.

Appendix II. A proposed law for statistical time asymmetry

Abstract

The concept of entropy is found to be insufficient to constitute a basis for a general description of physical time asymmetry. A few authors have previously tried to give such a description founded on time-directed conditional probabilities, and the main features of their work are investigated. In this connection, the theoretical and empirical bases for the difference in applicability between past-directed and future-directed probabilities are analysed and exemplified. A law to describe the statistical time asymmetry in physical processes is proposed and subsequently validated for the phenomenon of post-interactive correlations.

1 Introduction

The domains of physics embrace a variety of phenomena which, when they are evolving spontaneously, demonstrate time asymmetry. Radioactive atoms decay, gas expands, salt dissolves in liquid, oil forms a layer on water, tensioned rubber bands and springs relax and, at the astronomical level, stars, galaxies and black holes are formed.

Some proposals for the origins of such time directed processes have been made on the basis of the second law of thermodynamics, which describes the entropy of an isolated system as either increasing or being unaltered.[1] However, serious objections can be raised to these proposals.

- There is a troublesome mismatch between the *time asymmetry* of the entropy increase, described by macroscopic variables, and the *time symmetry* assumed to rule at the microscopic level of mechanical laws. How the time asymmetry can arise somewhere between these two levels calls for an explanation.[2]

- The entropy quantity has no *general* applicability to time asymmetric phenomena, since entropy in its strictly thermodynamic

[1] For references, see Earman (2006).

[2] A question similar to this was originally raised by Reichenbach (1956). Prigogine & Stengers (1984, p. 285) write: “Irreversibility is either true on all levels or on none. It cannot emerge as if by a miracle, by going from one level to another.”

version is defined only for a very limited selection of processes. When describing complex systems or systems in non-equilibrium, the statistical interpretation of entropy is not immediately applicable and the attribution of an amount of entropy to the universe as a whole appears to be impossible. Furthermore, there are various interpretations of what entropy actually measures, making the task even more difficult.[3]

- Low entropy is, as a rule, associated with inhomogeneous structures rather than homogeneity. Still, the universe at the time of the Big Bang was extremely homogeneous, even though it should have been in an ultimate state of low entropy according to the second law of thermodynamics. To solve this paradox, it has been proposed that the expansion of the universe, in combination with the contracting gravitational force, makes a continuous increase of entropy possible. Gravitational entropy therefore holds a potential solution to the problem, but up to now the attempts in this direction have not led to the desired enlargement of the entropy concept.[4]

Accordingly, there seems to be a need for a new general description of processes demonstrating time asymmetry. Such a description ought to be:

- applicable to both microscopic and macroscopic levels,
- valid also for non-equilibrium systems,
- applicable to various fields where time asymmetries occur, and
- capable of describing the evolution of the universe as a whole.

In Sections 2 and 3, such a description is sought in previous works that deal with a concept termed by Gal-Or (1972) as *statistical time asymmetry*. Some basic definitions are formulated in this connection. A law of statistical time asymmetry is proposed in Section 4, where also a statistical mechanical version of the law is presented, and in Section 6 the general version of the law is verified for two processes of post-interactive correlations. The fulfilment of the law is described in Section 7 and, in the last section, the main conclusions are given.

[3]Several authors have noted that the entropy concept lacks a clear definition for anything other than gas processes (Earman, 1974, 2006; Denbigh, 1989; Uffink, 2001, 2007).

[4]Earman (2006) raises objections to the concept of gravitational entropy, as well as to attempts to explain the present increasing entropy as a consequence of a low entropy state in the early universe. Ellis & Buchert (2005) conclude that the relation of entropy to spontaneous structure formation in the expanding universe is not yet properly understood.

