction models are derived from measurements which assign measured values, usually numbers, to physical structures. Numbers, in turn, are symbols that emerged by ritualisation in the early human history. In order to review certain key aspects of the related evolutionary processes, this paper is organised as follows. In Sect. 2, symbols and symbolic information are briefly introduced. Section 3 explains models, in particular also mental models such as that of naïve realism. Section 4 describes how symbols emerge by ritualisation transitions in the course of evolution, and looks at numbers, "the language of science"[20], as a special case of substantial interest. Numbers are the most important results of measurements, which is the scientific technique of observation described in Sect. 5. In physics, the symbolic results obtained from measurements are assembled into causal mental models for the prediction of future measurement results. Opposite opinions about causality as the fundamental concept of dynamics and prediction models are the topic of Sect. 6. Section 7 considers selected prediction tools. Section 8 discusses the key assumption that physical state quantities, being the basic elements of dynamical models, may not be observed and measured directly, and, as an example, the »Einstein-Planck paradox« is described under this perspective. In Sect. 9, a summary concludes this review.

Many of the ideas and conclusions collected here have been published previously by various authors. This is demonstrated by an extensive list of literal quotations embedded in the text. Brackets […] denote insets by this author. Quotations from external experts are exploited as arguments and support for the picture that is painted in this paper. They serve as appreciation for the thoughts and insights of previous thinkers and researchers related to the topic under consideration. Their sentences may hardly be formulated in a way better than they had originally been. Quote marks enclosing the borrowed sentences must not be omitted to avoid plagiarism when employing those helpful ideas. Literal quotations are presented here not intending to analyse or criticise their originators, rather, they are being used like »observational data« collected through the human history; they constitute essential puzzle pieces to form a clearer and more comprehensive picture of the issue presented. For easy and fluent reading, many of those quotations have been translated to English by the author; in case of doubt with respect to this subjective translation, the reader may rather turn to the original (mostly German) quotation that is carefully and intentionally reported in a footnote.

[19] Kant (2016): p. 7. Quoted text: „Beim Lichte besehen, ist diese Appellation [auf den gemeinen Menschenverstand] nichts anders, als eine Berufung auf das Urteil der Menge; ein Zuklatschen, über das der Philosoph errötet, der populäre Witzling aber triumphiert und trotzig tut.".

[20] Dantzig (1930).

2. Symbols and Symbolic Information

In this article, a *symbol* denotes an object that is used as representative for something different than the object itself. In the words of Carl Gustav Jung in 1961, "a word or an image is symbolic when it implies something more than its obvious and immediate meaning."[21] For example, tree rings are sources of information; 'dendrochronology' is a scientific discipline which counts and measures various properties of those rings. "Trees that may have been cut down a century or two ago but have retained a detailed record of how sweet their springs were, how harsh their winters, how clean their sources of water."[22] The information embodied originally by the rings may be termed *structural information*, in contrast to the related extracted information in the form of numbers, texts, photographs or computer bits, as denoted by *symbolic information* (Ebeling & Feistel, 1994; Feistel & Ebeling, 2011, 2016; Feistel, 2017a,b; Burgin & Feistel, 2017). While the carrier of structural information is the physical structure of an object, such as the visible tree ring, the carrier of symbolic information are symbols specified by convention, such as words or numbers attributed to the ring. The meaning of structural information is *objective*, independent of any receiver, while the meaning of symbolic information is *subjective*, depending on the properties of transmitter or receiver.

Names are special symbols associated with objects or persons. Plato had stated already about 430 BCE[23] that "no name belongs to a particular thing by nature, but only because of the rules and usage of those who establish the usage and call it by that name."[24] This is true not only for names, but also for any other symbols. While every physical object or process inherently carries structural information simply by its very existence, possibly transferred by interaction with other objects (Granger, 1969; Stips et al., 2016), it may become a carrier of symbolic information only when it is used externally as a symbol in an information-processing context. Since Plato, numerous philosophers have discussed fundamental relations between »things and signs« (Leibniz, 1904; Oehler, 1995; Coeckelbergh, 2020). But also very practically, "these two themes, information and structure, have combined as the dominant paradigm of medical research in recent decades."[25] The relation between structural and symbolic information may be compared with the relation between physics and semiotics, which "are just two different ways of seeing the same world."[26]

[21] Jung et al. (1979): p. 20. Quoted text: "Ein Wort oder ein Bild ist symbolisch, wenn es mehr enthält, als man auf den ersten Blick erkennen kann."

[22] Galchen (2022).

[23] BCE: "Before Common Era", as introduced by Johannes Kepler in 1615, https://en.wikipedia.org/wiki/Common_Era.

[24] Platon (2013): p. 547, Seventh letter. Quoted text: "Kein Name irgendeines Dinges gehört ihm von Natur, sondern durch Anordnung und Gewohnheit derer, welche die Wörter zur Gewohnheit machen und gebrauchen."

[25] Lane (2022): p. 14.

[26] Kull (2007): p. 171.

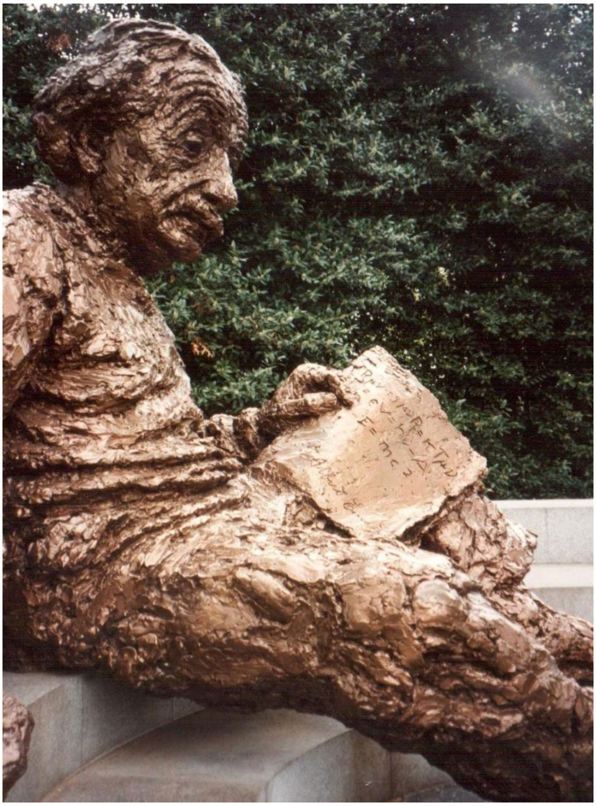

Fig. 1 Sculpture of Albert Einstein at the building of the National Academy of Sciences in Washington, D.C., created by Robert Berks. The paper in Einstein's hand symbolically shows key equations of his three most important theories, the General Theory of Relativity, the photo-electric effect, and the Special Theory of Relativity. Photo taken in April 1997

Another example for the distinction between structural and symbolic information is shown in Fig. 1. The shape of Einstein's sculpture, its material, its surface structure, all the physical and chemical properties constitute structural information which is independent of human interpretation. Natural processes may transfer this structural information to other physical carriers, such as to sunlight when this is absorbed or reflected by the sculpture. The reflected light, in turn, may take this structural information to our eye or camera. By contrast, the equations written on the paper sheet in Einstein's hand, or the fact that the sculpture is a model of the person Albert Einstein, represent symbolic information which is meaningful only to humans with suitable educational background knowledge to decode the conventionally associated meaning of those symbols.

The meaning of symbols is conventional; the same meaning may be carried by other physical objects. When we type the words of an email, the symbols of the text are carried by the keyboard, by a memory chip, by electromagnetic waves transferred through a wireless network, then perhaps by glass fibre cables or satellite relays until they appear optically on the screen of a friend and eventually of his/her retina. The other way round, the same physical carrier may represent different meanings, such as the bits in a computer memory or the dots on a TV screen, acting as carriers for arbitrary texts or images.

> "The basic building blocks of information are *symbols* and *meaning*, which cannot be reduced to one another. The *symbols of information* are the physical media of representation and the *means of transmission* of information. Without the associated meaning, the symbols of information have no significance since meaning is an ascribed and acquired quality and not an inherent property of the symbols. We can transmit symbols of information but cannot transmit meaning from one mind to another without a common protocol or convention."[27] "We do not merely inherit inert information in the form of genes – our inheritance includes this living metabolic network in the egg cell, a flame passed from generation to generation, without pause, right back to the emergence of life. … The genes are custodians of this flame, but without the flame life is – dead."[28]

The arbitrary mutual assignment between a structure and its meaning is a new symmetry, namely, the »code symmetry« or »code invariance«, that symbolic information possesses in distinction to structural information (Feistel, 1990; Ebeling & Feistel, 1992, 1994, 2018; Feistel & Ebeling, 2011). "We can formulate this as the *principle of code plurality* - which states that any text, any sign, any semiosis assumes the co-existence of several codes, of many codes."[29] With respect to the physical carriers employed for information transfer, *ritualisation* is (see Sect. 4), in philosophical terms, the self-organised transition »from the realm of necessity to the realm of freedom«, as Karl Marx had originally coined this popular phrase with respect to human labour (Klagge, 1986). This fundamental symmetry of code invariance, that is, the purely conventional character of the relation between the physical structure of a symbol and its meaning, was firmly emphasised by Deacon (2021), appreciating it as the *central dogma of semiotics*. As an illustration of this symmetry, the meaning of this article does not change whether it is displayed on a screen or printed on paper. "Different languages, for example, give different names to the same object precisely because there is no necessary connection between names and objects."[30] When a book is translated to another language, its content should (largely) be »invariant against language transformations«. This special symmetry is particularly important for scientific textbooks.

In quantum physics, structural information is rigorously subject to the *No-Cloning Theorem* (Wootters & Zurek, 1982). In distinction to structural information, suitably coded symbolic information may be stored and copied almost losslessly, as we know this from digitally recorded text, music or films. As a »conditio sine qua non« for Darwinian evolution, the self-organised use of symbolic information encoded in copyable chain molecules marks the beginning of life. "Records require some form of material symbols that represent the events and an agent that interprets the symbols. This largely arbitrary symbol-matter relation first appears with evolvable self-replication, which I define as the origin of life."[31] "Sign systems embrace all

[27] Çengel (2023): p. 1

[28] Lane (2022): p. 18

[29] Kull (2007): p. 174.

[30] Barbieri (2008): p. 168.

[31] Pattee and Rączaszek-Leonardi (2012): p. 2.

living systems, and the roots of semiotics lie in biology."[32] To accumulate individual experience, selected relevant fractions of sensually perceived environmental structural information can be stored as symbols, namely as modifications of an appropriate physical memory structure such as nerve cells and their network. This way, experience is formed if "a rate-dependent [external] dynamical state is coded into quiescent [internal] symbols."[33]

The word »symbol« is itself a symbol with a meaning specified by convention. Various different such conventions can be found in the literature. In this paper, »symbol« is a general term, associated with physical properties (Ebeling & Feistel, 1994; Pattee, 1996, 2001, 2008; Feistel & Ebeling, 2011; Feistel, 2017a), which is applicable to arbitrary organisms and human apparatuses, a term of which »signs«, »signals«, »images« or »models« are special cases. By contrast, the *semiotics* of Charles S. Peirce considers »sign« as the most general notion, which may either be an »icon«, an »index« or a »symbol« (Peirce, 1868a; Oehler, 1995; Nöth, 2000; Kjørup, 2009). So far, *Biosemiotics*, "the study of signs in living systems"[34], follows preferably also the nomenclature of Peirce. However, in the understanding of Ferdinand de Saussure (2001: p. 80 therein) a symbol is never completely arbitrary, rather, there is always a certain relation between the representative and the represented, which may in fact be true for most symbols in art (Kretschmer, 2021). Otherwise, what at all can we know about the meaning of a given bit pattern from its physical structure in a computer memory? At the ritualisation point, see Sect. 4, the symbol's structure still reflects its meaning, but because of the symbol's neutral stability associated with its code symmetry, fluctuations during the progressing evolution will gradually drive the structure away from its native shape.

Structural information recognised by organisms as if it were a symbol which triggers a certain activity, is known in ethology as a »cue«, see Sect. 7. Jung et al. (1979) investigate symbols mainly in the context of psychology and dreams. The philosophical dictionary of Klaus and Buhr (1969) recommends to abstain completely from the use of the term »symbol« for its diverse and inconsistent use, and suggests taking »signal« instead as the most general token. »Signal« is also used in behavioural biology (Tembrock, 1977) in a similar sense as »symbol« is used here. In the semiotic context, various further definitions of »signs«, »symbols« etc. are discussed in extensive detail by Nöth (2000: Section III.1 therein). For example, Nöth (2000: section IV.8.2.3) prefers the term »display« to denote an ethological »signal« of the communication between by higher animals. The German norm DIN 44 300 of information technology recommends »symbol« rather than »sign« for information carriers representing a different meaning (Nöth, 2000: Section III.1.2). Regrettably, a related uniform, sufficiently comprehensive and widely recognised »standard terminology« for symbolic information carriers is unavailable yet.

In the following Section, following Stachowiak (1973), *models* will be introduced as special symbols. We may imagine, for example, a numerical climate model as a complex »symbol«, dynamically representing the real climate system in a simplified

[32] Kull (2001): p. 1.

[33] Pattee (2001): p. 5.

[34] Barbieri (2008): p. 167.

manner. By contrast, denoting such a model as a »sign«, an »index« or a »signal« of the climate system, seems to appear as inappropriately restricted, static, superficial, or perhaps even misleading. A climate sign or a climate signal usually denote rather different items than a climate model.

3. Models and Naïve Realism

"The word 'model' … is used … to mean *an approximate description of an aspect of reality, with this description being developed for a specific purpose*."[35] Accordingly, a model represents something else than itself, in agreement with the general definition of a symbol. „By a model we … mean any physical or chemical system which has a similar relation-structure to that of the process it imitates. … [But] the model need not resemble the real object pictorially."[36] "A model is likewise … the most elementary item of perception as well as the most complex, most comprehensive theory."[37] The meaning of the word »model« is conventional as is that of any other symbol. The very wide and general understanding of models by Stachowiak (1973) employed here is in contrast to various other model concepts discussed in the literature. Their philosophical classifications are not relevant here. Some authors, for example, systematically distinguish models from theories, making those too narrowly constructed for the purpose of this paper, such as the one of Frigg ("how do models relate to theory?"[38]), or that of Suárez ("tradition assimilates the distinction between scientific theories and scientific models to the syntax/semantics distinction"[39]). Here, models are specific complex symbols, they are typically structures consisting of simpler, mutually related symbols. Various symbols have developed in the course of evolution because only they render prediction models possible which improve their owner's chance to survive.

"A photography constitutes a model of what is photographed."[40] Similarly, paintings, drawings or sculptures constitute models of what they represent. About 430 BCE, already Plato had stated that "also paintings … are … imitations of certain things."[41] For example, Fig. 2 shows three photographs, or models, of different objects. In the right panel (c), the object shown is a preserved part of the original observatory of Ulugh Beg at Samarkand in 1420. In the left panel (a), the photo is a 2D model of a 3D model of the original observatory. In the centre (b), the object represented is a drawing, explaining Bulatov's (2009) mental model of the functioning

[35] Willink (2013): p. 16.

[36] Craik (1943): p. 51.

[37] Stachowiak (1973): S. 56. Quoted text: "Modell … ist ebenso die elementarste Wahrnehmungsgegebenheit wie die komplizierteste, umfassendste Theorie."

[38] Frigg and Hartmann (2012).

[39] Suárez (2014): p. 14.

[40] Stachowiak (1973): S. 160. Quoted text: "Die Photographie stellt ein Modell des Photographierten dar."

[41] Platon (2013): Kratylos, p. 75. Quoted text: "Sokrates: Aber auch die Gemälde … sind … Nachahmungen gewisser Dinge.".

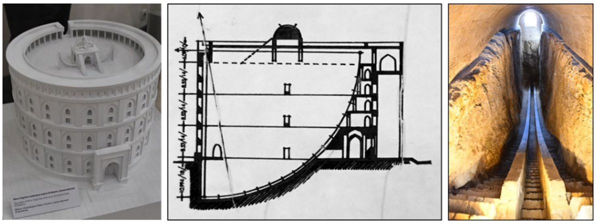

Fig. 2 Ulugh Beg’s observatory of 1420 at Samarkand. Left panel (a): Model of the cylindrical building with 40 m diameter. Centre (b): schematic of the building’s cross section showing the mural quadrant with a radius of about 35 m, as reconstructed by Bulatov (2009). Right panel (c): subterranean original remains of the mural quadrant. Photos taken at Samarkand in April 2022, edited

of the former mural quadrant, so, this image is a model of a model of a model. The images shown here are models composed of printed or displayed pixels whose physical properties let them act as symbols for the optical appearance of the real objects represented. Forming certain visible structures, those pixels are mutually related by their relative positions and their correlated brightness, that is, their local incident spectral light intensity.

Mental models are fundamental to humans. The Scottish philosopher Kenneth Craik is credited to be the originator of the concept of mental models; tragically, he died untimely in 1945 at the age of 31 in a traffic accident during the victory parade at Cambridge (Bartlett, 1945). The fundamental role of (mental) models for human understanding has often been emphasised across different fields. „Human thought has a definite function; it provides a convenient small-scale model of a process.“[42] “The mental image of the world around you which you carry in your head is a model.”[43] “The brain generates a mental image or model.”[44] “The ‘mind’ consists of a model formed by the ‘brain’: This would be a model of the entire environment.”[45] “The mental model is the arena where imagination takes place. It enables us to experiment with different scenarios by making local alterations to the model.”[46] „All our imaginations and notions are just internal thought images, if spoken out, combinations of sounds.”[47] “Without … an elementary model as guideline, theoretical investigations are impossible.“[48] “All thought … must necessarily be in signs.”[49] ”The rules of logic hold good of any symbols, of those which are written or spoken as well as of those

[42] Craik (1943): p. 59.

[43] Forrester (1971): p. 3.

[44] Hawking and Mlodinow (2011): p. 46. Quoted text: “Das Gehirn erzeugt ein mentales Bild oder Modell.“.

[45] Shiffrin et al. (2020): p. 29,299.

[46] Pearl and Mackenzie (2018): p. 26.

[47] Boltzmann (1899): p. 160. Quoted text: „Alle unsere Vorstellungen und Begriffe sind ja nur innere Gedankenbilder, wenn ausgesprochen Lautkombinationen.”

[48] Eco (2017): S. 18. Quoted text: “Man [kann] keine theoretische Untersuchung durchführen ohne … ein elementares Modell als Leitfaden.“.

[49] Peirce (1868b): p. 111.

which are thought.“[50] „All important experimental-physical discoveries arose from intuitions of men who forthrightly used models which for them were representatives of real things.”[51]

Politically, freedom of the individual may be understood as priority of internal mental models over externally imposed social constraints. Religions, astrology, philosophies and experimentally supported scientific theories such as physics are mental models. In principle, the number of different possible mental models representing the same object is not restricted at all; their mutual relation is arbitrary in this sense. For example, Ptolemy and Copernicus proposed different but mutually consistent models of the solar system (Hawking & Mlodinow, 2011: Ch. 3 therein). An essential »criterion of truth« of a mental model is its prediction capability. A model is considered to be correct if its predictions match all observations within the model's estimated range of validity and uncertainty. If this is true for several different available models, usually the simplest one is chosen, according to the selection criterion known as »Occam's Razor«.

Axiomatic mathematical models possess the key properties of consistency, completeness and independence. Well-structured models, such as the International System of Units, the »SI« (BIPM, 2019), or the geophysical thermodynamic standard »TEOS-10« (Feistel, 2018) are also organised in an axiomatic manner. Most practical constructs of mental models, however, tend to be inconsistent or incomplete or both, as are in particular the various »eternal« religious myths, prophecies, commandments or dogmas, often written down in »holy books«, such as the Teaching of Buddha (2015), the Popol Vuh (Cordan, 1962) of the Maya, or the Christian Testaments (Luther, 1922).

Imitation, learning, and discovery are fundamental mechanisms driving the successive improvement of individual mental models, as various researchers have demonstrated in bees, birds or monkeys. Animals and plants are able to communicate symbolically by colours, sounds, movements or olfaction (Lorenz, 1983). Only humans, however, seem to have gained the ability of mutual symbolic communication of entire mental models, be that by teaching infants and students or by propagating ideas orally or in written form, like this scientific article or countless other publications. “Humans have the option of using language to recode and re-represent their experience.”[52] The gradual while exponentially accelerated progress of human science and technology from generation to generation (Sagan, 1978) became possible only by passing successful mental models from individual to individual, improving those step by step, similar to but much faster than genetically encoded models. For example, the emergence, propagation and persistence of several different, often mutually hostile major religions relies on symbolic communication (copying) of their fundamental mental models (dogmas) between adults within certain cultural groups and the related indoctrination of children (Dawkins, 2006). The religious,

[50] Peirce (1868a): p. 6.

[51] Born (1954): p. 50. Quoted text: “Alle großen experimental-physikalischen Entdeckungen entsprangen der Intuition von Männern, die freimütig Modelle benutzten, welche für sie … Repräsentanten realer Dinge waren.“.