2 Early work on statistical time asymmetry

At the beginning of the twentieth century, Willard Gibbs, made the following statement:

> But while the distinction of prior and subsequent events may be immaterial with respect to mathematical fictions, it is quite otherwise with respect to the events of the real world. It should not be forgotten, when our ensembles are chosen to illustrate the probabilities of events in the real world, that while the probabilities of subsequent events may often be determined from the probabilities of prior events, it is rarely the case that probabilities of prior events can be determined from those of subsequent events, for we are rarely justified in excluding the consideration of the antecedent probability of the prior events. (Gibbs, 1902, p.150–151)

Gibbs seemingly proposes the existence of a bias in the applicability of probability calculus with respect to future and past time direction. He does not seem to have discussed this idea any further, but more than sixty years later the physicist Satosi Watanabe gives the proposal a more concrete form, when formulating the *Theorem of impossibility of law-like retrodiction*:[5]

> Let $\mathcal{E} = \{E_i\}$, and $\mathcal{F} = \{F_j\}$, be state descriptions (in terms of suitable variables) of an isolated physical system at two different times, t_1 and t_2, respectively. (Watanabe, 1965, p. 144)

> [...] the condition $t_1 < t_2$ is equivalent, except in the uncontrollable case and in the bilaterally deterministic case, to the condition that the $p(F_j|E_i)$ but not the $p(E_i|F_j)$ are determined by the nature of the physical system. (Watanabe, 1965, p. 145)

In Watanabe's terminology, the "uncontrollable case" means that the evolution is entirely determined by "the nature of the system", i.e. not available to what Watanabe calls the "free choice" of a "human agent". "The bilaterally deterministic case", on the other hand, means an evolution for which the conditional probabilities are either 0 or 1. Although Watanabe describes the uncontrollable case as "extremely rare", later

[5]Another attempt in this direction is the *law of conditional independence*, which is suggested by Penrose & Percival (1962). However, these authors try to found their law on a variant of the *common cause principle*, which is criticized by Arntzenius (2005) with convincing arguments.

in his article he seems to exemplify it with thermodynamic equilibrium, which is quite a common state.

Watanabe's analysis is also somewhat unclear in other respects. He does not indicate any method to anchor his theorem in direct empirical observations, and he tries to derive the macroscopic time asymmetry of thermodynamic processes from microscopic determinism in combination with the ability of the experimenter to make a "free initial choice". Such a derivation can hardly explain the time asymmetry of the thermodynamic processes occurring in nature.

3 Recent work on statistical time asymmetry

Since the work of Watanabe in the middle of the past century, most physicists seem to have lost interest in the idea of the statistical time asymmetry proposed by Gibbs. Instead, some philosophers of science have extended this line of thought. For example, Andrew Holster refers to Watanabe in his PhD thesis, where he is primarily directed at quantum mechanics (statistical mechanics is not mentioned). He writes:

> And this is what it appears to be like in the real world: there are (if the fundamental theory is probabilistic) generic probabilities directed forwards in time, but there are no generic probabilities directed backwards in time. (Holster, 1990, p. 37)

The philosopher Elliot Sober even formulates a mathematical proof:

> I will now show that a system whose expected state changes with time cannot have both a forward-directed time translation invariant law and a backward-directed time translation invariant law. (Sober, 1993, p. 173)

> The proof of the previous section shows that we must choose between forward-directed and backward-directed laws. It appears that science and common sense have opted for the former. (Sober, 1993, p. 176)

In other words, Sober's proof shows that a stochastic process with a finite number of states, whose expected state changes with time, cannot be correctly described by both future-directed and past-directed probabilities, if both are time translation invariant.[6] These time-directed

[6]Arntzenius (1997) has made a proof that aims to imply similar conclusions for *processes approaching equilibrium*, and which is applicable to systems with an infinite number of states.

probabilities are defined here as follows (where $A[t_1, t_2]$ and $B[t_3, t_4]$ denote arbitrary states of a given system at time intervals, where $t_1 \leq t_2 \leq t_3 \leq t_4$ and $t_1 < t_4$).[7]

> **Definition 1** *Future-directed probability is conditional probability in which the conditional state precedes the outcome state:*
>
> $$p(B[t_3, t_4]|A[t_1, t_2]) = \frac{p(A[t_1, t_2] \wedge B[t_3, t_4])}{p(A[t_1, t_2])} .$$

> **Definition 2** *Past-directed probability is conditional probability in which the outcome state precedes the conditional state:*
>
> $$p(A[t_1, t_2]|B[t_3, t_4]) = \frac{p(A[t_1, t_2] \wedge B[t_3, t_4])}{p(B[t_3, t_4])} .$$

Sober (1993) describes probabilities of states that exist at points in time rather than in time intervals, but his proof works just as well for the latter kind. A more serious limitation of his proof is the assumption that the conditional probabilities of the states in question to be preserved is not zero. In statistical mechanics this is certainly true for the macrostates involved in the conditional probabilities, but in quantum mechanics it is not always so. For example, when a photon is being detected both before and after meeting a half-silvered mirror, the conditional probability that the photon will remain at the initial or final position can be regarded as zero, since the photon is brought to existence at the source and ceases to exist at the detector.[8]

The philosopher Frank Arntzenius elaborates the ideas of Sober somewhat further when he writes:

> I claim that the actual world is filled with such time-asymmetric phenomena, and that the most plausible account of such time-asymmetric phenomena is that the development of the world is governed by invariant forwards transition chances (objective probabilities), while there are no backwards transition chances, no objective backwards transition probabilities. I admit, of course, that there are backwards relative frequencies of transitions. I deny, however, that there

[7] Some authors propose that conditional probability should be considered as a basic concept, which not has to be defined in terms of unconditional probabilities (Watanabe, 1965; Hájek, 2003). However, the conventional definition is used here, since it is closely related to the frequency interpretation.

[8] An experiment of this kind is analysed both in Section 6 and in Skoruppa (2022c).

> are any backwards transition chances, that there are objective backwards transition probabilities, which govern the development of (parts of) the world. (Arntzenius, 1995, p. 68)

It should be noted that Arntzenius describes the difference between the applicability of future-directed and past-directed probabilities (i.e. forwards and backwards transition chances) in terms of invariance in general, while Sober restricts himself to *time translation* invariance. If "invariant" refers to spatial translation and spatial rotation as well as time translation, Arntzenius' wider description of the difference may be preferable. Still, Sober's restriction is satisfactory; every physical law seems to be invariant in all three domains and, as a consequence, physical laws with time translation non-invariant conditional probabilities imply non-invariance under spatial translation and spatial rotation as well. Hence, in the following sections only *time translation* invariance will be considered in order to make the presentation concise.

More recently, the philosopher Jos Uffink has drawn conclusions, similar to Holster, Sober and Arntzenius in the field of statistical mechanics (here the time-directed probabilities are named forward and backward transition probabitlites):

> But here we see that assuming time translation invariance for a system of forward transition probabilities is not equivalent to assuming the same invariance for the backward transition probabilities. If one believes that one of the two is obvious, how will one go about explaining the failure of the other? (Uffink, 2007, p. 1060)

> Rather the appearance of irreversible behaviour is due to the choice to rely on the forward transition probabilities, and not the backward. (Uffink, 2007, p. 1062)

Another clue can be found in a recently formulated meta-symmetric asymmetry, stating that *future-directed process reversal invariance* (conventionally named "time reversal invariance") and its time reversed counterpart do not have the same status in physics (the superscript '^{T}' denotes the time reversed state by the transformation $T : t \to -t$ with respect to aspects such as velocity and magnetic field; Δt, here as well as in the rest of the article, denotes an arbitrary positive time interval):[9]

> **Meta-symmetric time asymmetry.**
> The symmetry $p(B[t + \Delta t]|A[t]) = p(A^T[t + \Delta t]|B^T[t])$ is, the decay of the neutral K-meson and the B-meson being the only observed exceptions, generally valid in quantum mechanics, while its time reversal (by the transformation $T : t \to -t$) $p(A[t]|B[t + \Delta t]) = p(B^T[t]|A^T[t + \Delta t])$ is not.

This means that a law-like symmetry rules the future-directed probabilities given by quantum mechanics, while there is no corresponding law-like symmetry that rules the past-directed probabilities. This meta-symmetric asymmetry thereby strengthens the proposals of Gibbs, Watanabe, Holster, Sober, Arntzenius, and Uffink.

On the basis of the findings presented above, a law that describes statistical processes demonstrating time asymmetry is formulated in the next section.