[52] Byrne und Bates (2010): p. 816.

cultural and scientific prosperity at the medieval Silk Road (Fig. 2) was substantially enhanced by relatively cheap paper for writing and painting after that had become available from unveiled, formerly secret Chinese technology, exploited in numerous local paper mills.

An important mental model is that of *naïve realism*, as it was termed by Max Born (1965a,b). “The reality of a simple, untaught human is what he/she [immediately] feels and recognises. … The reality of *those* things which surround him/her is self-evident to him/her. … This attitude is termed naïve realism. The large majority of humans remains with that.”[53] Naïve realism includes the mental model of objects moving in space and time which our mind automatically generates out of the information flux that our sensory cells permanently receive by interacting with the outside world. The Newtonian »classical« physics before quantum and relativity theory is a formal mathematical description of naïve realism. This model is apparently hard-coded in human minds as a kind of neuronal operating system, implemented and inherited genetically, and proved overly successful in ensuring the survival of all our human ancestors. “Naïve realism is a natural attitude expressing the biological situation of humans and all animals”[54], which, by offering a common innate reference system of terms, enables humans to communicate verbally with one another. “Niels Bohr, who has contributed more than others to the philosophy of modern natural science, declared repeatedly and emphatically that it is impossible to describe a real experiment without using colloquial language and the notions of naïve realism.”[55] In the common-sense experience of naïve realism by virtually every human, the world consists of distinguishable objects located at certain relative positions in a three-dimensional space; they may move in time and transform subject to certain conservation laws. Causality is a central element of this – historically acquired and inherited - mental model of dynamical processes.

Modern physics has provided abundant experimental evidence (see Sect. 8) that the real world is more complex than the natural mental model of naïve realism that used to be assumed to constitute the unquestionable »ultimate truth« by certain philosophers, as meticulously concluded from introspection in their »ivory towers«. “What Kant is addressing in his attempted proofs are fundamental traits of human cognition. … Indeed Kant tried to achieve consistency between his arguments based on introspection and Newton’s physics. For just this reason, however, Kant’s synthetic-a-priori theses were disproved by the development of modern physics. So, there is no principle of continuity in quantum mechanics, no persistence of substance and no causality principle. The a-priori of Euclidean space was rebutted by the Gen-

[53] Born (1965a): p. 53,54. Quoted text: “Die Wirklichkeit des einfachen, ungelehrten Menschen ist das, was er fühlt und wahrnimmt. Die Realität der Dinge, die ihn umgeben, ist ihm selbstverständlich. … Man nennt diese Einstellung naiven Realismus. Die große Mehrzahl der Menschen bleibt dabei stehen.“.

[54] Born (1965b): p. 106. Quoted text: „Der naive Realismus ist eine natürliche Haltung, die der biologischen Situation des Menschen wie aller Tiere entspricht.“.

[55] Born (1954): p. 51. Quoted text: „Niels Bohr, der mehr als andere zur Philosophie der modernen Naturwissenschaft beigetragen hat, erklärte wiederholt und nachdrücklich, daß man unmöglich ein tatsächliches Experiment beschreiben könne, ohne dabei die Umgangssprache und die Begriffe des naiven Realismus zu verwenden.“.

eral Theory of Relativity, absolute time by the Special Theory of Relativity, and the directedness of time is already challenged in classical physics."[56]

Through the many millions of generations of flies, their mental model of the world has implemented the undoubted experience that transparent things are rarely solid, and solid things are rarely transparent (except, perhaps, spider webs). When a fly encounters a modern window pane, it gets into a paradoxical situation that the fly cannot handle. This situation seems to be fairly similar to that of human mental models when those are confronted with the particle-wave paradox in quantum mechanics, see Sect. 8.

Before the advent of the physical models of Planck's quanta and of Einstein's relativity, different philosophers from Plato and Hume up to Engels and Lenin had largely agreed in that the roles of ideas and things in their diverse mental models should be consistent with the immediate and apparently so self-evident impression of perceiving real objects persisting in space and time. In the daily life, every human experiences a world as it is painted by the model of naïve realism. Historically, the virtually irresistible power of such models had placed philosophy in a leading position to define the frame into which each natural science like physics had to fit its specific mental models. A century ago, the experimental and theoretical breakdown of classical physics turned this subordination upside down; physics started to dictate what the world is like, and to the present day philosophy is merely running after the perplexing insights that physical experiments continue to reveal. Confusing phenomena that have been discovered and repeatedly confirmed are still lacking plausible mental models and rigorous philosophical guidelines in order to confine the wildest speculations to logically consistent mental models.

> "The first step toward a setting of a 'real external world' lies in the formation of the notion of a bodily object. This notion is not identical with the entirety of sensations, rather, it is a free creation of the human mind. The second step is that in our thinking (controlling our expectations), we assign to the notion of a bodily object a meaning which is largely independent of the sensations that had induced the notion. This is what we mean when we assign a 'real existence' to the bodily object. It is one of the great insights of Immanuel Kant that a setting of a real external world would be meaningless without understanding it. … The courageous creation of the notion 'space', which preceded all scientific geometry, transforms mentally the entity of positional relations of bodily objects

[56] Schurz (2021): Online excursus E10.1 - Mehr zur Transzendentalphilosophie Immanuel Kants, p. 42. Quoted text: „Worauf Kant in seinen Beweisversuchen hinweist, sind Grundmerkmale der menschlichen Kognition … In der Tat … versuchte Kant, seine auf Introspektion beruhenden Argumente mit der newtonschen Physik in Einklang zu bringen. Aus eben diesem Grund wurden Kants synthetisch-apriorische Grundsätze durch die Entwicklung der modernen Physik widerlegt. So gibt es in der Quantenmechanik kein Kontinuitätsprinzip, keine Beharrlichkeit der Substanz und kein Kausalitätsprinzip. Das Apriori des euklidischen Raums wurde in der allgemeinen Relativitätstheorie widerlegt, die absolute Zeit in der speziellen Relativitätstheorie und die Gerichtetheit der Zeit ist bereits in der klassischen Physik in Frage gestellt.".

Fig. 3 Grave of Immanuel Kant at the cathedral of Königsberg, today, Kaliningrad, Russia. Photo taken in July 2014

> into the entity of positions of bodily objects 'in space'."[57] "Classical physics believes in a space-time continuum in which separable bodies are moving."[58] For Kant, space and time were „purely elementary notions of sensation, to be rigorously distinguished from those of reason."[59]

At the time of Immanuel Kant (Fig. 3), the laws of Kepler and Newton were already known, those of Clausius and Darwin, however, not yet. Kant's famous work, "Kritik der reinen Vernunft", published in 1781 and in a revised 2nd edition in 1787, relies substantially on naïve realism. His careful introspective description may be understood as providing a detailed analysis of fundamental properties of the human mental model of naïve realism. Kant considered the origin of that model as given "a priori" rather than being the result of previous evolution. He emphasised the fundamental role of individual (that is, ontogenetic) experience by observation, but he was unaware of inherited phylogenetic experience (that is, Darwinian fitness). Naïve realism is a symbolically memorised product of accumulated phylogenetic experience. In particular, in his understanding, Kant characterised space and time as the model's mentally indispensable fundamental »stage« on which the play »nature« is watched.

- "*Space* is not an empirical notion but a requisite imagination a priori which is at the basis of all external perceptions. One may never create an imagination of absent space, even though one may easily imagine to find no objects in it. … The original imagination of space is perception a priori. … Space has only three dimensions; statements like this cannot be empirical or assessed from experience, nor be conclusions thereof."[60]
- "*Time* is not an empirical notion … but a requisite imagination which is at the basis of all perceptions. In viewing the phenomena one cannot at all abstain from time, although one may easily remove those phenomena from time. Hence, time

[57] Einstein (1936): p. 314, 320. Quoted text: "Der erste Schritt zur Setzung einer "realen Aussenwelt" liegt ... in der Bildung des Begriffes des körperlichen Objekts. ... Dieser Begriff [ist] nicht identisch mit der Gesamtheit jener Sinnesempfindungen, sondern er ist eine freie Schöpfung des menschlichen ... Geistes. ... Der zweite Schritt liegt darin, dass wir jenem Begriff des körperlichen Objektes in unserem (unsere Erwartungen bestimmenden) Denken von den jenen Begriff veranlassenden Sinnesempfindungen weitgehend unabhängige Bedeutung zuschreiben. Dies meinen wir, wenn wir dem körperlichen Objekt "reale Existenz" zuschreiben. ... Dass die Setzung einer realen Aussenwelt ohne jene Begreiflichkeit sinnlos wäre, ist eine der grossen Erkenntnisse Immanuel Kants. … Die kühne Begriffsbildung 'Raum', welche aller wissenschaftlichen Geometrie voranging, verwandelte gedanklich den Inbegriff der Lagenbeziehungen körperlicher Objekte in den Inbegriff der Lagen der körperlichen Objekte 'im Raume'."

[58] von Weizsäcker (1999): p. 6. Quoted text: "Die klassische Physik glaubt an ein Raum-Zeit-Kontinuum, in dem sich trennbare Körper … bewegen."

[59] Kant (2016): p. 71. Quoted text: „… die reinen Elementarbegriffe (Raum und Zeit) von denen des Verstandes mit Zuverlässigkeit zu unterscheiden und abzusondern."

[60] Kant (1956): p. 67, 69. Quoted text: „Der Raum ist kein empirischer Begriff, … [sondern] eine notwendige Vorstellung a priori, die allen äußeren Anschauungen zum Grund liegt. Man kann sich niemals eine Vorstellung machen, daß kein Raum sei, ob man sich gleich ganz wohl denken kann, daß keine Gegenstände darin angetroffen werden. … Die ursprüngliche Vorstellung vom Raume [ist] Anschauung a priori. … Der Raum hat nur drei Abmessungen; dergleichen Sätze aber können nicht empirische oder Erfahrungsurteile sein, noch aus ihnen geschlossen werden.".

is given a priori. It has only One dimension: different times are not together but in succession."[61]

- "There is only One time."[62] "Time on its own cannot be observed."[63]
- "We could only say: the common perception is teaching this; but not: so it must be. These principles serve as rules under which experience is possible at all, and they teach us before that rather than by means of that."[64]

It may be concluded that those rules of understanding were implemented phylogenetically at »design time« of the mental model of naïve realism, while conscious sensual experience, including scientific measurement, is made ontogenetically at »run time« of that model. Likely, our mental models of space and time are rather old; they may be very similar to those of cats or dogs, of horses or lizards. Actively moving animals benefit substantially from possessing remote-detection systems with respect to possible physical contact with external objects, be those obstacles, enemies, food or mating partners. For use during daylight, eyes evolved for the optical perception of structural information about the visible neighbourhood; after its conversion into symbolic information it is the task of mental models to extract from this wealth of raw information the portions that are relevant for survival, such as predicting from afar the kind of discernible objects, their distance, relative speed and estimated time left before contact, in combination with own intended movements. The »design time« of such mental models may consist of two stages; a conceptional development as a phylogenetic process long before we became humans, and the calibration and adjustment of this inherited model to actually prevailing conditions as an ontogenetic process of correlating various sensual signals received at the time of early infancy. When we later, at »run time«, make use of this biologically tailored model of naïve realism, we apparently possess no conscious memory of the previous »design-time« processes and, by introspection, may subjectively recognise and analyse their fundamental features as "given a priori".

Observations of relativistic and quantum phenomena have severely challenged Kant's mental model of space and time. We shall return to this model in Sect. 8.

[61] Kant (1956): p. 74. Quoted text: „Die Zeit ist kein empirischer Begriff. … [sondern] eine notwendige Vorstellung, die allen Anschauungen zum Grunde liegt. Man kann in Ansehung der Erscheinungen überhaupt die Zeit selbst nicht aufheben, ob man zwar ganz wohl die Erscheinungen aus der Zeit wegnehmen kann. Die Zeit ist also a priori gegeben. Sie hat nur Eine Dimension: verschiedene Zeiten sind nicht zugleich, sondern nacheinander.".

[62] Kant (1956): p. 240. Quoted text: „Denn es ist nur Eine Zeit.".

[63] Kant (1956): p. 235. Quoted text: „Nun kann die Zeit für sich nicht wahrgenommen werden.".

[64] Kant (1956): p. 75. Quoted text: „Wir würden nur sagen können: so lehrt es die gemeine Wahrnehmung; nicht aber: so muß es sich verhalten. Diese Grundsätze gelten als Regeln, unter denen überhaupt Erfahrungen möglich sind, und belehren uns vor derselben, und nicht durch dieselbe.".

4. Ritualisation: Numbers and Counting

Ritualisation is the transition process from non-symbolic structures to symbols, at »design time«. Semiotic aspects of this process are discussed by Nöth (2000: section IV.8.2.3 therein). "From the perspective of evolution theory, the world of sign-likes appears as a stage of evolution that was preceded by a world of not yet sign-likes." [65]

Numerous symbols and models may be found in human cultures which had freely been invented or defined, such as national anthems, coats of arms, the Morse code, or artificial structures as shown in Figs. 1, 2 and 3. In contrast to those, important symbols exist, in particular also ones used in non-human life, which appeared by self-organisation in the course of natural evolution. In this section, the latter »design« process of such evolutionarily emerging symbols, known as ritualisation, is briefly described as a universal phenomenon. Examples may be the genetic code, neuronal activities, mating rituals, or natural languages.

Models evolved from simpler symbols which in turn evolved from non-symbolic processes or structures. Physically, the emergence of a symbol is a symmetry-breaking kinetic phase transition that may be termed *ritualisation transition* (Feistel, 1990, 2017a, b; Ebeling & Feistel, 1992, 1994, 2015, 2018; Feistel & Ebeling, 2011, 2016). The emergent »arbitrariness«, »code invariance«, »neutral Lyapunov stability« or »Goldstone mode« constitutes the associated new additional symmetry established by the ritualisation transition. Common phase transitions are qualitative changes of thermodynamic equilibrium systems (Gibbs, 1878; Landau & Lifschitz, 1966; Stanley, 1971), either transitions of the 1st kind, such as the freezing of liquid water, or of the 2nd kind, such as the disappearance of ferromagnetism above the Curie temperature. Alternative to thermodynamic phase transitions, kinetic phase transitions with very similar qualitative properties are found in dynamical systems (Haken, 1977; Hirsch & Smale, 1974; Ebeling & Ulbricht, 1986; Nicolis & Prigogine, 1987; Feistel & Ebeling, 1989). For example, the onset of self-sustained oscillations, like those of a forced violin string, is a so-called »Hopf bifurcation« and represents a symmetry-breaking kinetic phase transition of the 2nd kind (Feistel & Ebeling, 1978, 2011; Ebeling & Feistel, 1982, 1994, 2018). Also the ritualisation transition is of this 2nd kind; its two phases possess different symmetries, their transition process proceeds continuously and without spatial nucleation threshold, and at the transition point the two phases are identical (Landau & Lifschitz, 1966: § 137 therein). When a new symbol is born by achieving arbitrariness, its native physical structure is still the same as that of its non-arbitrary predecessor before the transition.

The neutrality of a system with respect to small fluctuations, the absence of restoring forces, mathematically expressed by vanishing Lyapunov coefficients of a dynamical system (Hirsch & Smale, 1974; Haken, 1977), for example, is the reason for the appearance and persistent existence of many different regional dialects and languages. Neutral so-called »Goldstone modes« like this are characteristic for all carriers of symbolic information because of their arbitrariness with respect to assigning symbol to meaning by mere convention. Symmetry breaking, such as the

[65] Nöth (2000): p. 135. Quoted text: "Aus evolutionstheoretischer Sicht erscheint die Sphäre des Zeichenhaften zumeist als eine Stufe der Evolution, der eine Welt des noch nicht Zeichenhaften vorausgeht.".

emergence of the new coding symmetry along with the emergence of a symbol, is a fundamental physical phenomenon encountered also in various complex systems (Haken, 1973; Prigogine & Stengers, 1981; Feistel & Ebeling, 1989).

In 1914, when studying the pairing behaviour of certain waterfowls, Julian Huxley had first described the emergence of symbols in ethology as "if a ritual ceremony was developing out of a useful action, … [as] the gradual change of a useful action into a symbol and then into a ritual: or, in other words, the change by which the same act which first subserved a definite purpose directly comes later to subserve it only indirectly (symbolically) and then not at all."[66] Later, this transition process was termed *ritualisation* (Huxley, 1914, 1966; Lorenz, 1970, 1983; Tembrock, 1977; Klix, 1980; Feistel, 1990; Nöth, 2000).

"Ritualisation is the process by which the signal emerges from its 'unritualised' archetype."[67] "Phylogenetically, signal systems have derived from use systems. Ethology denotes … the emergence of signal activities as ritualisation."[68] "An activity chain which originally served other objective or subjective purposes ends in itself as soon as it has become an autonomous ritual."[69] In this paper, however, behavioural biology is considered as just a special case of universal ritualisation transitions which have coined the evolution of life since its very beginning (Feistel & Ebeling, 2011; Feistel, 2017a).

Although without actually employing the term *ritualisation*, conceptual models of molecular ritualisation transitions, such as the emergence of the genetic code, were described by Ebeling and Feistel (1982) and Deacon (2021). The convention defining the meaning of codons is implemented in the structure of tRNA molecules (Eigen, 2013) which during the translation process link the current codon to a certain amino acid included in the protein synthesis. In addition to this primary meaning, codons have a secondary, higher-level meaning in the functioning of the final protein (Lacková et al., 2017). In turn, the related hierarchy of meanings ultimately culminates in the organism's selective value and the associated phenotypic fitness landscape (Feistel & Ebeling, 1982, 2016). In addition to "naked" tRNA at the molecular level, the "living metabolic network in the egg cell" Lane (2022): p. 18 is also highly relevant for this holistic evaluation of the genetic information.

An important ritualisation example is the emergence of the human number system (Lévy-Brühl, 1921; Dantzig, 1930; Klix, 1980; Ifrah, 1991; Feistel, 2017a). Objects may exist in multiple instances, such as arrows, sheep or pieces of amber. Humans who own such things may be interested in an exchange of some of those for other things possessed by other humans. This leads naturally to the question of how many of one kind of good may be given away for how many of a different kind. In other

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[66] Huxley (1914): p. 504, 506.

[67] Lorenz (1970): p. 7. Quoted text: „Ritualisation ist der Vorgang, durch den … das Signal aus seinem »unritualiserten« Vorbild entsteht.".

[68] Tembrock (1977): p. 26. Quoted text: "Stammesgeschichtlich leiten sich Signalsysteme von Gebrauchssystemen ab. Die Ethologie bezeichnet mit Huxley die Entstehung von Signalbewegungen als Ritualisation."

[69] Lorenz (1983): p. 71. Ouoted text: „Die ursprünglich anderen objektiven und subjektiven Zwecken dienende Handlungskette *wird zu Selbstzweck, sowie sie zum autonomen Ritus geworden ist*.".

words, a method is required for the comparison of different sets. The cardinality of a set of objects is structural information, independent of any convention, while a spoken, written or otherwise stored numeral is symbolic information, depending on the convention of what the symbols of the numeral, the signs and positions of the digits, mean. Such symbols describing the amount of objects in a set emerged in ancient human history, while, by contrast, the actual amount of objects in a set does not depend on the presence of humans nor of any kind of symbols they may use. “In science, actually, the notion of size finds it position and meaning in the *number*; this in turn by the fingers, the corals of an abacus, or the dashes and dots put before the eyes.“[70]

By mapping one set to the other, element by element, two given sets may be compared without actually counting their cardinal numbers symbolically in an explicit manner. To compare a herd of horses with one of sheep, one may let one horse and one sheep pass a gate at the same time until one set is empty. Simpler than comparing two herds is a comparison of each herd separately with a suitable reference set, such as sticks, stones, scratches or fingers, one by one again. A convenient such reference set makes the effort unnecessary to bring two herds together to the same place for just the simple reason of comparing them. A mental representation of counting scratches in humans, birds or bees seems to be along a »mental number line«, from left to right

Fig. 4 Russian abacus »счёты« (»tally«), a reference set of movable beads used for counting. Photo by Staecker, public domain, https://en.wikipedia.org/wiki/Abacus

[70] Kant (1956): p. 290. Ouoted text: „Der Begriff der Größe sucht in eben der Wissenschaft seine Haltung und Sinn in der Zahl, diese aber an den Fingern, den Korallen des Rechenbretts, oder den Strichen und Punkten, die vor Augen gestellt werden.“.

(Giurfa et al., 2022). “One of the feral cognitive bases for modern symbolic thinking may be numerosity, that is, the ability to appreciate and understand numbers.”[71]

A reference set of sticks or fingers representing a herd of horses or sheep is symbolic; a finger acts as a symbol for a sheep. At this first stage of a ritualisation process, the structural information of the amount of sheep equals that of the amount of fingers. However, from the symbolic information of the fingers it cannot be concluded whether the represented objects are sheep or horses.