4 A proposed law

In the light of previous discussions on the topic of statistical time asymmetry, there are strong reasons to assume that future-directed probabilities have some kind of priority over the past-directed probabilities. This priority seemingly consists in a higher degree of "lawlikeness" of the former type or, in other words, that the future-directed probabilities more regularly are time translation invariant. Thus, a reasonable preliminary hypothesis is:

> In a process, where either past-directed or future-directed probabilities are generally translation invariant, it is always the future-directed probabilities that have this feature.

A physical law is valid only under certain conditions and these have to be specified. Isolation is a reasonable requirement, since it guarantees that no manipulation is made in order to mimic a spontaneous evolution in accordance with translation invariant past-directed probabilities. It is also suitable to define the states that is ruled by the law as existing during time interval rather than at points in time, since this widens the scope of the law, e.g. to include the probability, $p(R[t, t + \Delta t]|R[t]) = e^{\lambda \cdot \Delta t}$, that a radioactive atom, R, do not decay.

Furthermore, the law must deal with two states that both are defined by the same physical quantity, since otherwise some anomalous processes may falsify the law. Assume, for example, that the first state is the

[9] This asymmetry and the terms involved are described in greater detail in Skoruppa (2022i). However, the general validity of the T-symmetry $p(B[t + \Delta t]|A[t]) = p(A^T[t + \Delta t]|B^T[t])$ is questioned in Skoruppa (2022c).

occurrence of an even number of air molecules in the atmosphere at a certain moment, and that the second state is an eruption in the same atmosphere of a certain magnitude in any of the earth's volcanos. Then, the future-directed probability is not time translation invariant (since the probability of an eruption is heightened after a recent eruption), while the past-directed probability presumably always is $\frac{1}{2}$.

Finally, the law only concerns stochastic processes. Consider, for example, that the first state of a conditional probability is the occurrence of an earthquake of a magnitude < 2 on the Richter scale somewhere on the earth during a particular year, and that the second state is the occurrence of an earthquake of a magnitude > 8 during the following year. Then the future-directed probability is not time translation invariant (since the probability of an earthquake is heightened after a recent earthquake), while the past-directed probability in practice has the time translation invariant value 1, since there are always some minor movements in the crust of the earth. Therefore, the law must be defined only for processes that are non-deterministic.

The ground is now prepared for the proposal of a physical law, in which the dominance of the future-directed probabilities is described:

> **Law of statistical time asymmetry**
> Assume that $A[t_1, t_2]$ and $B[t_3, t_4]$, where $t_1 \leq t_2 \leq t_3 \leq t_4$ are physical states, defined by the same quantities in an isolated process, where only one of the non-deterministic probabilities $p(B[t_3, t_4]|A[t_1, t_2])$ and $p(A[t_1, t_2]|B[t_3, t_4])$ is time translation invariant. Then the former probability is always time translation invariant.

This law can be connected with Bayes' theorem, which states

$$p(A[t_1, t_2]|B[t_3, t_4]) = \frac{p(A[t_1, t_2])}{p(B[t_3, t_4])} \cdot p(B[t_3, t_4]|A[t_1, t_2]) \; .$$

Obviously, the future-directed probability $p(B[t_3, t_4]|A[t_1, t_2])$ and the past-directed probability $p(A[t_1, t_2]|B[t_3, t_4])$ cannot both be time translation invariant, if the quotient $p(A[t_1, t_2])/p(B[t_3, t_4])$ varies with time.[10] Since equilibrium is statistically defined by constant unconditional probabilities, and since the unconditional probability of a disequilibrium state varies with time, such a variable quotient appears in a system that develops from disequilibrium to equilibrium in the time interval $[t_1, t_4]$.[11] Thus, the following statistical mechanical version of the law above can

[10] This corresponds to the statement in the first quotation of Sober (1993) in Section 3.

[11] It is often possible to formulate time translation invariant past-directed probabilities that describe only the disequilibrium part of a process, e.g. that the probability of a gas molecule to *have passed* through a hole between two vessels is proportional

be formulated:

> **Law of statistical mechanical time asymmetry**
> Assume that $A[t_1, t_2]$ and $B[t_3, t_4]$, where $t_1 \leq t_2 \leq t_3 \leq t_4$ and $t_1 < t_4$, are macroscopic states, defined by the same quantities and the same degree of coarse graining in an isolated disequilibrium process. Then $p(B[t_3, t_4]|A[t_1, t_2])$ is always, while $p(A[t_1, t_2]|B[t_3, t_4])$ is never, time translation invariant through the entire evolution from disequilibrium to an enduring equilibrium.