Mapping a given set onto some reference set, such as {1, 2, 3, …} or suitable beads as shown in Fig. 4, of the same cardinality is a process known as *counting* (Dedekind, 1888). „Let us bring to our mind the way the notion of number is introduced. Starting from the notion of the number 1, the process of counting is usually producing the further integer rational positive numbers 2, 3, 4 … This method of introducing the notion of number we may call the *genetic method*.“[72] If the fingers of one hand are used as a reference set, one may e.g. count one-by-one up to cardinalities of 5. Beyond that, one may use a finger of the other hand to indicate »plus one hand« and start counting with the fingers of the first hand again. This will work up to 25, or »two hands«. To go on, one may use an additional object, such as a toe, a scratch or a pebble, to indicate »plus two hands« and start over again with the very first finger. In German pubs, the number of beers ordered is often marked in groups of five on the beer mat. In Lincolnshire, where Isaac Newton grew up in the 17th century, shepherds had developed their own way of counting subgroups of 20 sheep each. Their corresponding figures started with Yan, Tan, Thetera, Pethera for 1, 2, 3, 4, up to Figgit for 20 (de Padova, 2017: p. 37 therein). “A lot of aboriginal languages have very limited concept of counting. Certain languages have the maximum count of 9.”[73]

The ten-finger system is the same way an *abacus*, Fig. 4, counts which was invented in various forms already millennia ago by ancient cultures, long before the modern, so-called »Arabic« numeral system became in general use. By counting one-to-one only up to a small number, such as an abacus row, and then counting by the next row the number of such groups, then of groups of groups, etc., the required number of pieces of the abacus increases only logarithmically with the cardinality of the sets to be counted. Modern computers do it the same way by using only (0,1) as the basic group, namely, by a single bit being either set or reset.

Already an abacus is a model of a set. While the number of elements in the first abacus row offers the same structural information as the amount of elements of the original set, an element of the second row may symbolically represent the number of fictitiously completed first rows. Different elements of the abacus have different meanings, by convention, and possess mutual relations.

[71] Coolidge and Overmann (2012): p. 204.

[72] Hilbert (1900): p. 180. Quoted text: „Vergegenwärtigen wir uns … die Art und Weise der Einführung des Zahlbegriffs. Ausgehend von dem Begriff der Zahl 1, denkt man sich gewöhnlich durch der Prozeß des Zählens zunächst die weiteren ganzen rationalen positiven Zahlen 2, 3, 4 … entstanden. …. Wir können diese Methode der Einführung des Zahlbegriffs die *genetische Methode* nennen.“.

[73] Elsayed (2021): p. 34.

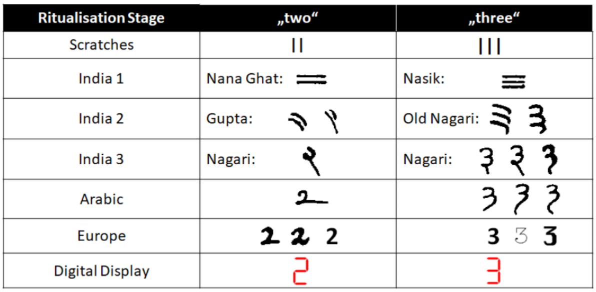

Fig. 5 Ritualisation and subsequent neutral drift of the so-called »Arabic« figures »two« and »three« at the bottom, starting from the original physical structures at the top. In the bottom row, even the structural similarity between scratches and horizontal bars is lost. Schematic modified from Ifrah (1991: Fig. 356 therein) and https://de.wikipedia.org/wiki/Drei

Very likely, body parts were the first natural reference sets used for counting. Ifrah (1991) decribes the three phases of ritualisation of spoken numerals:

- “*First phase*: … In the imagination [of humans], the number is still immediately bound to the perceived reality and not separable from the nature of objects in their immediate vicinity. ….
- *Second phase*: The numerals of the first phase, which in first instance are names of body parts, lose gradually their original meaning in the course of using them for counting. ….
- *Third phase*: … The numeral becomes distinguished from the name of the object and its pronunciation is modified so that the connection to the object is ultimately lost.”[74]

The ritualisation of written number symbols (Fig. 5) proceeds in a quite similar way as the spoken ones. Initially, an image (icon) of the optical appearance of the amount of elements in a reference set (fingers, sticks, scratches, pebbles) is drawn. The character becomes simplified for easier and faster writing by still maintaining a certain similarity with the original image. In the third phase, this similarity becomes irrelevant and the graphical symbols gain a meaning in their own right, forgetting about the initial shape. With the emergence of symbolic numerals, also the previous agreement has disappeared between the amount of counted elements and the counter; this step completes the ritualisation process of numbers.

> “Natural system itself requires from a man an ability to make some order of natural laws. Otherwise a man would not be able to survive in different parts of

[74] Ifrah (1991): p. 40, 42. Quoted text: “*Erste Phase*: … Die Zahl ist in seiner Vorstellung noch direkt an die wahrgenommene Realität gebunden und von der Natur der ihn unmittelbar umgebenden Gegenstände nicht ablösbar. … *Zweite Phase*: Die Zahlwörter der ersten Phase, die in erster Linie Namen für entsprechende Körperteile sind, verlieren durch ihren Gebrauch beim Zählen zunehmend ihre ursprüngliche Bedeutung. … *Dritte Phase*: Mit der Durchsetzung des Zahlworts … entsteht die Notwendigkeit, das Zahlwort vom Namen des Gegenstandes zu unterscheiden und seine Lautform so zu verändern, daß es in keinem Fall mehr mit dem Gegenstand in Verbindung gebracht wird.”.

times and different seasons of the year. This ability of ordering things led us to an ability counting and doing calculations."[75] Historically, numbers have developed from primitive ritualised symbols to powerful tools for the construction of scientific models; they suffice, for example, for a rigorous axiomatic definition of a spatial geometry (Hilbert, 1903). "Only by the purely logical construction of the number-science and the continuous number-realm gained by it, we have achieved the ability of precisely investigating our imaginations of space and time, relating those to the number-realm created in our mind."[76] "You don't need space to do geometry."[77]

Physically, after the ritualisation transition, the related newly emerged coding symmetry of an information-processing system constitutes a *Goldstone mode* of a dynamical system. A simple physical example for a Goldstone mode is the time displayed by a mechanical clock. One may change that setting arbitrarily without seeing the clock return automatically to some stable »ground state«, to some fictitious preferred natural time. Rather, without regular calibration, clocks tend to slip away from the intended precise time due to random perturbations, which is still a difficulty of modern atomic clocks (Gibney, 2022) and posed a grave problem to the navigation of medieval seafarers. For this reason, English navy chronometers had to be synchronised by a widely visible red »time ball« (see Fig. 7 below) raised exactly at 12:58 GMT on the top of the Greenwich observatory.

Such Goldstone modes are characterised by vanishing Lyapunov coefficients with respect to fluctuations, so that the system is neutrally stable and random deviations become neither suppressed nor amplified. Arbitrary symbols may »drift« by forming new »dialects« or graphical »fonts«, as it is well known from the historical evolution of natural languages. "In all aboriginal languages, vestiges of these sounds of nature are still to be heard; though, to be sure, they are not the principal fibres of human speech."[78] Regional dialects and languages have developed and continue to do so permitted by the conventional arbitrariness of assigning words to meanings, by the fact that human societies are neutrally stable with respect to changes in the symbols used for information exchange. Written language had significantly slowed down the »weathering« process of spoken language (Brunnhofer, 1871; Janson, 2002). While the early evolution of spoken languages did not leave structural marks still discernible today, various such traces of early written languages can be studied in archeol-

[75] Kulsariyeva and Zhumashova (2015): p. 1660

[76] Dedekind (1888): p. VIII. Quoted text: "Durch den rein logischen Aufbau der Zahlen=Wissenschaft und durch das in ihr gewonnene stetige Zahlen=Reich sind wir erst in den Stand gesetzt, unsere Vorstellungen von Raum und Zeit genau zu untersuchen, indem wir dieselben auf dieses in unserem Geiste geschaffene Zahlen=Reich beziehen."

[77] June Huh as quoted by Cepelewicz (2022)

[78] von Herder (1772): p. 10. Quoted text: „Jn allen Sprachen des Urſprungs tönen noch Reſte dieſer Naturtöne; nur freilich ſind ſie nicht die Hauptfäden der menſchlichen Sprache." English translation by Alexander Gode (1966).

ogy. “The doubt of ambiguity had often wiped out the deeds of humans, were they not established in memory by the eternal testimony of writing.”[79]

5. Observation and Measurement

Observation, or *symbolisation*, made by humans is a conversion process of structural into symbolic information at »run time« of a mental model. It requires the existence of previously ritualised symbols, such as numbers and languages, at »design time«. Of observation naturally performed by any organism, measurement constitutes the scientifically sophisticated version, resulting in external, objective symbols complementing the internal, subjective ones. “The general concept of measurement is a specific interaction of a measuring agent or instrument with a physical system that entails a symbolic outcome.”[80] “The term measurement denotes *an operation performed on a system for the purpose of obtaining a numerical value which can ... be assigned to some definite, nameable observable*.”[81] ”Measurement operations are … empirical procedures which, when performed upon physical systems, yield the *numbers* called data.”[82]

More than 500 million years ago, neurons possibly (Arendt, 2020, 2021) “emerged in the last common ancestor of today’s animals - and … their progenitors were secretory cells, whose primary function was to release chemicals into the environment.”[83] The emergence of neurons as carriers of symbolic information, starting from secretory or other specific effector cells, was a ritualisation transition which laid the hardware basis for the cognition processes of recent humans. “The modular model of [the human] visual system has developed from a model where action and perception are considered as segregate to a model where action and perception are considered as two labels of the same concept.”[84] Neuronal symbols are nerve pulses, transmitter substances and likely intracellular RNA molecules which function independently of the particular structural information they may represent, similar to digital memory chips and wires in modern computers.

“I can declare with absolute certainty that it is our brain that endows each of us with experience and memories, imaginations and dreams.”[85] “I mean that through the senses external objects convey into the mind something that produces there … perceptions [= ‘ideas’]. This great source of most of the ideas we have I call *sensation*.”[86]

[79] Borwin III (1252): Quoted text: “Gesta hominum plerumque ambiguitatis scrupulus aboleret, si non perhenni litterearum testimonio fulcirentur”.

[80] Pattee and Rączaszek-Leonardi (2012): p. 5.

[81] Margenau and Park (1973): p. 20.

[82] Park (1970): p. 25.

[83] Pennisi (2019): p. 212.

[84] Baccarini (2013): p. 229.

[85] Eccles (1976): p. 17. Quoted text: „Ich kann mit absoluter Sicherheit behaupten, daß es unser Gehirn ist, das jedem von uns Erfahrungen und Erinnerungen, Vorstellungen und Träume schenkt.“.

[86] Locke (1872): p. 83. Quoted text: „Ich [meine], dass die Sinne von äussern Gegenständen das der Seele zuführen, was die Vorstellung in ihr hervorbringt. Diese grosse Quelle unserer meisten Vorstellungen,

Fig. 6 Aneroid barometer. The metallic membrane in the background is deformed by air pressure (structural information) and turns the pointer in the foreground over a scale divided in units of mm Hg (symbolic information). Written number symbols serve for easier counting of the units. Private photo

When watching a scene, such as if looking at an instrument as shown in Fig. 6, light falls through the lenses of our eyes and produces an image of the scene at our retinas, which is structural information of the world carried by the light, independent of any arbitrary conventions. Inside the receptor cells, selected photons of the incoming light excite special optically sensitive molecules which, by complex cellular processes, generate a standardised conventional nerve pulse. The output frequency of

die ganz von unsern Sinnen abhängen, nenne ich die Sinnes-Wahrnehmung." English text from Jonathan Bennett, 2017.

such pulses is proportional to the local brightness of the image in a certain wavelength range, while the local colour and pixel position is encoded by the particularly excited nerve tract. This way, optical observation is the transformation of structural information, the brightness pattern on the retina, into symbolic information, the number and distribution of generated nerve pulses. "In the entire central nervous system *any signal transmission occurs by encoded information in the form of pulses of equal size*."[87] The convention of how symbolic neuronal information is related to the physical properties of arriving structural information is arbitrary and has been established, to some extent randomly, in the course of evolution.

At this point it may be relevant to emphasise that the visual receptor molecules absorb only single light quanta as those come in, and exchange related portions of energy between the incident ray of light and certain electrons of the sensor molecules; this quantum-mechanical exchange process is all we may actually perceive optically about the status of the entire world. The coloured picture we consciously recognise when we open our eyes is produced by our brain from those clouds of random photons, using an inherited mental prediction model which is processing exclusively symbolic information. "Objects and events are, in contrast to colour, loudness or brightness, no items that could be recognised immediately by our eyes and ears. Rather, we need to extract and derive them out of a flood of physical stimuli."[88] "Space, time and physical objects are not objective reality. They are simply the virtual world delivered by our senses to assist us in the game of life."[89] "The construction of the axioms of geometry and the investigation of their mutual relations … constitute a logical analysis of our spatial perception."[90]

Scientific measurement is a specific form of observation by which, typically, a measuring instrument is arranged between our receptor cells and the target of our interest, the so-called measurand (BIPM, 2012). While there exist also non-quantitative measurements (Pattee, 1986; White, 2011), we shall focus here on numerical measurement results. What is a »quantity«? "Quantities as used in sciences are therefore generalized forms of numbers. … Quantities do not exist in nature, cannot be observed in nature, and quantities are abstract mathematical concepts we use for describing nature."[91] It is straightforward in this case that measurement is a conversion process of structural information (physical structure of the measurand) to symbolic information (quantitative measurement result). "Measurement is a form of symbolisation. It consists in assigning numerals to objects or quantities."[92] The actual key process of this conversion is the counting of certain elements, Sect. 4, which is

[87] Eccles (1976): p. 28. Quoted text: „Im gesamten Zentralnervensystem … *erfolgt jegliche Signalgebung mittels codierter Information durch Impulse gleicher Größe*.".

[88] Donald (2008): p. 193. Quoted text: „Objekte und Ereignisse sind, im Gegensatz zu Farbe, Lautstärke oder Helligkeit, keine über die Augen und Ohren erfassbaren unmittelbaren Gegebenheiten. Wir müssen sie vielmehr aus einer Flut von physikalischen Impulsen herausfiltern und ableiten.".

[89] Hoffman (2020): p 15: Quoted text: „Raum, Zeit und physische Objekte sind nicht objektive Realität. Sie sind schlicht die von unseren Sinnen gelieferte virtuelle Welt, die uns beim Spiel des Lebens hilft.".

[90] Hilbert (1903): p. 1. Quoted text: "Die Aufstellung der Axiome der Geometrie und die Erforschung ihres Zusammenhanges … läuft auf die logische Analyse unserer räumlichen Anschauung hinaus."

[91] Feller (2011): p. 144.

[92] Craik (1943): p. 75.

the only way of assigning a symbolic number (subject to conventions) to a physical structure (independent of conventions). The traditional way of reading a measurement result is counting a number of arbitrarily specified units, such as the distance between two marks on the scale of a barometer, Fig. 6. Also the mural quadrant of Ulugh Beg, Fig. 2, had such a scale for counting. "The minutes of latitude [of Ulugh Beg's catalogue] indicate clearly that the instrument used was graduated to 3 minutes of the arc."[93] Modern measurement devices often use analog-to-digital converters to do the counting quicker and more precisely than the human eye, such as counting the number of oscillations registered within a definite time interval, and display the result as human-readable symbolic numbers or store computer-readable binary numbers. "Never measure anything but frequency"[94] is a guiding paradigm of metrologists.

Measurement instruments or experimental setups are often designed in a way that the change of the intended measurand is structurally connected in a well-known way with a spatial or temporal variation of a part of the instrument, so that the actual measurement is mapped onto a measurement of a spatial or temporal distance, as in the case of the barometer, Fig. 6, where a change of air pressure is indicated by a displacement of the pointer. Scientific measurement, such as of a length, is carried out by means of »metrological concepts« which represent special mental models. "Concepts are only mental constructs which we have conceived in our mind. … To find the length of an object, we have to perform certain physical operations. … The concept of length involves as much as and nothing more than the set of operations by which length is determined. … The concept is synonymous with a corresponding set of operations."[95]

When children play »ready or not«, in order to measure the waiting time, one is counting out loud up to 10 or so while the others are trying to hide. „A clock is understood as a thing which delivers countable events, … whose similar partial processes of the event sequence to be counted are permitted to be considered to equal one another."[96] "The 'time' of an event is understood as the time indication (pointer position) of those clocks which are (spatially) immediately adjacent to that event."[97] The numerical display of a common digital clock is a simple example for countable events, which is usually counting mechanical oscillations of a quartz crystal. Traditional mechanical clocks count oscillations of a pendulum or balance wheel, and map that number to a distance around the clock face, labelled with hours and minutes along the scale, converting time measurement to length measurement. Still in 1642, time was measured by monks who fastidiously watched a pendulum and counted patiently, until Christiaan Huygens eventually developed a mechanical counter, a stop-and-go gear to mechanically link the reversible motion of the pendulum to an

[93] Knobel (1917): p. 11.

[94] Bothwell et al. (2022): p. 420.

[95] Lee et al. (2022): p. 237.

[96] Einstein (1969): p. 5,6. Quoted text: „Unter einer Uhr versteht man ein Ding, welches abzählbare Erlebnisse liefert, … [deren] an ihr gezählten gleichartigen Teilvorgänge der Erlebnisfolge als einander gleich angesehen werden dürfen.".

[97] Einstein (1973), p. 23. Quoted text: „Man [versteht] unter der ‚Zeit' eines Ereignisses die Zeitangabe (Zeigerstellung) derjenigen … Uhren, welche dem Ereignis (räumlich) unmittelbar benachbart ist.".

irreversible, stepwise displacement of a pointer over a scale (de Padova, 2017: p. 75 therein; Haroche, 2022: p. 80 therein). Still today, the definition of time is a metrological and political challenge (Gibney, 2022; Levine et al., 2023).

"The length of a certain distance must be specified arbitrarily, such as to equal 1 (unity stick). It follows easily that placing a stick of length *s* along a straight line, repeatedly *n* times, results in a distance of length *n•s*. Therefore, a length means the result of a measurement carried out with a unity stick along a straight line."[98] In geometry, elementary counting of objects has advanced mathematically to establish a spatial metrology. "Pascal's Theorem permits introducing into geometry a calculation with line segments in which all calculation rules for real numbers remain valid without exception."[99] "The number of repetitions of placing [a unity stick] is the measured value of a distance. … Any measurement of distances relies thereon."[100] The unity segments of geometry are mental models of rigid bodies. For example, historical British distance units of length, arbitrarily defined, are shown in Fig. 7. An anecdote says that an English king defined the yard in a certain mood by ordering to "take the span between the middle of my chest and my finger tips."[101]

Experience is symbolically memorised observation, including scientific measurements. Roughly, phylogenetic experience, stored genetically by mutation and selection processes, is responsible for the hardware of mental models at »design time« while ontogenetic experience, stored neuronally (plus fairly recently by written or printed documents and on computers), provides the symbolic information for using mental prediction models at »run time«. Trying to distinguish by introspection the two contributions of genetic and neuronal information from one another constitutes a severe epistemic problem. "Experience never grants its conclusions true or rigorous, but only assumed and comparative generality, so that one should better say: as far as we have recognised, no exception has been found to this or that rule. …. Necessity and rigorous generality are therefore safe indicators of an a-priori insight, and belong inseparably together."[102] However, as far as Kant's "a-priori insight" is identified with the mental model acquired by phylogenetic experience, recorded genetically, the purported "necessity and rigorous generality" should be questioned similarly to that of any other experience.

[98] Einstein (1969): p. 9. Quoted text: „Die Länge einer bestimmten Strecke [muss] willkürlich festgesetzt, z. B. gleich 1 gesetzt werden (Einheitsmaßstab). Man [folgert] leicht, daß man durch *n*-maliges Abtragen einer Strecke *s* auf einer Geraden eine Stecke von der Länge *n s* erhält. Eine Länge bedeutet also das Ergebnis einer längs einer Geraden ausgeführten Messung mit Hilfe eines Einheitsmaßstabs.".

[99] Hilbert (1903): p. 39. Quoted text: „Der … Pascalsche Satz setzt uns in den Stand, in die Geometrie eine Rechnung mit Strecken einzuführen, in der die Rechnungsregeln für reelle Zahle sämtlich unverändert gültig sind.".

[100] Einstein (1973), p. 9,10. Quoted text: „Die Zahl der Wiederholungen des Abtragens [eines Einheitsmaßstabs] ist die Maßzahl der Strecke… Hierauf beruht alles Messen von Längen.".

[101] Schrödinger (2020): p. 37. Quoted text: „Nehmt die Spanne zwischen der Mitte meiner Brust und meinen Fingerspitzen.".

[102] Kant (1956): p. 40. Quoted text: „Erfahrung gibt niemals ihren Urteilen wahre oder strenge, sondern nur angenommene und komparative Allgemeinheit, so daß es eigentlich heißen muß: soviel wir bisher wahrgenommen haben, findet sich von dieser oder jener Regel keine Ausnahme. … Notwendigkeit und strenge Allgemeinheit sind also sichere Kennzeichen einer Erkenntnis a priori, und gehören auch unzertrennlich zueinander.".