The laws defined above may seem to be based on a violation of the symmetry

$$p(A[t_1, t_2]|B[t_3, t_4]) = p(B[t_3, t_4]|A[t_1, t_2]) \;, \tag{1}$$

which is analysed in Skoruppa (2022c). There it is described as lacking theoretical significance, but it is also noted that the same symmetry has been used by previous authors to test whether time translation invariant future-directed or past-directed probabilities rule the process in question. It is precisely this function that the comparison between the two probabilities in symmetry (1) has in the present context. In Section 6 such a test will be performed on a certain type of quantum mechanical process.

5 The role of physical symmetry in statistical time asymmetry

A concept which has played crucial role in the analysis of statistical time asymmetry in physical processes is the widely discussed "Stosszahlansatz", which was put forward by Maxwell (1867), and which was implicitly presupposed in the works of Ludwig Boltzmann. Uffink (2007) interprets Maxwell's application of the hypothesis in the following way:

> A crucial element in the argument is still an assumption about independence. But now, in the Stosszahlansatz, the initial velocities of colliding particles are assumed independent, instead of the orthogonal velocity components of a single particle. Maxwell does not expand on why we should assume this ansatz; he clearly regarded it as obvious. Yet it seems plausible to argue that he must have had in the back of his mind some version of the principle of insufficient reason, i.e., that we are entitled to treat the initial velocities of two

to the density of the gas in the vessel it is *arriving at*. However, such a description is not valid for an equilibrium state that is maintained for more than a very short while.

> colliding particles as independent because we have no reason to assume otherwise. (Uffink, 2007, p. 951)

However, the general applicability of the principle of insufficient reason (also known as the principle of indifference) is seriously questioned in probability theory by e.g. Keynes (1921) and Gillies (2000) as a consequence of the paradoxes it gives rise to. A more solid ground for the application of the preferred time-directed probabilities in physics is therefore given by a related principle, which has been denoted *non-enumerative statistical induction* by Strevens (1998). He writes:

> The Principle of Indifference is not even the right *kind* of rule to explain our successful inference. It purports to tell us which probabilities are rational given our ignorance, helping us to do the right thing under adverse epistemic circumstances. But our achievement is not mere rationality: it is truth. We infer the *correct* probability for the event in question. (Strevens, 1998, p. 231)

> We may consequently take ourselves to have empirical grounds for adopting a revised and differently deployed "Principle of Insufficient Reason" of the following form: *In the absence of any reason to think otherwise, assume that any standard variable is fairly smoothly distributed.* [...] Note that this principle of insufficient reason is defeasible. Sometimes we have sufficient reason to think that a particular standard variable θ is *not* smoothly distributed. (Strevens, 1998, p. 241)

The assumption "that any standard variable is fairly smoothly distributed" is according to (Strevens, 1998, p. 243) founded on "fallible, empirical knowledge of the physical constitution of the relevant mechanism and of the pertinent laws of natur" on the basis of the symmetrical properties of the physical system in question. Dice and roulett wheels, for example, have physical symmetries (when well balanced), which provide uniform probability distributions of the possible outcomes according to all available empirical knowledge. In the realm of physics the similarity between constituent particles gives empirically based reasons to accept the assumption that macroscopic quantities such as number, volume and density gives enough information to predict the macroscopic behaviour of the system, especially in statistical mechanics. According to the terminology of North (2006) this is cases of *symmetry-based inference.*

The assumed influence of *physical symmetry* on the resulting probabilities is, in its turn, implicitly based on the assumption that the resulting probabilities are time translation invariant. This must be the case, since the assumption that physical symmetry has impact on probabilities presupposes that the constituent probabilities are constant through time, i.e. that they are time translation invariant, which also makes the resulting probabilities of the macroscopic behavior of the system time translation invariant. Consequently, the *law of statistical time asymmetry* from Section 4 can be applied on the concept of physical symmetry:

> **The time asymmetry of the physical symmetry assumption**
> The assumption of physical symmetry means that each physically equal constituent of a system have the same probability connected with a certain outcome of the process of the system. If this assumption is applicable to a process in the form of either time translation invariant future-directed or time translation invariant past-directed probabilities, but not both, the assumption is always applicable in the form of future-directed probabilities.