Fig. 7 British imperial units of length measurement at the Greenwich observatory. Photo taken in September 2013

Kant understood the fundamental role of our evolutionarily emerged mental model for any kind observation in a way that "all of our opinion is nothing but an imagination of phenomena: all the things at which we look are for themselves not the same as they seem to us, nor are their relations on their own conditioned as they appear to us. If we ultimately remove our subject, or even only our subjective construction of senses, all the structure, all the relations of objects in space and time, even space and time would disappear, and can exits as phenomena only inside us and not on their own. It remains completely unknown what the case is of things-in-themselves, isolated from all the receptivity of our sensation. We do not know any other than our peculiar way of perceiving things."[103]

Most of famous philosophers and physicists agree that experience is the very origin of our understanding of the world and the basis of human mental models. „The

[103] Kant (1956): p. 83. Quoted text: „Wir haben also sagen wollen: daß alle unsere Anschauung nichts als die Vorstellung von Erscheinung sei: daß die Dinge, die wir anschauen, nicht das an sich selbst sind, wofür wir sie anschauen, noch ihre Verhältnisse so an sich selbst beschaffen sind, als sie uns erscheinen, und daß, wenn wir unser Subjekt oder auch nur unsere subjektive Beschaffenheit der Sinne überhaupt aufheben, alle die Beschaffenheit, alle Verhältnisse der Objekte im Raum und Zeit, ja selbst Raum und Zeit verschwinden würden, und als Erscheinungen nicht an sich selbst, sondern nur in uns existieren können. Was es für eine Bewandtnis mit den Gegenständen an sich und abgesondert von aller dieser Rezeptivität unserer Sinnlichkeit haben möge, bleibt uns gänzlich unbekannt. Wir kennen nichts, als unsere Art, sie wahrzunehmen, die uns eigentümlich ist.".

notion of a ‚real external world‘ of everyday life is exclusively based on sensual impressions.”[104] „Without doubt, the primary assumption of epistemology is that the sensations are the only source of our knowledge.“[105] „There appear not to be any ideas in the mind before the senses have conveyed any.“[106] „The sense provides the thing, but the mind assigns a name to it. … What the deed is in the sense is only the name in the mind.”[107] „Without sensation no object were given to us, and without understanding no one were thought.“[108] “The big fundamental question of all … philosophy is that of the relation between thought and being.”[109] While some authors argue that „any contemplation and any knowledge can be represented linguistically”[110], others “doubt that the language for our perceptions … may design a true description of what is.”[111] “It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.“[112] In this sense, theoretical physics may be considered as a collection of mental, mostly mathematical models for observed and predicted fundamental properties of the real world, represented symbolically in the form of written natural laws, empirical rules and equations for measurable and related unmeasurable quantities.

6. Causality: Natural Law or Model Concept ?

The *world*, wrote Immanuel Kant in 1787, is „the mathematical entity of all phenomena“, in contrast to *nature*, which „denotes the *world* considered as a *dynamical* entity.“[113] “Causality … characterises the connection between cause and effect events through time for a dynamical system.”[114] „Any succession of phenomena is only change; all changes happen by the law of *causality*, by the connection between cause

[104] Einstein (1936): p. 314. Quoted text: „Der Begriff der ‚realen Aussenwelt‘ des Alltagsdenkens stützt sich ausschliesslich auf die Sinneseindrücke.“.

[105] Lenin (1975): p. 121. Quoted text: „Die erste Annahme der Erkenntnistheorie besteht ohne Zweifel darin, daß die Empfindungen die einzige Quelle unserer Kenntnisse sind.“.

[106] Locke (1872): p. 679. Quoted text: „Nichts ist im Geist, was nicht vorher in den Sinnen war.“.

[107] Feuerbach (1848): p. 245: Quoted text: „Der Sinn gibt die Sache, der Verstand aber gibt den Namen dazu her. … Was im Sinne der Tat nach, das ist im Verstande nur dem Namen nach.“ For this quotation, Feuerbach had referred to Leibniz (1765): p. 292, „Il s’ensuit de ce que je venois de dire que ce qu’on appelle general et universel n’appartient point à l’existence des choses, mais que c’est un ouvrage de l’entendement.“.

[108] Kant (1956): p. 95. Quoted text: „Ohne Sinnlichkeit würde uns kein Gegenstand gegeben, und ohne Verstand keiner gedacht werden.“.

[109] Engels (1952): p. 343. Quoted text: „Die große Grundfrage aller … Philosophie ist die nach dem Verhältnis von Denken und Sein.“.

[110] Schimming (2022): p. 23. Quoted text: „Jede Überlegung und jedes Wissen kann sprachlich dargestellt werden.“.

[111] Hoffman (2020): p. 84: Quoted text: „Ich bezweifle auch, dass die Sprache für unsere Wahrnehmungen … eine wahre Beschreibung dessen entwerfen kann, was ist.“.

[112] Petersen (1963): p. 12.

[113] Kant (1956): p. 447. Quoted text: „Welt … bedeutet das mathematische Ganze aller Erscheinungen. … Eben dieselbe Welt wird aber Natur genannt, sofern sie als ein dynamisches *Ganzes* betrachtet wird.“.

[114] Zhang and Liu (2023): p. 1.

and effect. [This] connection is not a result from mere observation but is rather the product of the synthetic ability to imagine two virtual states of which one precedes the other in time.“[115] Virtual states constitute information stored in symbolic form. The perception of dynamical processes is possible only if observation can be stored symbolically in memory. "A cognitive system can compare memories only if it can split its attention between two mental objects."[116]

"Natural science, at its core … is concerned with empirically determinable alternatives."[117] "All natural laws and all efficacy of bodies are exclusively discovered by experience."[118] "A physical law is only a summary of experimental results."[119] "By natural law we tend denote nothing else than a regularity in the process of appearance, registered with sufficient certainty, *as far as this regularity is thought of as necessary in the sense of the causality principle*."[120] "A natural law is nothing but idealised experience, a lucky summary of a larger or lesser number of observational facts."[121] Stored experience and observational facts are symbolic information, so that also natural laws are expressed as symbolic information.

Natural laws are symbolic rules that discriminate between invalid and valid mental models with respect to their representation of observations. "Laws are something that mainly consists of prohibiting possible cases."[122] "The laws of physics … can be interpreted as counterfactual assertions"[123] as they describe fictitious, mentally imagined situations together with facts. "A law exists … only there where also injustice exists, because the law is the distinction between justice and injustice."[124] With respect to physics, violation of natural laws is possible only by mental models but is by definition not observable in nature. "A miracle is a violation of natural laws …

[115] Kant (1956): p. 241, 242. Quoted text: „Aller Wechsel (Sukzession) der Erscheinungen ist nur Veränderung. … Alle Veränderungen geschehen nach dem Gesetze der Verknüpfung der Ursache und Wirkung. … Verknüpfung [ist] kein Werk des bloßen Sinnes und der Anschauung, sondern hier das Produkt eines synthetischen Vermögens der Einbildungskraft. … Diese kann aber gedachte zwei Zustände auf zweierlei Art verbinden, so, daß der eine oder der andere in der Zeit vorausgehe.“.

[116] Donald (2008): p. 238. Quoted text: „Ein kognitives System … [kann] Erinnerungen nur dann vergleichen, wenn es … im Stande ist, seine Aufmerksamkeit zwischen zwei mentalen Objekten aufzuteilen.“.

[117] Görnitz (1999) referring to C.F. von Weizsäcker: p. 200. Quoted text: „Naturwissenschaft in ihrem Kern … befaßt sich mit empirisch entscheidbaren Alternativen.“.

[118] Hume (1967): p. 45. Quoted text: „Alle Naturgesetze und alle Wirksamkeiten der Körper [werden] ausnahmslos nur durch Erfahrung erkannt.“.

[119] Brillouin (2013): p. 289.

[120] Schrödinger (1979): p. 10. Quoted text: „Als Naturgesetz … bezeichnen wir doch wohl nichts anderes als eine mit genügender Sicherheit fest gestellte Regelmäßigkeit im Erscheinungsablauf, *sofern sie als notwendig im Sinne des [Kausalitätsprinzips] gedacht wird*.“.

[121] Nernst (1922): p. 489. Quoted text: „Ein Naturgesetz ist nichts anderes als idealisierte Erfahrung, eine glückliche Zusammenfassung einer mehr oder weniger großen Zahl von Beobachtungstatsachen.“.

[122] Stachowiak (1973): p. 29. Quoted text: "*Gesetzmäßigkeit* [ist] etwas, das vor allem im Verbieten möglicher Fälle besteht.“.

[123] Pearl & Mackenzie (2018): p. 33.

[124] Aristoteles (2019): Fifth book, p. 135. Quoted text: "Ein Gesetz gibt es … nur dort, wo es auch Ungerechtigkeit gibt; denn das Recht ist die Unterscheidung des Gerechten vom Ungerechten."

No testimony may suffice to state a miracle."[125] Nature does neither need nor possess enacted laws to function the way it does, only humans need symbolic natural laws in order to describe and understand this functioning. "Nature … cannot do otherwise but always acting lawfully."[126]

Immanuel Kant made an "apparently daring" (as he had put it) statement regarding natural laws. "*Understanding does not extract its laws* (a priori) *from nature but dictates those to nature*."[127] He explained his thesis by specifying what »nature« in this context means. Here, "we do not refer to the nature of *things in themselves*, which is independent of the conditions of our sensation and understanding, but rather to the nature as a subject of possible experience."[128] Here, we follow Kant in the sense that natural laws are human symbolic statements that apply to mental models of the world rather than to the physical reality itself.

Here it is agreed with physicists such as Einstein or Landau in demanding that even in the theory of relativity, the causality law is rigorously obeyed in the sense that any cause happens earlier than the effect, no matter from which reference frame this sequence may be observed. Phenomena like goal setting or morphogenesis, if the final goal is identified with the cause of the process, may be described using an alternative definition of causality. In particular, semiotic causality is a concept of semiotic mental models (Nöth, 2000: Sections III.2.3.4 and III.11.4 therein).

"An extreme situation arises when we have what is referred to as a *causality violation* in which closed timelike curves can occur, and it becomes possible for a signal to be sent from some event into the past of that same event! … Some physicists … [are] prepared to admit the possibility of *time travel* that such closed timelike curves would allow."[129] Accordingly, time travel violating causality is possible in certain mental models but has never been observed yet in reality. Mental models are tools permitting the imagination of virtual worlds beyond familiar experience and established natural laws, such as in scientific hypotheses, legends, films, novels or computer simulations. As one may easily imagine, in certain mental models such as a reverse movie, even a broken egg shell like »Humpty Dumpty« could be "put together again".

Discovered from astronomical observation, the dynamical laws of Johannes Kepler and Isaac Newton are valid for classical mechanics, which is a mental model consistent with naïve realism, but those laws fail in explaining quantum or relativistic phenomena. "Copernicus' solar system was a hypothesis for three hundred years …; but when Leverrier calculated from the data of that system not only the necessity of the existence of an unknown planet, but even the place where this planet must be located in the sky, and Galle eventually really found that planet, then Copernicus' system was

[125] Hume (1967): p. 147, 149. Quoted text: „Ein Wunder ist eine Verletzung der Naturgesetze … Kein Zeugnis genügt, um ein Wunder zu konstatieren.".

[126] Goethe (2016): p. 134. Quoted text: „Die Natur … kann nicht anders als ewig recht handeln.".

[127] Kant (2016): p. 67. Quoted text: "*Der Verstand schöpft seine Gesetze* (a priori) *nicht aus der Natur, sondern schreibt sie dieser vor*."

[128] Kant (2016): p. 69. Quoted text: "Wir haben es nicht mit der Natur *der Dinge an sich selbst* zu tun, die ist sowohl von den Bedingungen unsrer Sinnlichkeit als des Verstandes unabhängig, sondern mit der Natur, als einem Gegenstand möglicher Erfahrung."

[129] Penrose (2004): p. 409.

proven."[130] The discovery of planet Neptune in 1846 was also an important confirmation of the natural laws formulated by Kepler and Newton for remote regions of the world, inaccessible to experiments at their time, but accessible to observation. To investigate the mutual relation between these laws, Henri Poincare had argued that "the ultimate goal of celestial mechanics is to resolve the great problem of determining if Newton's law alone explains all astronomical phenomena."[131] He concluded that "rather than studying directly the phenomenon's whole succession, one can limit oneself to writing out its 'differential equation'; in place of Kepler's laws, one substitutes those of Newton."[132]

Causality cannot be observed. "Through its sensational properties, no object may ever reveal the causes that produced it nor the effects that will result from it."[133] "The idea can only be an idea of pure understanding which is not in perception, and this idea is that of the relation between cause and effect."[134] "Ever since metaphysics has appeared, no occurrence other than *David Hume*'s attack on it could have become more crucially, considering the fate of this science. …. *Hume* mainly started from the only but important notion of metaphysics, namely the *connection between cause and effect* (and along with that also implied notions such as force and action). He proved unequivocally: that it is strictly impossible for the understanding, a priori, and from the notions to think of such a connection, … that the reason completely dupes itself with this notion, falsely taking it for its own child while it is just a bastard of the force of imagination, inseminated by experience."[135] "The notion of cause includes a rule after which a state is necessarily followed by another state; experience, however, can only show us that often … a state is followed by another one, and can therefore neither provide rigorous generality nor necessity."[136]

130 Engels (1952): p. 345. Quoted text: „Das kopernikanische Sonnensystem war dreihundert Jahre lang eine Hypothese … ; als aber Leverrier aus den durch dies System gegebenen Daten nicht nur die Notwendigkeit der Existenz eines unbekannten Planeten, sondern auch den Ort berechnete, wo dieser Planet am Himmel steht müsse, und Galle dann diesen Planeten wirklich fand, da war das kopernikanische System bewiesen.".

131 Goroff (1993): p. I17.

132 Goroff (1993): p. I18.

133 Hume (1967): p. 44. Quoted text: „Kein Gegenstand enthüllt jemals durch seine sinnfälligen Eigenschaften die Ursachen, die ihn hervorgebracht haben, oder die Wirkungen, die aus ihm entstehen werden.".

134 Kant (1956): p. 242 (edition B). Quoted text: "Der Begriff … kann nur ein reiner Verstandesbegriff sein, der nicht in der Wahrnehmung liegt, und das ist hier der Begriff des Verhältnisses der Ursache und Wirkung."

135 Kant (2016): p. 6. Quoted text: "Seit dem Entstehen der Metaphysik … hat sich keine Begebenheit zugetragen, die in Ansehung des Schicksals dieser Wissenschaft hätte entscheidender werden können, als der Angriff, den *David Hume* auf dieselbe machte. … *Hume* ging hauptsächlich von dem einzigen, aber wichtigen Begriffe der Metaphysik, nämlich der *Verknüpfung der Ursache und Wirkung* (und mithin auch dessen Folgebegriffe der Kraft und Handlung etc.) aus. … Er bewies unwidersprechlich: daß es der Vernunft gänzlich unmöglich sei, a priori, und aus den Begriffen eine solche Verbindung zu denken, … daß die Vernunft sich mit diesem Begriffe ganz und gar betriege, daß sie ihn fälschlich für ihr eigen Kind halte, da er doch nichts anders als ein Bastard der Einbildungskraft sei, … durch die Erfahrung beschwängert.".

136 Kant (2016): p. 63. Quoted text: "Der Begriff der Ursache enthält eine Regel, nach der aus einem Zustande ein anderer notwendiger Weise folgt; aber die Erfahrung kann uns nur zeigen, daß oft … auf einen Zustand der Dinge ein anderer folge, und kann also weder strenge Allgemeinheit, noch Notwendigkeit verschaffen."

"I know well that with respect to the observable no causality exists; I consider this insight as ultimate."[137] "When in 1926 the quantum and wave mechanics had come to a completion, it had an end with the causality in the sense of classical physics."[138] "Statistics … tells us that correlation is not causation, but it does not tell us what causation is."[139] "Despite all its Sisyphean efforts, philosophy cannot define and explain antecedent causality in reasonably transparent terms."[140] Repeated observations of the barometer, Fig. 5, confirm correlation between deformations of the membrane in the back and the pointer in front, but do not reveal their mutual causal relation. Temporally highly resolved observations, however, may reveal a tiny delay between the two indicators. "People use temporal information including order, delay, and variability to infer causality between events."[141] "The temporal sequence, however, is the only empirical criterion of the effect in relation to the cause which precedes the effect."[142] From the logical problems with defining notions such as *causality*, *cause*, *effect*, *necessity* or *event*, Bertrand Russell concluded that „the reason why physics has ceased to look for causes is that, in fact, there are no such things. … All philosophers, of every school, imagine that causation is one of the fundamental axioms or postulates of science, yet, oddly enough, in advanced sciences … the word 'cause' never occurs. … The law of causality, I believe, … is a relic of a beyond age."[143] The greatest scientific achievement of Bertrand Arthur William, the Third Earl Russell, so his full name, "is in mathematical logic, ranking him … with history's greatest logicians."[144]

Causality is a human mental prediction tool (Orcutt, 1952). In 1948, with respect to the "presently prevalent struggle about the meaning and validity of the causal law in modern physics"[145], Max Planck suggested that "an event is causally conditioned if it can be predicted with certainty, … [while accepting that] in not a single case it is possible to precisely predict a physical event."[146] Particular natural laws are assumed to be valid for certain groups of mental models. Repeated observations of model predictions may or may not confirm this validity. Causality is such an assumption.

Causality is an essential concept of human mental model building. "*Hume* had never cast any doubt on whether the notion of cause were correct, useful, and indis-

[137] Einstein and Born (1982): p. 222. Quoted text: „Ich weiß wohl, daß in Bezug auf das Beobachtbare keine Kausalität existiert; ich halte diese Erkenntnis für endgültig.".

[138] Born (1965a): p. 62. Quoted text: „ Als 1926 … die Quanten- und Wellenmechanik zum Abschluß kam, hatte es ein Ende mit … der Kausalität im Sinne der klassischen Physik. ".

[139] Pearl and Mackenzie (2018): p. 5.

[140] Klimenko (2022): p. 1.

[141] Rehder et al. (2022): p. 1.

[142] Kant (1956): p. 253 (edition A). Quoted text: "Die Zeitfolge allerdings [ist] das einzige empirische Kriterium der Wirkung, in Bezug auf die Ursache, die vorhergeht."

[143] Russell (1919): p. 180.

[144] Doxiadis and Papadimitriou (2009): p. 335.

[145] Planck (1948a): p. 3. Quoted text: " … in dem gegenwärtig herrschenden Streit über die Bedeutung und die Gültigkeit des Kausalgesetzes in der modernen Physik …".

[146] Planck (1948a): p. 4,5. Quoted text: "Ein Ereignis ist dann kausal bedingt, wenn es mit Sicherheit vorausgesagt werden kann. … In keinem einzigen Falle ist es möglich, ein physikalisches Ereignis genau vorauszusagen.".

pensable with respect to the entire understanding of Nature."[147] "For anybody who denies causality, every natural law is a hypothesis."[148] "Only very very reluctantly I give up perfect causality."[149] "All physical laws are based on complexes of causal relations."[150] „Causality is the supposition for any gain of experience. Nothing could be explained without causality."[151] "The human brain is the most advanced tool ever devised for managing causes and effects. … Causal explanations, not dry facts, make up the bulk of our knowledge."[152] Max Born came to the conclusion that "some of the fundamental notions of physics cannot be reduced to anything deeper but must be accepted by an act of belief. … Causality is such an irreducible principle if defined as the belief in the existence of a mutual physical dependency of observable situations."[153] "The validity of the causal law is connected with the possibility of making correct predictions for the future."[154] "By means of causality, temporally extended objects can be integrated uniformly."[155] "Learning about causal structure is central to higher level cognition because it allows people to predict the future, select beneficial actions, and make sense of the past."[156] In climate research, for example, asking for causality and to distinguish between cause and effect is a crucial task (Frankignoul & Kestenare, 2005; Feistel & Ebeling, 2011; Stips et al., 2016).

Causality is a phylogenetically inherited construction principle for mental prediction models. Similarly to space and time, the idea of causality seems to be anchored deeply and rigidly in our genetically implemented mental model of naïve realism which has ensured unbroken survival of innumerous generations of our ancestors. When the first humans appeared, their native curiosity turned into addiction to causality. Virtually every culture invented its own ghosts and gods to explain the unexplained (Azlan, 2019). "As the causal law occupies already immediately the awaking soul of a child and puts the tireless question 'why?' into its mouth, so it accom-

[147] Kant (2016): p. 7. Quoted text: "Ob der Begriff der Ursache richtig, brauchbar, und in Ansehung der ganzen Naturerkenntnis unentbehrlich sei, … hatte *Hume* niemals in Zweifel gezogen.".

[148] Engels (2017): p. 204. Quoted text: „Wer Kausalität leugnet, dem ist jedes Naturgesetz eine Hypothese.".

[149] Einstein et al. (1982): Letter to Max Born on 27 Jan 1920, p. 44. Quoted text: „Ich verzichte aber sehr sehr ungern auf die vollständige Kausalität.".

[150] Röseberg (1975): p. 60. Quoted text: „Allen physikalischen Gesetzen liegen Komplexe von Kausalitätsbeziehungen zugrunde.".