The most prominent example, where the assumption of physical symmetry is applied, and where not both time translation invariant future-directed probabilities and time translation invariant past-directed probabilities correctly can describe the process, is in statistical mechanical processes that develops from disequilibrium to a state of equilibrium. This is implied by the proof of Sober (1993) that is described in Section 3. The physical consequences of this time asymmetric application of the assumption of physical symmetry is described in detail in Skoruppa (2022a) and is also exemplified in Section 4 in Skoruppa (2022h).

6 The statistical time asymmetry of post-interactive correlations

A time asymmetry, given only sparse attention in previous research, can be found in a kind of processes termed *postinteractive correlations*.[12] The term refers to what happens when a microscopic system interacts with some kind of macroscopic object in a way that results in causal influence on the microscopic system *after*, but not before, the interaction.

As an example, Price (1997) describes the polarization direction of a photon that interacts with a polarization filter, and, as another example, Penrose (1989) describes a photon that interacts with a half-silvered mirror (the latter illustrated in Figure 1, where L is a light source, M is

[12] Price (1997) describes this kind of correlations and writes (1997, p. S236): "Given T-symmetry, I contend, pre- and postinteractive correlations should be on the same footing in microphysics."

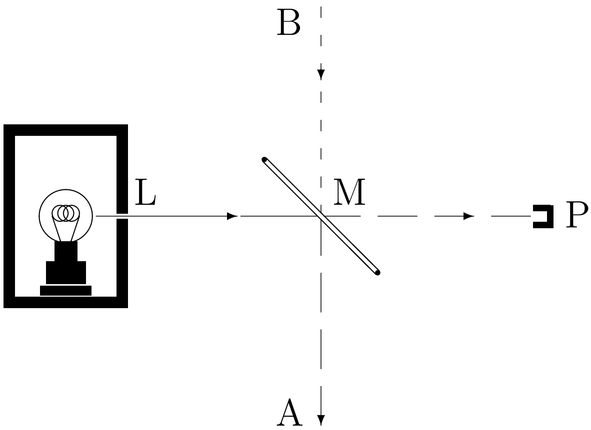

Figure 1: The half-silvered mirror.

the mirror, and P is a photon detector). In these cases, the state of the photon gives evidence of influence *after* the interaction with the filter and the mirror, respectively. In the first case, the polarization direction of the photon *after* the passage is determined by the angle of polarizer. In the second case, the photon has fifty percent probability of following either of two paths *after* it has met the mirror. Yet another examples is the influence of a double slit on the probable path of an electron, *after* it has passed the slit. A similar phenomenon, exclusively in the microscopic realm, is the correlations of gas molecule velocities, *after* the molecules have collided.[13]

All these examples can be correctly described by translation invariant future-directed probabilities, e.g. (with γ denoting a photon):

$$p(\gamma \text{ through } 45^\circ \text{ polarizer } [t+\Delta t] | \gamma \text{ through } 0^\circ \text{ polarizer } [t]) = \frac{1}{2}\,, \quad (2)$$

and (position notation in accordance with Figure 1)

$$p(P[t+\Delta t]|L[t]) = \frac{1}{2}\,. \quad (3)$$

In contrast, the corresponding past-directed probabilities are am-

[13]The example with the correlated molecules is usually connected with the well-known *Stosszahlansatz* in thermodynamics, and it is analysed in depth in Skoruppa (2022g).

biguous under the given conditions, i.e.[14]

$$p(\text{photon through } 45^\circ \text{ polarizer}[t]|\text{photon through } 0^\circ \text{ polarizer}[t+\Delta t]) \tag{4}$$

and

$$p(L[t]|P[t+\Delta t]) \tag{5}$$

are not translation invariant.