[151] Riedl and Kaspar (1981): p. 120. Quoted text: „Kausalität ist … eine Voraussetzung jedes Erfahrungs-Gewinns. Nichts ließe sich ohne Kausalität erklären.".

[152] Pearl and Mackenzie (2018): p. 2, 24.

[153] Einstein et al. (1982): p. 223, 324. Quoted text: „Einige der Fundamentalbegriffe der Physik [können] auf nichts Tieferes zurückgeführt werden …, sondern [müssen] durch einen Glaubensakt angenommen werden. … Die Kausalität ist solch ein [irreduzibles] Prinzip, wenn sie als der Glaube an das Vorhandensein einer gegenseitigen physikalischen Abhängigkeit beobachtbarer Situationen definiert wird.".

[154] Planck (1948a): p. 3. Quoted text: „Die Gültigkeit des Kausalgesetzes … [steht in Verbindung] mit der Möglichkeit, zutreffende Voraussagen für die Zukunft zu machen.".

[155] Kull (2001): p. 4. Quoted text of Jakob von Uexküll: „Mit Hilfe der Kausalität [können] die zeitlich ausgedehnten Objekte einheitlich zusammengefasst werden.".

[156] Rehder et al. (2022): p. 1.

panies the researcher through his whole life.“[157] Controlled by mental prediction models, and in turn testing those, “it is the human activity that gives rise to the idea of causality.“[158] „We struggle for attributing cause and effect. Seeing events causally connected is an outstanding strategy to master our daily life.“[159]

7. Prediction: Life's Imperative

Causal mental models made humans overwhelmingly predominant in biological and social competition. Our obsessive thinking in terms of causality is a genetic heritage from countless generations of successful biological ancestors. It is so fundamental to the human mind that Immanuel Kant (1956) classified causality as an a-priori principle of reason rather than an empirical conclusion from experience.

> "For an organism the world must be predictable, otherwise it cannot live therein."[160] Causal mental models provide a systematic option of predicting expected future experience with fairly reliable results. „One of the most powerful properties of thought is its power of predicting events.“[161] "It is the function of our thinking to use and to connect [our ideas] in such a way that with its help, we always meet the correct decisions with uttermost ease.“[162] "Those who know the laws of phenomena may gain this way insight in the future progress of those phenomena."[163] "The method, though, which we always use for deriving futurity from the past, and therefore to gain the desired foresight, is this: we build for ourselves internal virtual images, or symbols, of the external objects in such a way that the thought-necessary consequences of those images may always be images of the nature-necessary consequences of the external objects previously mapped."[164]

[157] Planck (1948a): p. 23. Quoted text: „Wie das Kausalgesetz schon die erwachende Seele des Kindes sogleich in Beschlag nimmt und ihm die unermüdliche Frage ‚warum?' in den Mund legt, so begleitet es den Forscher durch sein ganzes Leben.“.

[158] Röseberg (1975): p. 54. Text as quoted from Engels (2017), p. 202: "Durch die *Tätigkeit des Menschen* begründet sich die Vorstellung von *Kausalität*.“.

[159] Mast (2020): p. 32. Quoted text: „Ereignisse als kausal verknüpft zu sehen ist eine hervorragende Strategie, mit der wir den Alltag erfolgreich meistern.“.

[160] Eibl-Eibesfeld (1998): p. 21. Quoted text: "Für einen Organismus muß die Welt voraussagbar sein, sonst kann er in ihr nicht leben.“

[161] Craik (1943): p. 50

[162] Boltzmann (1899): p. 160. Quoted text: "Die Aufgabe unseres Denkens ist es, [unsere inneren Gedankenbilder] so zu gebrauchen und zu verbinden, daß wir mit ihrer Hilfe allezeit mit größter Leichtigkeit die richtigen Handlungen treffen."

[163] von Helmholtz (1903): p. 339, as quoted by Nernst (1922): p. 490. Quoted text: "Wer das Gesetz der Phänomene kennt, gewinnt dadurch … die Einsicht in den zukünftigen Verlauf dieser selben Phänomene."

[164] Hertz (1894): p. 1. Quoted text: „Das Verfahren aber, dessen wir uns zur Ableitung des Zukünftigen aus dem Vergangenen und damit zur Erlangung der erstrebten Voraussicht stets bedienen, ist dieses: Wir machen uns innere Scheinbilder oder Symbole der äußeren Gegenstände, und zwar machen wir sie in der Art, daß die denknotwendigen Folgen der Bilder stets wieder die Bilder seien von den naturnotwendigen Folgen der abgebildeten Gegenstände.“

Summer or winter, dry or rainy seasons, organisms use natural indicators to predict expected environmental conditions and to start appropriate activities. For example, "migration strategies can be seen as the mapping of actions (continued feeding, departure or cessation of migration) on cues (e.g., day length, feeding or wind conditions)."[165] Birds start singing in the morning or building nests in spring. Trees begin blossoming when the winter has passed and drop their leaves before it returns. Similarly, the behaviour of a certain individual in a social group may be observed by other group members and may be interpreted by them as a signal to flee, to attack or to mate. "Organisms time activities by using environmental cues to forecast the future availability of important resources."[166]

Semiotic aspects of cues as stimuli, triggers or signals are discussed by Nöth (2000: sections III.3.1.2 and IV.8.2.2 therein). "A »cue« is an object or event which, after its occurrence, initiates processes that are functional with respect to the cue (advantageous with high probability under the future conditions). Those processes may be of biological/physical nature or initiated by cognitive perception and its interpretation in the framework of a causal model."[167] Cues may transfer structural or symbolic information. Cues carrying structural information are observed by organisms and converted into symbolic information, to be processed by prediction models as if those cues were proper symbols. However, the meaning of such cues is not subject to arbitrary convention. Cues have not necessarily undergone the ritualisation transition. *Biological cues* which originate from other organisms may later evolve, by virtue of feedback loops between originator and receiver of the cue, to proper conventional symbols in the course of a ritualisation process. *Physical cues* which do not originate from organisms cannot be affected by the receiver and cannot be ritualised by virtue of feedback loops between receiver and emitter.

The ability of mammals to decide about their immediate activity on the basis of predictions of potential future situations is regarded as *deliberation* (LeDoux, 2021: § 45 therein). Exploiting mental models, this simulation method permits quick reactions under circumstances never experienced before. "The most carefully studied example of a mental model is a spatial map in which insights about certain orientation points are depicted. Many animals – including bees, birds and mammals – use such spatial maps to search food, to avoid dangers, or simply, to orientate themselves."[168]

Spatial maps, recipes, metrological concepts, genetic and technical construction plans or numerical algorithms are static kinds of prediction models, similar to written laws and equations in natural sciences and technology. Upon execution of such a

[165] Winkler et al. (2014): p. 2.

[166] McNamara et al. (2011): p. 1183.

[167] Robert Hagen, priv. comm. of 30 Nov. 2021: „Ein »Cue« ist ein Objekt oder Ereignis, nach dessen Eintritt Prozesse initiiert werden, die hinsichtlich des Cues zweckmäßig (mit hoher Wahrscheinlichkeit für künftige Bedingungen von Vorteil) sind. Diese Prozesse können biologischer/physischer Natur sein oder durch die kognitive Wahrnehmung und deren Interpretation im Rahmen eines kausalen Modells hervorgerufen werden.".

[168] LeDoux (2021): p. 249. Quoted text: „Das am gründlichsten untersuchte Beispiel eines mentalen Modells ist eine räumliche Karte, in der Erkenntnisse über bestimmte Orientierungspunkte dargestellt werden. Viele Tiere – Bienen, Vögel und Säugetiere eingeschlossen – bedienen sich solcher räumlichen Karten bei der Futtersuche, um Gefahren aus dem Weg zu gehen, oder schlicht, um sich zurechtzufinden.".

model by its user, they control associated dynamical processes which should produce the predicted structures. Biological ontogenesis, for example, is such a dynamical process of materialisation of the prediction encoded statically in the phylogenetically designed genetic model.

Preferred prediction models of physics are differential equations for the temporal evolution of suitable state quantities. However, "directly observable quantities do not occur in the physical picture of the world, but only symbols."[169] Constructed actually from merely the sensation of energy fluxes across the 2D interface between us and the world outside, 3D state quantities are certain artificial creations of mental models. They are designed in a way to be consistent with those exchange quantities observed immediately, rather than rigorously representing the latter themselves symbolically. For example, when a single photon hits our eye as a sudden flash, it is commonly concluded that this photon had been flying before as a localised particle through space from some distant source. But, do light particles really exist as state quantities, or only as exchange quantities? Our inherited mental model of naïve realism suggests that an object crossing a given surface has previously been moving toward that surface along a certain trajectory, like a stone being thrown into a pond. However, quantum mechanical experiments cast doubt on this intuitive picture. The distinction between physical state and exchange quantities warrants some further, rather general consideration.

8. Physical States: Mental Models

8.1 State Quantities: Prediction Models for Exchange Quantities

Physical state quantities cannot be measured directly but may be concluded from experienced observations of physical exchange quantities, exploiting mental prediction models such as experimental constructions, mathematical equations, physical theories and interpretations. In turn, those state quantities may serve as prediction models for future observations of exchange quantities. This applies similarly also to the inherited mental model of naïve realism, suggesting a perceived state of the world, composed of things located in space and time.

„The main progress in the structure of physical terms consists … in the discovery that a quantity used to be considered as a property of an object is in reality only the property of a projection.“[170] „The explicit and consequent distinction between the quantities of the sensational world and the equally denoted quantities of the physical image of the world is indispensable for the clarification of notions."[171] However,

[169] Planck (1948a): p. 9. Quoted text: "Direkt beobachtbare Größen kommen im [physikalischen] Weltbild überhaupt nicht vor, sondern nur Symbole."

[170] Born (1954): p. 55. Quoted text: "Der Hauptfortschritt in der Begriffsstruktur der Physik besteht … in der Entdeckung, daß eine bestimmte Größe, die man als Eigenschaft eines Gegenstandes betrachtet hatte, in Wirklichkeit nur die Eigenschaft einer Projektion ist.“.

[171] Planck (1948a): p. 8. Quoted text: "Die deutliche und konsequente Unterscheidung zwischen den Größen der Sinnenwelt und den gleichbenannten Größen des [physikalischen] Weltbildes ist für die Klärung der Begriffe durchaus unerläßlich.“.

„there is often a tendency to identify theoretical constructs of highly successful models with reality itself."[172] In this Section, in a tentative attempt of taking seriously the latter grave criticism, we may speculate about some hypothetical physical scenarios in order to illustrate certain putative consequences of taking mental models for physical reality.

Pending paradoxes in the interpretation of experimental results, in particular in quantum mechanics (Gribbin, 1987; Hoffman, 2020), may perhaps find their explanations in the involuntary, inappropriate application of parts of the mental model of naïve realism. "Classical physics remains essential in quantum theory, including … quantum phenomena, defined by what is observed in measuring instruments and described, along with the observable parts of these instruments, by classical physics."[173] In order to painfully adapt our familiar human mental model to unexpected but unequivocal observations, some physicists believe that philosophers may not be helpful: "Philosophers were unable to keep pace with the development of theories in natural sciences."[174] Philosophers, on the other hand, argue that only they may find the proper answers: "Only the philosophers may see the things themselves, rather than just the shadows of those at the wall."[175]

Thermodynamics has taught physicists to carefully distinguish *state quantities* from *exchange quantities*. If we put a certain amount of heat into a system such as a steam engine, or extract work from it, it is wrong to conclude that the system must internally contain some heat and some work separately from one another. Heat and work are exchange quantities; "the obsolete hypothesis of heat being a substance is excluded"[176]. All that our senses or measuring instruments may receive are exchange quantities in the course of a dynamical observation or measurement process. "In Experientially Natural form of Thermodynamics, we accept that *processes* rather than states are products of experience."[177]

"The distinction [between either finding a system in a certain state or measuring a value associated theoretically with such a state] … is not merely semantic, but *has genuine physical significance*."[178] Concluding the actual state of the system under observation from those exchange quantities is exclusively performed by making use of mental models which may or may not be consistent with the observations in the given case. State quantities can never be observed or measured, even though this may often be believed to be authentically true in practice. Commonly, the term »physical observable« is frequently used also for state quantities, but, rather than being observed directly, these quantities are linked to the actual measurands only via mental models of the measurement process. In particular, "a quantum measurement

[172] Boughn (2022): p. 6.

[173] Plotnitsky (2022): p. 2.

[174] Hawking and Mlodinow (2005): p. 167. Quoted text: "Die Philosophen [waren] nicht in der Lage, mit der Entwicklung naturwissenschaftlicher Theorien Schritt zu halten."

[175] Stary and Fuchs-Kittowski (2020): p. 2. Quoted text: "Nur der Philosoph … kann … die Dinge selbst sehen, nicht nur deren Schatten an der Wand."

[176] Sommerfeld (1988): p. 6. Quoted text: "Damit ist die ältere *Stofftheorie der Wärme* ausgeschlossen.".

[177] Fuchs et al. (2022): p. 2.

[178] Park (1970): p. 24.

does not measure or, in the first place, does not observe any property of this reality, which it would be assumed to possess before or even during the act of observation… An act of observation in quantum physics establishes, that is, creates, quantum phenomena from an interaction between the instrument and the quantum object."[179] Measurement is impossible without energy exchange between the measurand and the measuring device, without structural information about the measurand transferred to the instrument or sensor for associated conversion into symbolic information.

The so-called *No-Go Theorem* of Park (1970) addresses the problem of whether any measurement performed must necessarily affect the existing quantum state. "While it is factually correct that measurement operations upon microphysical systems tend to have catastrophic effects upon their states, the notion of uncontrollable *disturbance* of a state by a measurement act … should not be regarded as a *universal* trait of the measurement act. … It is generally impossible to equate measurement with simple observation of the [quantum] system itself. Instead, the act of measurement necessarily involves interaction with a secondary system, the apparatus, which in turn produces some effect that can be directly apprehended by the senses. … A measurement interaction must correlate the numerical results which will be obtained from examining the apparatus with the (fictitious) measurement result that would be obtained if the system could be directly observed."[180] Such a fictitious measurement, however, is a mental model, as is the causal functioning principle of the magnifying apparatus.

Assuming that our senses and measuring instruments are only capable of recognising exchange quantities, an immediate conclusion is that exclusively all state quantities cannot be observed directly and may result solely from mental models invented in order to explain the observations. This is in particular true for the mental model of naïve realism, see Sect. 3 above; all humans feel deeply convinced that our perception of the world immediately provides its current status in the form of bodies located in space and changing in time, rather than in fact merely recognising the world's exchange fluxes with our sensory cells. In fact, though, "reality, as we know it, is nothing but a generated model which our brains have constructed."[181]

Evidently, if a state quantity is derived from measured exchange values which appear as differences of that quantity, then the absolute value of that quantity does neither affect any measurable properties nor may it be determined from those. Typically, the absolute values of such quantities are empirically unavailable and must be concluded from theoretical models. For example, this is the case with mechanical energy, whose absolute value became only known as a »rest energy« from Einstein's famous relation between energy and mass, Fig. 1, as a mental model. This is also the case with Clausius' (1876) entropy whose absolute value may only be derived from theoretical models (Planck, 1906, 1948b; Pauling, 1935; Bekenstein, 1973; Feistel, 2019). Measurable electromagnetic fields can be defined in terms of a single relativistic 4D vector potential (Einstein, 1969) whose absolute reference values still lack an explaining physical model and are commonly assumed to obey an arbitrary »Lorentz

[179] Plotnitsky (2022): p. 9.

[180] Park (1970): p. 25, 26.

[181] Elsayed (2021): p. 27.

gauge« (Landau & Lifschitz, 1967: § 18, § 62 therein). "Physically meaningful are only those quantities which are invariant with respect to such transformations of the potentials."[182]

What is a »state quantity«? „The actual state of the world depends only on the most recent past, without being directly influenced, so to speak, by the memory of the distant past"[183] wrote Henri Poincaré in a report to the International Congress of Physics in 1900. „A state quantity is independent of the former history of a body and is given by its instantaneous state alone."[184] In the words of Max Planck, a state of a physical system at a certain point of time is „the epitome of all those mutually independent quantities by which the temporal progress of processes occurring in that system is uniquely determined under given boundary conditions"[185]. All these specifications of a physical »state« apply to the mathematical (mental) model of a state rather than to anything existing in physical reality that is independent of the presence of human observers.

8.2 Einstein-Planck Paradox: Neither Particle nor Wave

Solar cells used for photovoltaics or photo sensors convert the energy of sunlight into electricity. The power they produce is proportional to the brightness of the incident light. However, beyond a critical wavelength of the irradiation, the gain of electric energy suddenly ceases no matter how intense the light may be. Einstein explained this so-called photo-electric effect with the existence of »light quanta« - later termed »photons« - which Planck had proposed shortly before, and was eventually awarded with the 1921 Nobel Prize for his theory. Einstein's 1905 hypothesis was that "when a light beam is emitted from a point, its energy will not spread continuously over larger and larger spatial regions, but it will consist of a finite number of energy quanta localised in points of space, which move without splitting up and can be absorbed and produced only as a whole."[186] "Einstein had believed in the reality of photons long before Planck and even still before Bohr."[187]

Actually, just Einstein's final clause that photons "can be absorbed and produced only as a whole" is adopted from Planck's radiation theory. This assumption is already

[182] Landau and Lifschitz (1967): p. 54. Quoted text: "Physikalisch sinnvoll sind nur jene Größen, die gegenüber den Potentialtransformationen … invariant sind."

[183] Poincaré and Goroff (1993): p. I18.

[184] Sommerfeld (1988): p. 1. Quoted text: "Eine *Zustandsgröße* … ist unabhängig von der Vorgeschichte des Körpers, allein durch seinen augenblicklichen Zustand gegeben.".

[185] Planck (1906): p. 137. Quoted text: „Unter dem ‚Zustand' eines physikalischen Systems zu einer bestimmten Zeit verstehen wir den Inbegriff aller derjenigen voneinander unabhängigen Größen, durch welche der zeitliche Verlauf der im System stattfindenden Vorgänge, soweit sie der Messung zugänglich sind, bei gegebenen Grenzbedingungen eindeutig bestimmt wird.".

[186] Einstein (1905): p. 133. Quoted text: „Nach der hier ins Auge zu fassenden Annahme ist bei Ausbreitung eines von einem Punkte ausgehenden Lichtstrahles die Energie nicht kontinuierlich auf größer und größer werdende Raume verteilt, sondern es besteht dieselbe aus einer endlichen Zahl von in Raumpunkten lokalisierten Energiequanten, welche sich bewegen, ohne sich zu teilen und nur als Ganze absorbiert und erzeugt werden können.".

[187] Haroche (2022): p. 263. Quoted text: „Einstein hatte lange vor Planck und sogar noch vor Bohr an die Realität von Photonen geglaubt.".

sufficient to explain the photo effect as caused by quantised photons as *exchange quantities*, as described by his second equation shown in Fig. 1. However, apparently needlessly and perhaps only for the plausibility and beauty of the model, he extended his hypothesis to *state quantities* in the form of "energy quanta localised in points of space, which move without splitting up". Einstein motivated this model by the fact „that the entropy of monochromatic radiation of sufficiently low density varies by the same law as the entropy of an ideal gas or of a dilute solution."[188] As the title of his 1905 paper, »concerning generation and transformation of light«, properly reveals, one may conclude that Einstein's »photon flux model« for exchange quantities is sufficient and necessary for explaining the observed photo effect while his additional »photon gas model« for state quantities, possibly inspired by his mental model of naïve realism, is sufficient but actually not necessary for that purpose. As an aside, the statistical physics of the photon gas model is presented in excellent form by Landau and Lifschitz (1966) or Kittel (1973).

Einstein's »state model« of spatially localised, indivisibly moving photons cannot explain the observations made in the double-slit experiment conducted first by Thomas Young in 1801 (Lindner, 1963: Fig. 33 therein; Gribbin, 1987: Fig. 8.2 therein; Hawking & Mlodinow, 2005: p. 115 therein; Haroche, 2022: Fig. III.2 therein). According to naïve reality, a single such photon can hardly pass simultaneously through two spatially separate slits in a screen, and subsequently interfere with itself behind that screen. An alternative simple model, consistent with the double-slit observation, is one in which a photon appears as a local particle (as exchange quantity) only at its birth and death, but as a spatially extended, continuous electromagnetic or Schrödinger wave (as state quantity) in between (Haroche, 2022, as displayed in Fig. 8). This is Planck's mental model of light as described in his letter to Einstein on 6 July 1907, in which he explicitly disagreed with Einstein: "I do not see the importance of the elementary action quantum (light quantum) in the vacuum but rather at the places of absorption and emission, and I assume that the processes in vacuum are exactly represented by Maxwell's equations."[189] To obey physical conservation laws, such a wave may carry the structural information of the initial particle. The particle's kinetic energy may appear as the wave's Poynting vector, its momentum as the wave's light pressure, and the photon's spin as the wave's polarisation. "It appears to me absolutely justified to seriously consider the question of whether the fundamentals of field physics are consistent with the quantum facts."[190] "The fact that quantum mechanics … describes the amount and nature of the smearing of all variables in a consistent way, shows that this is not unrealistic."[191]

[188] Einstein (1905): p. 139. Quoted text: „… daß die Entropie einer monochromatischen Strahlung von genügend kleiner Dichte nach dem gleichen Gesetze mit dem Volumen variiert wie die Entropie eines idealen Gases oder die einer verdünnten Lösung.".

[189] Planck in 1907 as quoted by Hermann (2022): p. 43. Quoted text: „Ich suche die Bedeutung des elementaren Wirkungsquantums (Lichtquants) nicht im Vakuum, sondern an den Stellen der Absorption und Emission, und nehme an, daß die Vorgänge im Vakuum durch die Maxwellschen Gleichungen *genau* dargestellt werden.".

[190] Einstein (1936): p. 343. Quoted text: „Es erscheint mir durchaus gerechtfertigt, die Frage ernsthaft zu erwägen, ob nicht doch die Grundlage der Feldphysik mit den Quanten-Tatsachen vereinbar ist.".

[191] Schrödinger (1935): p. 8.

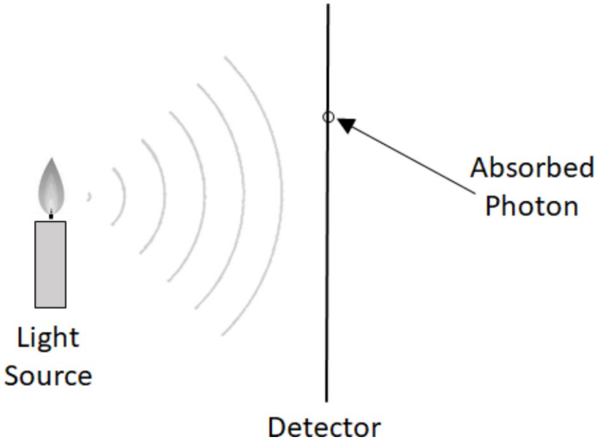

Fig. 8 Schematic of light propagation: "… light to be a wave when it propagates and interferes but to consist of single particles when it interacts with matter."[1] A single photon emitted from a light source is observed by a detector as a localised quantum of energy exchanged between the incident light beam and the target device. Einstein's (1905) hypothesis that the locally impacted light quantum automatically implies the existence of an equivalent, spatially localised, indivisible light quantum travelling through space between emission and absorption is likely a consequence of his mental model of the physical state of a light beam. However, his bullet model of photons is not underpinned by observation and is inconsistent with double-slit experiments. By contrast, the alternative process model suggested by this schematic is inconsistent with naïve realism. If the detector is a human retina, and the source a distant star, the entire wave extending over many cosmic lightyears must "spookily" collapse instantaneously into a single human eye as soon as we see the star

[1] Haroche (2022): p. 241. Quoted text: „… Licht sei eine Welle, wenn es sich ausbreite und durch Interferenzphänomene manifestiere, und es bestehe aus einzelnen Teilchen, wenn es in Wechselwirkung mit der Materie trete.".

Such a hypothetical model, in which light appears as a particulate photon as exchange quantity but as a spacious wave as state quantity, is consistent with observation but is inconsistent with other physical models. In order to appear as a localised particle upon absorption, the incident wave has to suddenly »collapse«, contracting its distributed energy into a single »point«. To be consistent with observation, this collapse must apparently happen instantaneously. If this collapse were understood as a real physical (rather than a merely thought) process, it would constitute a "spooky action at a distance", violating the relativity theory which denies the possibility of events happening at spatially distant locations at exactly the same time from whatever reference frame the collapse may be observed. "The remote action happens instantaneously, even though Einstein has taught us that *instantaneous* cannot mean the same in every reference system."[192] As an attempt to prevent such a model from being discarded straight away, one may therefore require to challenge the validity of the physical »locality« hypothesis and the relativistic space-time metrics

[192] Muller (2018): p. 304. Quoted text: „Die Fernwirkung findet sofort statt, obwohl Einstein uns gelehrt hat, dass *sofort* nicht in allen Bezugssystemen das Gleiche bedeuten kann.".

within microscopic »entangled states« like a putative photon wave. »Locality« may be "defined simply as the non-existence of effects propagating faster than light"[193].

> "Already the introduction of a space-time continuum must possibly be considered as being against nature, taking into account the molecular structure of all small-scale processes."[194] „The underlying problem is that … the space is treated like an undoubtedly classical quantity."[195] "One should first have a firm understanding of how quantum theory does allow a classical world at all, with pre-existing notions of time and space."[196] "Classical physics remains being essential in quantum theory as applicable to quantum phenomena, defined by what is observed in measuring instruments and described, along with the observable parts of these instruments, by classical physics."[197] Persistent marks tagged at rigid bodies, defining geometrical length measurement macroscopically and this way a classical reference frame, see Section 5, do not exist at all in the quantum world. Only random events of exchange processes can be observed there, such as thermal radiation or radioactive emanation. "The usual picture of space and time, and particles moving around in them, is a construct. … It must not be fundamental – it must be emergent."[198] "Space-time is doomed!"[199] "Our perceptions of space, time, and objects are no more than a user interface that guides adaptive action."[200]

When we look at a star at night, its light may have travelled a vast number lightyears. When its photon hits our retina, the fictitious distributed wave energy should instantaneously collapse over a spatial region possibly sized of many lightyears as well, just to condense into a tiny molecular light spot in our eye. Such a giant quantum effect would by no means be microscopic anymore. Entangled quantum states extending over many kilometres could in fact be demonstrated experimentally, such as between the Canary Islands of Tenerife and La Palma (Ma et al., 2012; van Leent et al., 2022). Related experiments, unequivocally confirming the existence of a physical "spooky action at a distance", have just been awarded with the 2022 physics Nobel Prize (Castelvecchi & Gibney, 2022). Quantum entanglement and quantum coherence are mutually equivalent phenomena (Tan & Jeong, 2018). Mental models of quantum entanglement even between black holes, and the putative conservation of their struc-

[193] Hnilo (2023): p. 3.

[194] Einstein (1936): p. 343. Quoted text: "… bereits die Einführung eines raum-zeitlichen Kontinuums angesichts der molekularen Struktur allen Geschehens im Kleinen [sei] möglicherweise als naturwidrig anzusehen."

[195] Görnitz (1999): p. 197. Quoted text: „Das zugrundeliegende Problem besteht darin, daß … der Raum wie eine unzweifelbar klassische Größe behandelt wird."

[196] Gill (2022): p. 11

[197] Plotnitsky (2022): p.2

[198] Wolchover (2013)

[199] Nima Arkani-Hamed quoted by Hoffman (2020): p. 174. Quoted text: "Die Raumzeit ist verloren."

[200] Hoffman et al. (2023): p. 1

tural information, known as »Hawking's information paradox«, are subject to recent quantum gravity research (Almheiri et al., 2020).

> "Still, the double-slit experiment remains the most famous quantum experiment and is most frequently used to illustrate the conundrums of quantum physics."[201] However, rather than highly sophisticated quantum experiments, conventional optics in a class room is already sufficient to demonstrate that a propagating photon cannot be indivisibly localised. In distinction to a laser, an ordinary light source is assumed to emit random, mutually incoherent photons. The light of two separate lamps, if it overlaps on a desk, does never show any interference patterns. But, if the light beam of just one such lamp is split into a pair of rays, such as by two slanted mirrors, those partial rays may subsequently be brought to mutual interference (Barrera et al., 2007). This was shown by Augustin Fresnel already in 1816, the »year without summer«. In naïve realism, though, such interference patterns cannot be understood unless each single photon is first divided and later superimposed with itself. "Each photon. .. interferes only with itself. Interference between different photons never occurs."[202] Textbooks tend to downplay this virtually paradoxical observational evidence by explaining that "natural light consists of a sum of mutually incoherent wave tracks, each of those being coherent only with itself."[203] The optical model of divisible individual wave tracks is incompatible with Einstein's particulate photon-gas model. "It is simply a contradiction of definitions to describe a single object as a wave and a particle. … A single object is simply not simultaneously picturable as a wave and a particle. This impossibility is the root behind the particle-wave duality paradox, and … this paradox or 'mystery' is only resolved by an ontological interpretation of the quantum theory."[204]

In addition to its obvious conflict with the locality principle, another exotic aspect of a physical model of a spacious wave collapsing instantaneously to a local particle, is its irreversibility; it violates the physical law of microscopic reversibility and Kirchhoff's symmetry between emission and absorption acts. "Quantum laws are reversible and measurement is irreversible."[205] Perhaps, "the second law [of thermodynamics] comes about not because of classical probabilities but because of quantum effects such as entanglement."[206] "The ultimate challenge for physics is in identifying and detecting the fine mechanism that implements this arrow of time microscopically."[207] A reverse collapse would constitute an instantaneous inflation of

201 Plotnitsky (2022): p. 15

202 Plotnitsky (2022): p. 18

203 Schallreuter (1962): p. 130. Quoted text: "*Natürliches Licht besteht aus einer Summe untereinander inkohärenter Wellenzüge*, deren jeder nur in sich selbst kohärent ist."

204 Kaloyerou (2016): p. 143

205 Pattee and Rączaszek-Leonardi (2012): p. 9.

206 Ball (2022).

207 Klimenko (2022): p.1.

a local particle into a spatially extended wave possessing a size independent of the properties of the initial particle. Such a process has never been observed.

Note that Einstein may have had good physical reasons to suggest "light quanta moving indivisibly" between emission and absorption, in contrast to the prevailing wave model of light. In June 1905, he had published both his explanation of the photo effect as well as his Special Theory of Relativity. According to the latter, watched by an observer at rest, a fast-moving clock runs slower than that of the observer. This effect is well-known from high-energy myons produced in the upper atmosphere which reach the ground after, say, 100 µs rather than decaying within the first 500 m, as to be expected from their half-life of only 2.2 µs. As a limiting case, a clock will ultimately stall if moving asymptotically at light speed. If a photon is imagined as some physical object obeying the relativity laws, between its emission and absorption this object is impossible to undergo any physical changes such as those apparently observed in Fresnel's optical experiment. A photon remains always at zero age; its birth and death happen simultaneously. If the cosmos were a perfect vacuum, this would be true even for the light of most distant stars that has travelled billions of years to arrive at our space telescope. For an external resting observer, if a photon starts as a localised quantum, it should remain exactly the same until absorption. Accordingly, within zero proper (»eigen«) time of flight, there is no way for a photon to gradually inflate to an expanding wave, in the sense of "light to be a wave when it propagates and interferes but to consist of single particles when it interacts with matter."[208]

Einstein's particle model of light is in obvious contradiction to the wave model concluded from optical interference experiments. However, the state of a flying photon cannot be observed directly; all we have available for the description of its state are two mutually inconsistent mental models, either particle or wave, borrowed from naïve realism, which are evidently paradoxical and require revision. "Indeed the question of whether the light rays are either quantised themselves, or their quantum effect happens only within the matter, might constitute the primary and gravest dilemma to the entire quantum theory."[209] Formulated this way a century ago by Max Planck, his fundamental physical conundrum is still awaiting a conclusive solution. "In the last one hundred years, countless concepts have been published in order to explain quantum phenomena. … Until now, it was not possible to find a complete solution that was very convincing."[210]

Perhaps, rather than representing a photon in its own right, interfering waves of propagating light, spreading gradually and collapsing suddenly, may just be mental prediction models for the location where the photon impact is expected to be eventually observed. This view is commonly offered by the widely accepted »Copenhagen interpretation« of quantum mechanics. Similarly, when throwing dice, the equally

[208] Haroche (2022): p. 241. Quoted text: „… Licht sei eine Welle, wenn es sich ausbreite und durch Interferenzphänomene manifestiere, und es bestehe aus einzelnen Teilchen, wenn es in Wechselwirkung mit der Materie trete.".

[209] Planck (2018): p. 24. Quoted text: "In der Tat ist die Frage, ob die Lichtstrahlen selber gequantelt sind, oder ob die Quantenwirkung nur in der Materie stattfindet, wohl das erste und schwerste Dilemma, vor das die ganze Quantentheorie gestellt wird.".

[210] Jung (2022): p.1.

distributed probability as predicted by mental models is also instantaneously collapsing to certainty as soon as the model's owner knows the outcome. Probabilities are state quantities and cannot be observed. Based on the »continuity principle of life«, Sect. 1, probabilities are understood as mental prediction models for frequencies of events to be observed in the future, extrapolated from frequencies observed in the past under the assumption of persisting relevant external circumstances. According to Richard von Mises (1928), "in its frequency interpretation, probability is exclusively determined a posteriori."[211] "The past is particles, the future is a wave."[212]

It is concluded that *the photon gas model is sufficient but not necessary for explaining the photo-electric effect.* Being sufficient but not necessary is a typical property of obsolete models. For instance, the Antikythera model (Freeth et al., 2021) is sufficient but not necessary for the prediction of planetary motions in the sky.

8.3 Entropy Flux of Thermal Radiation: Is Light a Photon Gas?

A different instructive example for an apparently lacking necessity of the photon gas model is the entropy flux of thermal radiation. For isochoric processes, Gibbs' fundamental equation is (Clausius, 1876: p. 205 therein)

$$\mathrm{d}E = T\,\mathrm{d}S, \tag{1}$$

where E is the (internal) energy of a system at equilibrium at the temperature T, the entropy is S, and $T\mathrm{d}S$ is the heat exchanged across the system's boundary. Accordingly, the heat flux J_Q is related to the entropy flux J_S by:

$$J_Q = T J_S \tag{2}$$

For thermal radiation, surprisingly, the corresponding relation between the fluxes of energy and entropy is different, namely (Planck, 1906; Bekenstein, 1973; Fortak, 1979; Ebeling & Feistel, 1982; Feistel, 2011; Kabelac & Conrad, 2012; Pelkowski, 2014)

$$J_Q = \frac{3}{4} T\,J_S. \tag{3}$$

Originally, Planck (1906: § 151 therein) had, by assigning a temperature to a monochromatic light ray, thermodynamically inferred his equation for the entropy flux of thermal radiation from the energy flux of electromagnetic waves whose energy is split up into finite portions. Later, Planck (1966), referring to Newton's emanation theory of light, derived the radiative entropy flux formula (3) from the entropy density of the photon gas with the argument that "on a surface, the irradiation energy from a ray of light propagating in vacuum equals the kinetic energy of the light particles

211 Sačkov (1978): p. 123. Quoted text: „Bei der Häufigkeitsinterpretation wird die Wahrscheinlichkeit ausschließlich a posteriori bestimmt.“.

212 Gill (2022): p.1.

hitting that surface, all of those moving with the constant velocity *c*."[213] Apparently, this argument relies on the existence of Einstein's hypothetical photons as particles localised in space and moving indivisibly at the speed of light. Yet in 1913, however, Planck had criticised Einstein "to have with his speculations occasionally overshoot the mark, such as with his hypothesis of light quanta."[214]

Borrowed from naïve realism, the simple rule used by Planck in that case, »flux = density × velocity«, which relates exchange quantity (flux) to state quantity (density), may often work but is not rigorous; it does not apply, for example, to the conductive heat flux or to the flux of hydrodynamic momentum (Landau & Lifschitz, 1974: § 7 therein). Therefore, a conclusion would be premature which is assuming that an observed flux of, say, heat across a surface must necessarily imply the existence of heat in the form of some substance within the volume enclosed by that surface. Photons registered as particulate events at a surface do not require compellingly the existence of a photon gas extending over the volume enclosed.

The fact that Eq. (3) is commonly derived in the literature from Planck's quantum theory of thermal radiation may lead to the impression that this relation results from quantum effects. However, Eq. (3) is actually inappropriate to witness the existence of photons, neither as a proper »state model«, nor even as a requisite »flux model«. The relation (3) can be derived directly from only two general empirical laws of classical physics, the 2nd law of thermodynamics and the Stefan-Boltzmann law of black-body radiation (Feistel, 2011b; Feistel & Ebeling, 2011). The latter law was empirically derived from historical flux measurements of Stefan, Lummer, Pringsheim, Kurlbaum (Planck, 1966: p. 64 therein) and others, and theoretically confirmed by Boltzmann's (1884) electromagnetic model. Clausius' (1876) entropy law was derived from heat exchange measurements of cyclic thermal processes. Hence, except for the state quantity »temperature« involved, Eq. (3) is an empirical result from observing exchange quantities, which does not necessarily require a light-quantum model.

It is concluded that *the photon gas model is sufficient but not necessary for explaining* Eq. (3).

In the case of Eq. (3), the »state model« and the »flux model« have led to mutually consistent results. The point here is that the »flux model« is supported by experiment while the »state model« is just a mental model, likely inappropriate, as assumed in the beginning of this Section, without rigorous observational underpinning, and may possibly be replaced by better mental models, as soon as available, at any time.

8.4 Schrödinger's Cat: A Mental State Model

Erwin Schrödinger's Cat is perhaps the most spectacular example for a paradoxical quantum state. "Imagine a cat locked up in a room of steel together with the follow-

[213] Planck (1966): p. 57. Quoted text: „… die durch einen im Vakuum fortschreitenden Lichtstrahl einer Fläche zugestrahlte Energie gleich der lebendigen Kraft der auf die Fläche treffenden Lichtpartikel [ist], die sich alle mit der konstanten Geschwindigkeit *c* bewegen.".

[214] Hoffmann (2008): p. 64. Quoted text: "… dass Einstein in seinen Spekulationen gelegentlich auch einmal über das Ziel hinaus geschossen haben mag, wie z.B. in seiner Hypothese der Lichtquanten.".

ing hellish machine (which has to be secured from direct attack by the cat): A tiny amount of radioactive material is placed inside a Geiger counter, so tiny that during one hour perhaps one of its atoms decays, but equally likely none. If it does decay then the counter is triggered and activates, via a relais, a little hammer which breaks a container of prussic acid. After this system has been left alone for one hour, one can say that the cat is still alive provided no atom has decayed in the mean time. The first decay of an atom would have poisoned the cat. In terms of the ψ-function of the entire system this is expressed as a mixture of a living and a dead cat."[215]

"A mixture of a living and a dead cat" is some mental state model. The related exchange model applies to the case when the cat in the box is observed, which, however, has in practice never revealed yet any paradoxical status of a real cat. If a mental model leads to paradoxical results, possibly due to involuntarily incorporated elements of the inherited human mental model of naïve realism, this does not prove that Nature in itself is paradoxical or even not real (Baggott, 2013). The utility criterion for a mental model, rather than being either »true« or »false«, is its capability of systematically and reliably predicting observations under given initial and boundary conditions. We remember that „there is often a tendency to identify theoretical constructs of highly successful models with reality itself."[216] However, „it is entirely impossible to escape from this conflict between the reason and itself, as long as objects of the world of sensation are taken as things in themselves, rather than what they indeed are, namely mere phenomena."[217]

9. Summary

Struggling for survival, organisms need to respond to temporally or spatially changing ambient conditions. Successful behaviour requires abilities of conducted activity, of instantaneous sensual perception, and of recording information about previously performed combinations of sensation and action, depending on the respective benefit or failure of those combinations. Such abilities were achieved by the evolution of symbols and prediction models, capable of simulating and evaluating experienced past, present and estimated future situations.

In the course of phylogenetic processes of Darwinian evolution, *symbols* and *models* emerged and improved at their »design time«. Models constitute specific, complex symbols. Successful such models are transferred genetically to offspring. *Ritualisation* is the universal symmetry-breaking kinetic phase transition by which symbols appear as new information carriers.

In the course of the ontogenetic process of individual maturation and mastering the daily life, inherited models are exploited and tested at their »run time«. Additional individual models result from imitating, learning or discovering. Successful

[215] Schrödinger (1935): p. 9.

[216] Boughn (2022): p. 6.

[217] Kant (2016): p. 95. Quoted text: " Es [ist] ganz unmöglich, aus diesem Widerstreit der Vernunft mit sich selbst herauszukommen, so lange man die Gegenstände der Sinnenwelt vor Sachen an sich selbst nimmt, und nicht vor das, was sie in der Tat sind, nämlich bloße Erscheinungen.".

such models are transferred socially to offspring or fellows by symbolic communication. Perception, observation and measurement are *symbolisation* processes by which environmental *structural information* is converted into *symbolic information* to be stored and processed by models for prediction and for conducting advantageous activities. Receiving structural information is possible exclusively by energy exchange between environment and sensory cells. It is reasonable to assume that structural information can never be wrong or paradoxical, while by contrast symbolic information is typically incomplete, immature and only tentative, may possibly be erroneous or deceptive, or even intentionally false and misleading.

Neurons are symbolic information processors which emerged by ritualisation of, likely, former secretory cells. Based on neuronal networks, humans inherit, develop and exchange numerous individual *mental models*. The most fundamental such model is that of *naïve realism*; it appears as a virtual world model of state quantities, being consistent with the exchange quantities perceived by the biological senses. This world model consists of objects located in *space* and changing in *time* by processes ruled by the *causality* law. The evident success of this model for human prehistoric survival resulted in our mental addiction to causality.

As a scientific method of observation, quantitative *measurement* is a symbolisation process of converting structural information, exchanged between a measurand and a sensor, into symbolic information of numbers as measurement results, obtained from *counting*. Numbers, i.e., symbolic reference sets used for counting, emerged by ritualisation from physical comparison sets. Consistent with human experience, direct experimental evidence can be assumed to exist exclusively for physical *exchange quantities* from which any *state quantities* are commonly derived using mental models. However, those state quantities are, in turn, the preferred subject of human imagination and related dynamical prediction models.