In other words, the angle of a passed polarization filter decides the probability that the photon passes the next polarization filter in its path, while this angle does not influence the probability of a previous passage of a polarization filter. Regarding the photon interaction with the half-silvered mirror, the probability of one or other of the subsequent paths is $\frac{1}{2}$, given a certain position of the photon *before* the interaction, while the probability of the two possible previous paths, given a certain position *after* the interaction, is not translation invariant (i.e. the proportion of photons sent from position B, given detection at P, is not decided by physical law).

Consequently, the following symmetries are *not* generally valid:

$$\begin{aligned} &p(\gamma \text{ through } 45^\circ \text{ polarizer}[t+\Delta t]|\gamma \text{ through } 0^\circ \text{ polarizer } [t]) \\ &= p(\gamma \text{ through } 45^\circ \text{ polarizer}[t]|\gamma \text{ through } 0^\circ \text{ polarizer } [t+\Delta t]) \; , \end{aligned} \tag{6}$$

and

$$p(P[t+\Delta t]|L[t]) = p(L[t]|P[t+\Delta t]) \; , \tag{7}$$

where the superscript '^{T}' is omitted for the sake of simplicity in (6).

Symmetry (6) is a case of *probabilistic time reversal invariance* according to Skoruppa (2022i), and equation (7) represents yet another type of symmetry that, however, has been shown to have limited physical significance in the same article.

In summary, the post-interactive correlations described above can be correctly described by future-directed probabilities that are time translation invariant, while past-directed probabilities that are time translation invariant cannot serve this aim. Consequently, these processes develops in accordance with the law of statistical time asymmetry, which is defined in the previous section.

7 What the law accomplishes

In Section 1, a new general description of the various time asymmetries in our universe was requested. Four criteria were formulated, which this

[14]Some physicists, e.g. Bedingham (2015), search for an *explanation* for this time asymmetry, either in an inherent time asymmetry of the Born rule or in the initial boundary conditions of the experiment. Here, the time asymmetry is just *described* in terms of time-directed probabilities. However, in Skoruppa (2022b) the role of the initial boundary condition of the universe is discussed in depth.

description should meet without being marred by the weaknesses found in the concept of entropy.

Now a test can be made to see whether the proposed *law of statistical time asymmetry* meets these criteria. The first and the second criterion is met since analyses of several processes in Skoruppa (2022a,f,g) show that the macroscopic time asymmetry can be derived on the basis of the microscopic time-directed probabilities that are stipulated by the *law of statistical time asymmetry*. Furthermore, in Skoruppa (2022c,h), the validity of these two criteria is demonstrated to be evident for various other kinds of physical processes, which implies that the law also satisfies the third criterion. Finally, the forth criterion is satisfied in Skoruppa (2022b), in which the proposed law will be applied to a simple model of the universe.

Consequently, there is preliminary evidence supporting that the *law of statistical time asymmetry* outperforms the predominant entropy concept with regard to all of these four criteria. However, in Skoruppa (2022e) a modified entropy concept will be presented, which better meets the requirements presented in this work. In addition, the *law of statistical time asymmetry* can constitute the basis of a derivation of *The Equilibrium Principle*, which can be considered one of many formulations of the second law of thermodynamics.[15]

8 Conclusions

On the basis of empirical findings, as well as the analyses of previous authors, a *law of statistical time asymmetry* is proposed in the present work. This law formalizes the dominance of time translation invariant future-directed probabilities in the description of stochastic physical processes. Among other things, this means that probabilistic laws describing any kind of physical stochastic processes in non-equlibrium must be based on future-directed probabilities.

When examined in accordance with the criteria presented in Section 1, there are indications that the *law of statistical time asymmetry* is a suitable candidate for describing various time asymmetric phenomena in our universe at both the microscopic and macroscopic levels. Consequently, according to the preliminary empirical evidence, this law outperforms the predominant entropy concept as a road to a better understanding of these phenomena and their relation to the evolution of the universe as a whole.

[15] The equilibrium principle is described in Brown & Uffink (2001) and a sketchy derivation of this principle is presented in Skoruppa (2022d). In addition, in Skoruppa (2022e), section 4, the second law of thermodynamics is derived from a formula for *statistical* entropy difference which, in turn, is derived on the basis of the *law of statistical time asymmetry*.