Such as symbolic differential equations in theoretical physics, dynamical models for predicting future properties of state quantities from their past and present properties suffer from the inherent problem that the state quantities they typically describe are elements of mental models with uncertain validity. Such models may prove inappropriate with respect to future observations. This deficiency applies in particular to natural laws if those are expressed in terms of state quantities. It is suggested that apparently paradoxical or counterintuitive interpretations of observations, such as described in exaggerated manner by Schrödinger's Cat in quantum mechanics, may result from involuntarily confusing inherited or acquired mental state models with physical reality.

All (mentally sane) humans share the inherited common attitude of naïve realism. By introspection, outstanding philosophers such as Immanuel Kant analysed this mental model in very detail. Modern experiments and discoveries continue to reveal apparent paradoxes which challenge physicists to develop, imagine and formulate sophisticated novel mental models that go beyond that native understanding of the world. Our present mental models of quantum mechanics and relativity theory still include distinct substantial portions of naïve realism, such as the model of mass points moving along proper trajectories, or the model of geometrical distances, measured by counting persistent rigid »unity sticks« along a straight light ray. The yet pending unification of those theories will need physicists who may find a way of identifying and eliminating those crucial portions, based on the understanding of how the human mental model of naïve realism has evolved and how exactly it is implemented in our brain.

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References

Almheiri, A., Hartman, T., Maldaceda, J., Shagoulian, E., & Tajdini, A. (2020). Replica wormholes and the entropy of Hawking radiation. JHEP05,013, https://doi.org/10.1007/JHEP05(2020)013

Arendt, D. (2020). The Evolutionary Assembly of neuronal Machinery. *Current Biology*, *30*, R603–R616. https://doi.org/10.1016/j.cub.2020.04.008

Arendt, D. (2021). Elementary nervous systems. *Philosophical Transaction of the Royal Society B*, *376*, 20200347. https://doi.org/10.1098/rstb.2020.0347

Aristoteles. (2019). *Nikomachische Ethik*. Ditzingen: Philipp Reclam jun.

Azlan, R. (2019). *Gott. Eine Geschichte der Menschen*. München: Pantheon.

Baccarini, M. (2013). The multiple Pathways Model of Visual System. A review. *Humana Mente Journal of Philosophical Studies*, *24*, 229–244. https://www.humanamente.eu/index.php/HM/article/view/157

Baggott, J. (2013). *Farewell to reality*. London: Constable.

Ball, P. (2022). Physicists Rewrite the Fundamental Law That Leads to Disorder. Quanta Magazine May 26, 2022, https://www.quantamagazine.org/physicists-trace-the-rise-in-entropy-to-quantum-information-20220526

Barbieri, M. (2008). Biosemiotics: A new understanding of life. *Naturwissenschaften*, *95*, 577–599. https://doi.org/10.1007/s00114-008-0368-x

Barrera, J. F., Medina, F. F., & Garcia-Sucerquia, J. (2007). Discussion on Fresnel's mirrors and Young's double-slit interferometers. *Optik*, *118*, 402–406. https://doi.org/10.1016/j.ijleo.2006.04.007

Bartlett, F. C. (1945). Dr. K. J. W. Craik [obituary]. *Nature*, *155*, 720. https://doi.org/10.1038/155720a0

Becker, A. (2022). What Is Spacetime Really Made Of? Scientific American, February 1, 2022, https://www.scientificamerican.com/article/what-is-spacetime-really-made-of/ This article was originally published with the title "The Origins of Space and Time" in Scientific American 326, 2, 26–33 (February 2022), https://doi.org/10.1038/scientificamerican0222-26

Bekenstein, J. D. (1973). Black holes and Entropy. *Physical Review D*, *7*, 2333–2346. https://doi.org/10.1103/PhysRevD.7.2333
BIPM (2012). International vocabulary of metrology – Basic and general concepts and associated terms (VIM). https://www.bipm.org/en/committees/jc/jcgm/publications
BIPM (2019). The International System of Units (SI). 9th edition of the SI Brochure, available from the BIPM. https://www.bipm.org/en/publications/si-brochure
Boltzmann, L. (1884). Ableitung des Stefan'schen Gesetzes, betreffend die Abhängigkeit der Wärmestrahlung von der Temperatur aus der electromagnetischen Lichttheorie. *Annalen der Physik*, *258*, 291–294. https://doi.org/10.1002/andp.18842580616
Boltzmann, L. (1899). Über die Grundprinzipien und Grundgleichungen der Mechanik. Vorlesung gehalten an der Clark-University. In: Broda, E. (1979): Ludwig Boltzmann – Populäre Schriften. Friedr. Vieweg & Sohn, Braunschweig/Wiesbaden, https://doi.org/10.1007/978-3-322-86111-5
Born, M. (1954). Physikalische Wirklichkeit. *Physikalische Blätter*, *10*, 49–61. https://doi.org/10.1002/phbl.19540100201
Born, M. (1965a). Symbol und Wirklichkeit I. *Physikalische Blätter*, *21*, 53–63. https://doi.org/10.1002/phbl.19650210201
Born, M. (1965b). Symbol und Wirklichkeit II. *Physikalische Blätter*, *21*, 106–108. https://doi.org/10.1002/phbl.19650210302
Born, M. (1966). *Physik im Wandel meiner Zeit*. Braunschweig: Vieweg & Sohn.
Borwin III, H. (1252). Heinrich Borwin III. verkauft der Stadt Rostock die Rostocker Heide und verleiht ihr weitere Rechte. 25. März 1252. Niedersächsische Staats- und Universitätsbibliothek Göttingen, https://www.deutsche-digitale-bibliothek.de/item/NRLEO2Y755ASSSSPUK237ZYUZAJHADOP
Bothwell, T., Kennedy, C. J., Aeppli, A., Kedar, D., Robinson, J. M., Oelker, E., Staron, A., & Ye, J. (2022). Resolving the gravitational redshift across a millimetre-scale atomic sample. *Nature*, *602*, 420–424. https://doi.org/10.1038/s41586-021-04349-7
Boughn, S. (2022). There is no spooky action at a Distance in Quantum mechanics. *Entropy*, *24*, 560. https://doi.org/10.3390/e24040560
Brillouin, L. (2013). *Science and Information Theory*. New York: Dover Publications, Mineola.
Brunnhofer, H. (1871). *ΓΑΛΑ (ΓΑΛΑΚΤΟΣ), Lac (Lactis), der græcoitalische name der milch. Ein monographischer beitrag zur ältesten empfindungsgeschichte der indogermanischen völker*. Aarau: H. R. Sauerländer.
Buddha (2015). *Die Lehre Buddhas. Siebenundzwanzigste, revidierte Auflage*. Tokyo: Bukkyo Dendo Kyokai.
Bulatov, M. S. (2009). *Космос и архитектура (Cosmos and Architecture, in russian)*. Tashkent: Smi-Aziya.
Burgin, M., & Feistel, R. (2017). Structural and symbolic information in the context of the General Theory of Information. *Information*, *8*, 139. https://doi.org/10.3390/info8040139
Byrne, R. W., & Bates, L. A. (2010). Primate Social Cognition: Uniquely Primate, uniquely Social. *or Just Unique? Neuron*, *65*, 815–830. https://doi.org/10.1016/j.neuron.2010.03.010
Castelvecchi, D., & Gibney, E. (2022). 'Spooky' quantum-entanglement experiments win physics Nobel. Nature News 04 Oct 2022. https://doi.org/10.1038/d41586-022-03088-7
Çengel, Y. A. (2023). A concise account of information as meaning ascribed to Symbols and its association with conscious mind. *Entropy*, *25*, 177. https://doi.org/10.3390/e25010177
Cepelewicz, J. (2022). He Dropped Out to Become a Poet. *Now He's Won a Fields Medal*. Quanta Magazine July 5, 2022. https://www.quantamagazine.org/june-huh-high-school-dropout-wins-the-fields-medal-20220705/
Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*, 181–204. https://doi.org/10.1017/S0140525X12000477
Clausius, R. (1876). *Die mechanische Wärmetheorie*. Braunschweig: Friedrich Vieweg und Sohn.
Coeckelbergh, M. (2020). *Using words and things: Language and Philosophy of Technology*. London and New York: Routledge.
Coolidge, F. L., & Overmann, K. A. (2012). Numerosity, Abstraction, and the emergence of symbolic thinking. *Current Anthropology*, *53*, 204–225. https://doi.org/10.1086/664818
Cordan, W. (1962). *Popol Vuh. Das Buch des Rates. Mythos und Geschichte der Maya*. Düsseldorf: Diederichs.
Craik, K. J. W. (1943). *The Nature of Explanation*. Cambridge, UK: Cambridge University Press, reprint 1967.
Dantzig, T. (1930). *Number: The Language of Science*. New York: Macmillan.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. London: John Murray.
Dawkins, R. (2006). *The God Delusion*. Boston: Houghton Mifflin Harcourt.
Deacon, T. W. (2021). How Molecules Became Signs. *Biosemiotics*, *14*, 537–559. https://doi.org/10.1007/s12304-021-09453-9
Dedekind, R. (1888). Was sind und was sollen die Zahlen? Friedrich Vieweg und Sohn, Braunschweig. https://doi.org/10.24355/dbbs.084-200902200100-1
De Padova, T. (2017). *Leibniz, Newton und die Erfindung der Zeit*. München: Piper.
de Saussure, F. (2001). *Grundfragen der allgemeinen Sprachwissenschaft*. Berlin: Walter de Gruyter.
Donald, M. (2008). *Triumph des Bewusstseins. Die Evolution des menschlichen Geistes*. Stuttgart: Klett-Cotta.
Doxiadis, A., & Papadimitriou, C. H. (2009). *Logicomix. An epic search for Truth*. New York: Bloomsbury.
Ebeling, W., & Feistel, R. (1982). *Physik der Selbstorganisation und Evolution*. Berlin: Akademie-Verlag.
Ebeling, W., & Feistel, R. (1992). Theory of selforganization and evolution: The role of Entropy, Value and Information. *Journal of Non-Equilibrium Thermodynamics*, *17*, 303–332.
Ebeling, W., & Feistel, R. (1994). *Chaos und Kosmos: Prinzipien der Evolution*. Heidelberg: Spektrum Akademischer Verlag.
Ebeling, W., & Feistel, R. (2015). Chap. 9: Selforganization of Symbols and Information. In G. Nicolis, & V. Basios (Eds.), *Chaos, Information Processing and Paradoxical Games: The legacy of John S Nicolis* (pp. 141–184). Singapore: World Scientific. https://doi.org/10.1142/9789814602136_0009
Ebeling, W., & Feistel, R. (2018). Studies on Manfred Eigen's model for the self-organization of information processing. *European Biophysics Journal*, *47*, 395–401. https://doi.org/10.1007/s00249-018-1287-1
Ebeling, W., & Ulbricht, H. (1986). *Selforganization by nonlinear irreversible processes*. Berlin/Heidelberg: Springer.
Eccles, J. C. (1976). *Das Gehirn des Menschen*. München: Piper.
Eco, U. (2017). *Einführung in die semiotik*. Paderborn: Wilhem Fink Verlag.
Eibl-Eibesfeldt, I. (1998). Ernst Haeckel – Der Künstler im Wissenschaftler. In: Haeckel, E. (1904): Kunstformen der Natur. Neudruck 1988, München, S. 19–30.
Eigen, M. (1971). Selforganization of matter and the evolution of biological macromolecules. *Naturwissenschaften*, *58*, 465–523. https://doi.org/10.1007/BF00623322
Eigen, M. (2013). *From strange simplicity to Complex Familiarity*. Oxford: Oxford University Press.
Einstein, A. (1905). Über einen die Erzeugung und Verwandlung des Lichts betreffenden heuristischen Gesichtspunkt. *Annalen der Physik*, *322*, 132–148. https://doi.org/10.1002/andp.19053220607
Einstein, A. (1936). Physik und Realität. *Journal of the Franklin Institute*, *221*, 313–347. https://doi.org/10.1016/S0016-0032(36)91047-5
Einstein, A. (1969). *Grundzüge der Relativitätstheorie*. Berlin, Pergamon Press, Oxford, Vieweg & Sohn, Braunschweig: Akademie-Verlag.
Einstein, A. (1973). *Über die spezielle und die allgemeine Relativitätstheorie*. Berlin, Pergamon Press, Oxford, Vieweg & Sohn, Braunschweig: Akademie-Verlag.
Einstein, A., Born, H., & Born, M. (1982). *Briefwechsel 1916–1955*. Frankfurt: Edition Erbrich.
Elsayed, M. (2021). *The Bitter Truth of Reality: The route to Skepticism and the case against objective reality*. Independently published (7 Jun. 2021), ISBN 979-8747182264.
Engels, F. (1952). Ludwig Feuerbach und der Ausgang der klassischen deutschen Philosophie. In K. Marx, & F. Engels (Eds.), *Ausgewählte Schriften, Band II* (pp. 333–375). Berlin: Dietz Verlag.
Engels, F. (2017). *Dialektik der Natur*. Berlin: Verlag der Contumax GmbH.
Feigenbaum, E. A., & Feldman, J. (1963). Artificial Intelligence. In E. A. Feigenbaum, & J. Feldman (Eds.), *Computers and thought* (pp. 1–8). New York: McGraw-Hill.
Feistel, R. (1990). Ritualisation und die Selbstorganisation der Information. In U. Niedersen, & L. Pohlmann (Eds.), *Selbstorganisation und determination* (pp. 83–98). Berlin: Duncker & Humblot.
Feistel, R. (2011a). Radiative entropy balance and vertical stability of a gray atmosphere. *European Physical Journal B: Condensed Matter And Complex Systems*, *82*, 197–206. https://doi.org/10.1140/epjb/e2011-20328-2
Feistel, R. (2011b). Entropy flux and entropy production of stationary black-body radiation. *J Non-Equil Thermody*, *36*, 131–139. https://doi.org/10.1515/jnetdy.2011.009
Feistel, R. (2017a). Self-organisation of symbolic information. *The European Physical Journal Special Topics*, *226*, 207–228. https://doi.org/10.1140/epjst/e2016-60170-9

Feistel, R. (2017b). Chap. 4: Emergence of symbolic information by the Ritualisation transition. In M. Burgin, & W. Hofkirchner (Eds.), *Information Studies and the Quest for Transdisciplinarity* (pp. 115–164). Singapore: World Scientific. https://doi.org/10.1142/9789813109001_0004
Feistel, R. (2018). Thermodynamic properties of seawater, ice and humid air: TEOS-10, before and beyond. *Ocean Science*, *14*, 471–502. https://doi.org/10.5194/os-14-471-2018
Feistel, R. (2019). Distinguishing between Clausius, Boltzmann and Pauling Entropies of Frozen Non-Equilibrium States. *Entropy*, *21*, 799. https://doi.org/10.3390/e21080799
Feistel, R., & Ebeling, W. (1978). Deterministic and stochastic theory of sustained oscillations in autocatalytic reaction Systems. *Physica*, *93A*, 114–137. https://doi.org/10.1016/0378-4371(78)90213-3
Feistel, R., & Ebeling, W. (1982). Models of darwinian processes and evolutionary principles. *BioSystems, 15*, 291–299. https://doi.org/10.1016/0303-2647(82)90044-2
Feistel, R., & Ebeling, W. (1989). *Evolution of Complex Systems*. Dordrecht: Kluwer Academic Publishers.
Feistel, R., & Ebeling, W. (2011). *Physics of Self-Organization and Evolution*. Weinheim: Wiley-VCH.
Feistel, R., & Ebeling, W. (2016). Entropy and the Self-Organization of Information and Value. *Entropy*, *18*, 193. https://doi.org/10.3390/e18050193
Feller, U. (2011). The International System of Units—a case for reconsideration. *Accreditation And Quality Assurance*, *16*, 143–153. https://doi.org/10.1007/s00769-010-0747-9
Feuerbach, L. (1848). *Darstellung, Entwicklung und Kritik der Leibnitz'schen Philosophie. Ludwig Feuerbach's sämmtliche Werke, Fünfter Band*. Leipzig: Verlag von Otto Wigand.
Fisher, R. A. (1930). *The Genetical Theory of Natural selection*. Oxford: Clarendon Press.
Forrester, J. W. (1971). Counterintuitive behavior of social systems. *Technological Forecasting and Social Change*, *3*, 1–22. https://doi.org/10.1016/S0040-1625(71)80001-X
Fortak, H. (1979). Entropy and Climate. *Developments in Atmospheric Science*, *10*, 1–14. https://doi.org/10.1016/B978-0-444-41766-4.50008-4
Frankignoul, C., & Kestenare, E. (2005). Air–sea interactions in the Tropical Atlantic: A View based on lagged rotated Maximum Covariance Analysis. *Journal of Climate*, *18*, 3874–3890. https://doi.org/10.1175/JCLI3498.1
Freeth, T., Higgon, D., Dacanalis, A., MacDonald, L., Georgakopoulou, M., & Wojcik, A. (2021). A model of the Cosmos in the ancient greek antikythera mechanism. *Science Reports*, *11*, 5821. https://doi.org/10.1038/s41598-021-84310-w
Frigg, R., & Hartmann, S. (2012). : Models in Science. In Zalta, E.N. (ed.): The Stanford Encyclopedia of Philosophy, https://plato.stanford.edu/archives/fall2012/entries/models-science/
Fuchs, H. U., D'Anna, M., & Corni, F. (2022). Entropy and the experience of heat. *Entropy*, *24*, 646. https://doi.org/10.3390/e24050646
Galchen, R. (2022). Making New Climate Data from Old Timber. The New Yorker, May 6, 2022. https://www.newyorker.com/science/elements/making-new-climate-data-from-old-timber
Gibbs, J. W. (1878). On the equilibrium of heterogeneous substances. *Transactions of the Connecticut Academy of Arts and Sciences*, *111*, 198–248. https://doi.org/10.5479/sil.421748.39088007099781
Gibney, E. (2022). Chinese team syncs clocks over record distance using lasers. *Nature*, *610*, 616–617. https://doi.org/10.1038/d41586-022-03297-0
Gill, R. D. (2022). Schrödinger's cat meets Occam's Razor. *Entropy*, *24*, 1586. https://doi.org/10.3390/e24111586
Giurfa, M., Marcout, C., Hilpert, P., Thevenot, C., & Rugani, R. (2022). An insect brain organizes numbers on a left-to-right mental number line. *Proceedings of the National Academy of Sciences of the United States of America*, *119*, e2203584119. https://doi.org/10.1073/pnas.2203584119
Glaser, R. (2012). *Biophysics*. Berlin Heidelberg: Springer.
Gode, A. (1966). Essay on the Origin of Language. *Two Essays on the origin of Language, Jean-Jacques Rousseau and Johann Gottfried Herder* (pp. 85–166). Chicago and London: The University of Chicago Press.
Goethe, J. W. (2016). Maximen und Reflexionen. 4. Auflage, Berliner Ausgabe, Michael Holzinger.
Goroff, D. L. (1993). Henri Poincare and the birth of Chaos Theory. In H. Poincare (Ed.), *New methods of celestial mechanics* (pp. I1–I107). American Institute of Physics.
Granger, C. W. J. (1969). Investigating causal relations by Econometric Models and cross-spectral methods. *Econometrica*, *37*, 424–438. https://doi.org/10.2307/1912791
Gribbin, J. (1987). *Auf der Suche nach Schrödingers Katze*. München: Piper.
Görnitz, T. (1999). *Quanten sind anders*. Heidelberg: Spektrum Akademischer Verlag.
Haken, H. (1973). *Synergetics. Cooperative Phenomena in Multi-Component Systems*. Wiesbaden: Springer.

Haken, H. (1977). *Synergetics. An introduction. Nonequilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology*. Berlin Heidelberg New York: Springer.
Haroche, S. (2022). *Licht. Eine Geschichte*. Stuttgart: Klett-Cotta.
Hawking, S. W., & Mlodinow, L. (2005). *Die kürzeste Geschichte der Zeit*. Hamburg: Rowohlt.
Hawking, S. W., & Mlodinow, L. (2011). *Der Grosse Entwurf*. Hamburg: Rowohlt.
Hermann, A. (2022). *Max Planck*. Berlin: Rowohlt.
Hertz, H. (1894). Die Prinzipien der Mechanik. Johann Ambrosius Barth, Leipzig. Photocopy reprint (1963): Wissenschaftliche Buchgesellschaft, Darmstadt.
Hilbert, D. (1900). Über den Zahlbegriff. *Jahresbericht der Deutschen Mathematiker-Vereinigung*, *8*, 180–184. http://resolver.sub.uni-goettingen.de/purl?PPN37721857X_0008
Hilbert, D. (1903). *Grundlagen der Geometrie*. Leipzig: Teubner.
Hirsch, M. W., & Smale, S. (1974). *Differential equations, Dynamical Systems, and Linear Algebra*. New York: Academic Press.
Hnilo, A. A. (2023). Locality, realism, ergodicity and randomness in Bell's experiment. *Entropy*, *25*, 160. https://doi.org/10.3390/e25010160
Hoffman, D. D. (2020). Relativ Real. *Warum wir die Wirklichkeit nicht erfassen können und wie die Evolution unsere Wahrnehmung geformt hat*. München: dtv.
Hoffman, D. D., Prakash, C., & Prentner, R. (2023). Fusions of consciousness. *Entropy*, *25*, 129. https://doi.org/10.3390/e25010129
Hoffmann, D. (2008). *Max Planck. Die Entstehung der modernen Physik*. München: C.H. Beck.
Hume, D. (1967). *Eine Untersuchung über den menschlichen Verstand*. Ditzingen: Reclam.
Huxley, J. (1966). A discussion on ritualization of Behaviour in Animals and Man. Philosophical transactions of the Royal Society of London. *Series B Biological Sciences*, *251*, 249–269. https://www.jstor.org/stable/i318188
Huxley, J. S. (1914). The Courtship-habits of the Great Crested Grebe (*Podiceps cristatus*); with an addition to the Theory of Sexual Selection. *Proceedings of the General Meetings for Scientific Business of the Zoological Society of London,35*, 491–562. https://archive.org/details/biostor-107422/page/n13/mode/2up
Ifrah, G. (1991). *Universalgeschichte der Zahlen*. Fankfurt/Main: Campus-Verlag.
Janson, T. (2002). *A short history of Languages*. Oxford: Oxford University Press.
Jones, N. A., Ross, H., Lynam, L., Perez, P., & Leitch, A. (2011). Mental models: An interdisciplinary synthesis of theory and methods. *Ecology and Society*, *16*, 46. https://doi.org/10.5751/ES-03802-160146
Jung, C. G., von Franz, M. L., Henderson, J. L., Jacobi, J., & Jaffé, A. (1979). *Der Mensch und seine Symbole*. Olten und Freiburg im Breisgau: Walter-Verlag.
Jung, K. (2022). A proposed interpretation of the Wave–Particle Duality. *Entropy*, *24*, 1535. https://doi.org/10.3390/e24111535
Kabelac, S., & Conrad, R. (2012). Entropy Generation during the Interaction of Thermal Radiation with a surface. *Entropy*, *14*, 717–735. https://doi.org/10.3390/e14040717
Kaloyerou, P. N. (2016). Critique of Quantum Optical Experimental Refutations of Bohr's Principle of Complementarity, of the Wootters–Zurek Principle of Complementarity, and of the Particle–Wave Duality Relation. *Foundations of Physics*, *46*, 138–175. https://doi.org/10.1007/s10701-015-9959-5
Kant, I. (1956). *Kritik der reinen Vernunft*. Felix Meiner, Hamburg. Originalausgaben A: 1781, B: 1787.
Kant, I. (2016). *Prolegomena zu einer jeden künftigen Metaphysik*. Berliner Ausgabe, Erstdruck (1783): Hartknoch, Riga.
Kittel, C. (1973). *Physik der Wärme*. Frankfurt am Main: Olderbourg, München; John Wiley.
Kjørup, S. (2009). *Semiotik*. Paderborn: Wilhelm Fink.
Klagge, J. C. (1986). Marx's Realms of 'Freedom' and 'necessity'. *Canadian Journal of Philosophy*, *16*, 769–777. https://doi.org/10.1080/00455091.1986.10717147
Klaus, G., & Buhr, M. (Eds.). (1969). *Philosophisches Wörterbuch*. Leipzig: Bibliographisches Institut.
Klimenko, A. Y. (2022). The Second Law, asymmetry of Time and their implications. *Entropy*, *24*, 862. https://doi.org/10.3390/e24070862
Klix, F. (1980). *Erwachendes Denken*. Berlin: VEB Deutscher Verlag der Wissenschaften.
Kämmerer, W. (1974). *Einführung in die mathematischen Methoden der Kybernetik*. Berlin: Akademie-Verlag.
Knobel, E. B. (1917). *Ulugh Beg's catalogue of Stars*. Washington: The Carnegie Institution of Washington.
Krauss, P., & Maier, A. (2020). Will we ever have conscious Machines? Front. *Comput Neurosci*, *14*, 556544. https://doi.org/10.3389/fncom.2020.556544
Kretschmer, H. (2021). *Lexikon der Symbole und Attribute in der Kunst*. Ditzingen: Reclam.

Kull, K. (2001). Jakob von Uexküll: An introduction. *Semiotica*, *134*, 1–59. https://doi.org/10.1515/semi.2001.013
Kull, K. (2007). Biosemiotics and Biophysics – the fundamental approaches to the study of life. In M. Barbieri (Ed.), *Introduction to Biosemiotics* (pp. 167–177). Dordrecht: Springer. https://doi.org/10.1007/1-4020-4814-9_7
Kulsariyeva, A. T., & Zhumashova, Z. (2015). Numbers as Cultural Significant. *Procedia - Social and Behavioral Sciences*, *191*, 1660–1664. https://doi.org/10.1016/j.sbspro.2015.04.688
Lacková, L., Matlach, V., & Faltýnek, D. (2017). Arbitrariness is not enough: Towards a functional approach to the genetic code. *Theory in Biosciences*, *136*, 187–191. https://doi.org/10.1007/s12064-017-0246-1
Landau, L. D., & Lifschitz, E. M. (1966). *Lehrbuch der Theoretischen Physik Band V, Statistische Physik*. Berlin: Akademie-Verlag.
Landau, L. D., & Lifschitz, E. M. (1967). *Lehrbuch der Theoretischen Physik Band II, Klassische Feldtheorie*. Berlin: Akademie-Verlag.
Landau, L. D., & Lifschitz, E. M. (1974). *Lehrbuch der Theoretischen Physik Band VI, Hydrodynamik*. Berlin: Akademie-Verlag.
Lane, N. (2022). *Transformer. The Deep Chemistry of Life and Death*. London: Profile Books.
LeDoux, J. (2021). *Bewusstsein. Die ersten vier Milliarden Jahre*. Stuttgart: Klett-Cotta.
Lee, J. W., Hwang, E., & Kacker, R. N. (2022). True value, error, and measurement uncertainty: Two views. *Accreditation and Quality Assurance*, *27*, 235–242. https://doi.org/10.1007/s00769-022-01508-9
Leibniz, G. W. (1765). *Nouveaux essais sur l'entendement humain. Amsterdam/Leipzig. Reprint 1990*. Berlin: Akademie-Verlag.
Leibniz, G. W. (1904). *Neue Abhandlungen über den menschlichen Verstand*. Leipzig: Dürr.
Lenin, W. I. (1975). *Band 14. Materialismus und Empiriokritizismus*. Berlin: Dietz Verlag.
Levine, J., Tavella, P., & Milton, M. (2023). Towards a consensus on a continuous coordinated Universal Time. *Metrologia*, *60*, 014001. https://doi.org/10.1088/1681-7575/ac9da5
Lewicki, M. S. (2010). A signal take on speech. *Nature*, *466*, 821–822. https://doi.org/10.1038/466821a
Lindner, H. (1963). *Grundriss der Atom- und Kernphysik*. Leipzig: Fachbuchverlag.
Locke, J. (1872). Versuch über den menschlichen Verstand. *Die vier Teile in einem Buch. Reprint 2016*. Berlin: Contumax GmbH.
Lorenz, K. (1970). *Vorwort zu Koenig, O.: Kultur und Verhaltensforschung*. München: Dtv.
Lorenz, K. (1983). *Das sogenannte Böse. Zur Naturgeschichte der Aggression*. München: dtv.
Luther, M. (1922). Die Bibel oder die ganze Heilige Schrift des Alten und Neuen Testaments, nach der deutschen Übersetzung Dr. Martin Luthers, 503. Auflage. Von Gasteinsche Bibel = Anstalt, Halle a.d.S.
Lévy-Brühl, L. (1921). *Das Denken der Naturvölker*. Wien: Braumüller.
Margenau, H., & Park, J. L. (1973). The physics and the semantics of Quantum Measurement. *Foundations of Physics*, *3*, 20–28. https://doi.org/10.1007/BF00708597
Mast, F. (2020). *Black Mamba oder die Macht der Imagination*. Freiburg i. B: Verlag Herder.
Ma, X. S., Herbst, T., Scheidl, T., Wang, D., Kropatschek, S., Naylor, W., Wittmann, B., Mech, A., Kofler, J., Anisimova, E., Makarov, V., Jennewein, T., Ursin, R., & Zeilinger, A. (2012). Quantum teleportation over 143 kilometres using active feed-forward. *Nature*, *489*, 269–273. https://doi.org/10.1038/nature11472
McNamara, J. M., Barta, Z., Klaassen, M., & Bauer, S. (2011). Cues and the optimal timing of activities under environmental changes. *Ecology Letter*, *14*, 1183–1190. https://doi.org/10.1111/j.1461-0248.2011.01686.x
Muller, R. A. (2018). *Jetzt. Die Physik der Zeit*. Frankfurt am Main: S. Fischer.
Nernst, W. (1922). Zum Gültigkeitsbereich der Naturgesetze. *Die Naturwissenschaften*, *10*, 489–495. https://doi.org/10.1007/BF01568543
Nicolis, G., & Prigogine, I. (1987). *Die Erforschung des Komplexen*. München: Piper.
Nöth, W. (2000). Handbuch der Semiotik, 2nd edition. J.B. Metzler, Stuttgart.
Oehler, K. (1995). *Sachen und Zeichen. Zur Philosophie des Pragmatismus*. Frankfurt am Main: Vittorio Klostermann.
Orcutt, G. H. (1952). Actions, Consequences, and Causal Relations. *The Review of Economics and Statistics*, *34*, 305–313. https://doi.org/10.2307/1926858
Park, J. L. (1970). The concept of transition in quantum mechanics. *Foundations of Physics*, *1*, 23–33. https://doi.org/10.1007/BF00708652

Pattee, H. H. (1986). Chap. 10: Universal Principles of Measurement and Language Functions in Evolving Systems. In J. L. Casti, & A. Karlquist (Eds.), *Complexity, Language, and life: Mathematical approaches* (16 vol., pp. 268–281). Berlin-Heidelberg-New York-Tokyo: Springer.
Pattee, H. H. (1996). The Physics of Symbols and the Evolution of Semiotic Controls. *Paper presented at the Workshop on Control Mechanisms for Complex Systems: Issues of Measurement and Semiotic Analysis*, Las Cruces, New Mexico. December 8–12, 1996.
Pattee, H. H. (2001). The physics of symbols: Bridging the epistemic cut. *Biosystems*, *60*, 5–21. https://doi.org/10.1016/s0303-2647(01)00104-6
Pattee, H. H. (2008). Physical and functional conditions for symbols, Codes, and Languages. *Biosemiotics*, *1*, 147–168. https://doi.org/10.1007/s12304-008-9012-6
Pattee, H. H., & Rączaszek-Leonardi, J. (2012). *Historical introduction to Laws Language and Life*. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-5161-3
Pauling, L. (1935). The structure and entropy of ice and of other crystals with some randomness of atomic arrangement. *Journal Of The American Chemical Society*, *57*, 2680–2684. https://doi.org/10.1021/ja01315a102
Pearl, J., & Mackenzie, D. (2018). *The Book of why*. The New Science of Cause and Effect. Penguin Books.
Peirce, C. S. (1868a). On a New List of Categories. *Proceedings of the American Academy of Arts and Sciences*, *7*, 287–298. http://www.bocc.ubi.pt/pag/peirce--charles-list-categories.pdf
Peirce, C. S. (1868b). Questions concerning certain faculties claimed for man. *The Journal of Speculative Philosophy*, *2*, 103–114. https://www.jstor.org/stable/25665643
Pelkowski, J. (2014). On the Clausius-Duhem Inequality and Maximum Entropy production in a simple radiating system. *Entropy*, *16*, 2291–2308. https://doi.org/10.3390/e16042291
Pennisi, E. (2019). Did neurons arise from an early secretory cell? *Science*, *363*, 212–213. https://doi.org/10.1126/science.363.6424.212
Penrose, R. (2004). *The Road to reality*. New York: Vintage Books.
Petersen, A. (1963). The philosophy of Niels Bohr. *Bulletin of the Atomic Scientists*, *19*, 8–14. https://doi.org/10.1080/00963402.1963.11454520
Planck, M. (1906). *Vorlesungen über die Theorie der Wärmestrahlung*. Leipzig: Johann Ambrosius Barth.
Planck, M. (1948a). *Der Kausalbegriff in der Physik*. Leipzig: Johann Ambrosius Barth.
Planck, M. (1948b). *Wissenschaftliche Selbstbiographie*. Leipzig: Johann Ambrosius Barth.
Planck, M. (1958). *Physikalische Abhandlungen und Vorträge. Band I-III*. Braunschweig: Vieweg.
Planck, M. (1966). *Theorie der Wärmestrahlung*. Leipzig: Johann Ambrosius Barth.
Planck, M. (2018). *Das Wesen des Lichts.* ad fontes wissenschaft, Torrazza Piemonte. Originally published by Julius Springer 1920.
Platon (2013). Sämtliche Werke, Band 3, 37. Auflage. Rowohlt Taschenbuch Verlag, Reinbek bei Hamburg.
Plotnitsky, A. (2022). "Yet once More": The double-slit experiment and Quantum Discontinuity. *Entropy*, *24*, 1455. https://doi.org/10.3390/e24101455
Poincaré, H., & Goroff, D. L. (1993). *New methods of celestial mechanics*. American Institute of Physics.
Prigogine, I. (1969). *Structure, dissipation and life*. Amsterdam: North-Holland Publ. Company.
Prigogine, I., Nicolis, G., & Babloyantz, A. (1972). Thermodynamics of evolution. *Physics Today*, *25*, 23–31. https://doi.org/10.1063/1.3071090
Prigogine, I., & Stengers, I. (1981). *Dialog mit der Natur*. München: Piper.
Rehder, B., Davis, Z. J., & Bramley, N. (2022). The Paradox of Time in Dynamic Causal Systems. *Entropy*, *24*, 863. https://doi.org/10.3390/e24070863
Riedl, R., & Kaspar, R. (1981). *Biologie der Erkenntnis*. Berlin und Hamburg: Paul Parey.
Romanovsky, Y. M., Stepanova, N. V., & Chernavsky, D. S. (1975). *Mathematical modelling in biophysics (in russian)*. Moscow: Nauka.
Röseberg, U. (1975). *Determinismus und Physik*. Berlin: Akademie-Verlag.
Russell, B. (1919). Mysticism and Logic and Other Essays. Chapter IX: On the Notion of Cause. Longmans, Green and Co., London, p. 180–208. https://en.wikisource.org/wiki/Mysticism_and_Logic_and_Other_Essays
Sačkov, J. V. (1978). *Wahrscheinlichkeit und Struktur*. Berlin: Akademie-Verlag.
Sagan, C. (1978). *Die Drachen von Eden. Das Wunder der menschlichen Intelligenz*. München/Zürich: Droemer/Knaur.
Sarafyazd, M., & Jazayeri, M. (2019). Hierarchical reasoning by neural circuits in the frontal cortex. *Science*, *364*, eaav8911. https://doi.org/10.1126/science.aav8911
Schallreuter, W. (1962). *Grimsehl Lehrbuch der Physik, Dritter Band, Optik*. Leipzig: B. G. Teubner.

Schimming, R. (2022). Essay über Einfachheit. *Sitzungsberichte der Leibniz-Sozietät der Wissenschaften zu Berlin*, *149*, 17–25. https://leibnizsozietaet.de/publikationen/sitzungsberichte/
Schrödinger, E. (1935). The Present Status of Quantum Mechanics. https://www.jstor.org/stable/986572, translated from the German original: Die gegenwärtige Situation in der Quantenmechanik. Naturwissenschaften 23, 807–812. https://doi.org/10.1007/BF01491891
Schrödinger, E. (1979). *Was ist ein Naturgesetz? R*. München: Oldenbourg Verlag.
Schrödinger, E. (2020). *Was ist Leben?* Piper: München.
Schurz, G., & Metzler, J. B. (2021). *Erkenntnistheorie.* Berlin. Online excursus at https://doi.org/10.1007/978-3-476-04755-7_1
Shiffrin, R. M., Bassett, D. S., Kriegeskorte, N., & Tenenbaum, J. B. (2020). The brain produces mind by modeling. *Proceedings of the National Academy of Sciences of the United States of America,* 117, 29299–29301. https://doi.org/10.1073/pnas.1912340117
Sommerfeld, A. (1988). *Thermodynamik und Statistik*. Frankfurt/M: Verlag Harri Deutsch, Thun.
Stachowiak, H. (1973). *Allgemeine Modelltheorie*. Wien: Springer-Verlag.
Stanley, H. E. (1971). *Introduction to phase transitions and critical phenomena*. Oxford: Clarendon Press.
Stary, C., & Fuchs-Kittowski, K. (2020). Zur Wiedergewinnung des Realismus als notwendige grundlage einer am Menschen orientierten Informationssystemgestaltung und Softwareentwicklung. *Leibniz Online*, *41*, 1–17. https://leibnizsozietaet.de/publikationen/leibniz-online/
Steinbuch, K. (1961). *Automat und Mensch. Über menschliche und maschinelle Intelligenz*. Berlin/Göttingen/Heidelberg: Springer.
Stewart, J. E. (2022). The evolution and development of consciousness: The subject-object emergence hypothesis. *Biosystems*, *217*, 104687. https://doi.org/10.1016/j.biosystems.2022.104687
Stips, A., Macias, D., Coughlan, C., Garcia-Gorriz, E., & Liang, X. S. (2016). On the causal structure between CO_2 and global temperature. *Scientific Reports*, *6*, 21691. https://doi.org/10.1038/srep21691
Suárez, M. (2014). *Models of the World, Data-models and the practice of Science: The semantics of Quantum Theory*. Ann Arbor: ProQuest LLC.
Tan, K. C., & Jeong, H. (2018). Entanglement as the symmetric portion of correlated coherence. *Physical Review Letters*, *121*, 220401. https://doi.org/10.1103/PhysRevLett.121.220401
Tembrock, G. (1977). Grundlagen des Tierverhaltens. Akademie-Verlag, Berlin.
Turing, A. M. (1950). Computing machinery and intelligence. *Mind*, *59*, 433–460. http://www.jstor.org/stable/2251299
van Leent, T., Bock, M., Fertig, F., Garthoff, R., Eppelt, S., Zhou, Y., Malik, P., Seubert, M., Bauer, T., Rosenfeld, W., Zhang, W., Becher, C., & Weinfurter, H. (2022). Entangling single atoms over 33 km telecom fibre. *Nature*, *607*, 69–73. https://doi.org/10.1038/s41586-022-04764-4
Vater, C. (2011). *Können Maschinen denken?" - Turing-Maschinen und Intelligenz*. Magisterarbeit im Fach Philosophie: Institut für Philosophie der Universität Kassel.
Volkenshtein, M. V. (1978). *General Biophysics (in Russian)*. Moscow: Nauka.
Volterra, V. (1931). *Leçons sur la théorie mathématique de la lutte pour la vie*. Paris: Gauthier-Villars.
von Helmholtz, H. (1903). *Vorträge und Reden, Band 2*. Braunschweig: Vieweg und Sohn.
von Herder, J. G. (1772). *Abhandlung über den Ursprung der Sprache, welche den von der Königl. Academie der Wissenschaften für das Jahr 1770 gesezten Preis erhalten hat*. Berlin: Christian Friedrich Voß. http://www.deutschestextarchiv.de/book/show/herder_abhandlung_1772
von Mises, R. (1928). *Wahrscheinlichkeit, Statistik und Wahrheit*. Wien: Julius Springer.
von Weizsäcker, C. F. (1999). Wonach strebt die Wissenschaft von der Natur? In: Görnitz, T. (1999): Quanten sind anders. Spektrum Akademischer Verlag, Heidelberg, pp. 5–7.
White, R. (2011). The meaning of measurement in metrology. *Accreditation and Quality Assurance*, *16*, 31–41. https://doi.org/10.1007/s00769-010-0698-1
Willink, R. (2013). *Measurement uncertainty and probability*. Cambridge: Cambridge University Press.
Wilson, E. O., & Bossert, W. H. (1973). *Einführung in die populationsbiologie*. Berlin Heidelberg: Springer.
Winkler, D. W., Jørgensen, C., Both, C., Houston, A. I., McNamara, J. M., Levey, D. J., Partecke, J., Fudickar, A., Kacelnik, A., Roshier, D., & Piersma, T. (2014). Cues, strategies, and outcomes: How migrating vertebrates track environmental change. *Movement Ecology*, *2*, 10. https://doi.org/10.1186/2051-3933-2-10
Wolchover, N. (2013). A Jewel at the Heart of Quantum Physics. Quanta Magazine, September 17, 2013. https://www.quantamagazine.org/physicists-discover-geometry-underlying-particle-physics-20130917/#
Wootters, W., & Zurek, W. (1982). A single quantum cannot be cloned. *Nature*, *299*, 802–803. https://doi.org/10.1038/299802a0

Zhang, J., & Liu, K. (2023). Neural information Squeezer for Causal Emergence. *Entropy*, *25*, 26. https://doi.org/10.3390/e25010026