References

Arntzenius, F. (1995). Indeterminism and the direction of time. *Topoi*, 14, 67–81.

Arntzenius, F. (1997). Transition chances and causation. *Pacific Philosophical Quarterly*, 78, 149–168.

Arntzenius, F. (2005). Reichenbach's common cause principle. In E. N. Zalta (Ed.), *Stanford Encyclopedia of Philosophy.* The Metaphysics Research Lab, Stanford University. Available at `http://plato.stanford.edu/`.

Bedingham, D. (2015). Time symmetry in wave function collapse models. Available at `http://arxiv.org/abs/quant-ph/1502.07092v1`.

Brown, H. R. & Uffink, J. (2001). The origins of time-asymmetry in thermodynamics: The minus first law. *Studies in History and Philosophy of Modern Physics*, 32, 525–538.

Denbigh, K. G. (1989). Note on entropy, disorder and disorganization. *The British Journal for the Philosophy of Science*, 40, 323–332.

Earman, J. (1974). An attempt to add a little direction to "the problem of the direction of time". *Philosophy of Science*, 41, 15–47.

Earman, J. (2006). "The past hypothesis": Not even false. *Studies in History and Philosophy of Modern Physics*, 37, 399–430.

Ellis, G. F. R. & Buchert, T. (2005). The universe seen at different scales. *Physics Letters A*, 347, 38–46.

Gal-Or, B. (1972). The crisis about the origin of irreversibility and time anisotropy. *Science*, 176, 11–17.

Gibbs, W. (1902). *Elementary Principles in Statistical Mechanics.* New York: C. Scribner's Sons.

Gillies, D. (2000). *Philosophical Theories of Probability.* London: Routledge.

Hájek, A. (2003). What conditional probability could not be. *Synthese*, 137, 273–323.

Holster, A. (1990). Time flow and reversibility in a probabilistic universe. PhD thesis. Available at
`https://philpapers.org/rec/HOLFA-3`.

Keynes, J. M. (1921). *A treatise on probability.* Macmillan.

Maxwell, J. C. (1867). On the dynamical theory of gases. *Philosophical Transactions of the Royal Society of London*, 157, 49–88.

North, J. (2006). Symmetry and probability. Available at Internet: phil-sci/2978.

Penrose, O. & Percival, I. C. (1962). The direction of time. *Proceedings of the Physical Society*, 79, 605–616.

Penrose, R. (1989). *The Emperor's New Mind.* Oxford: Oxford University Press.

Price, H. (1997). Time symmetry in microphysics. *Philosophy of Science*, 64, S235–S244.

Prigogine, I. & Stengers, I. (1984). *Order out of chaos.* London: Heinemann.

Reichenbach, H. (1956). *The Direction of Time.* Berkley: University of California Press.

Skoruppa, B. (2022a). Derivation of rate equations from time-directed probabilities of individual particles. Appendix IV.

Skoruppa, B. (2022b). The influence of boundary conditions on a probabilistic evolution governed by time symmetrical laws. Appendix VII.

Skoruppa, B. (2022c). Probabilistic time asymmetry in quantum mechanical processes. Appendix VI.

Skoruppa, B. (2022d). A sketchy derivation of the Equilibrium Principle from a modified 'Past Hypothesis'. Appendix X.

Skoruppa, B. (2022e). Statistical entropy difference. Appendix VIII.

Skoruppa, B. (2022f). Statistical entropy difference in chemical processes. Appendix IX.

Skoruppa, B. (2022g). Stosszahlansatz revisited: How law-like time asymmetry in statistical mechanics manifests itself in systems consisting of one or two particles. Appendix XII.

Skoruppa, B. (2022h). Time asymmetry in macroscopic stochastic processes. Appendix V.

Skoruppa, B. (2022i). Time reversal invariance and asymmetry in probability based laws. Appendix I.

Sober, E. (1993). Temporally oriented laws. *Synthese*, 94, 171–189.

Strevens, M. (1998). Inferring probabilities from symmetries. *Nos*, 32, 231–246.

Uffink, J. (2001). Bluff your way in the second law of thermodynamics. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 32, 305–394.

Uffink, J. (2007). Compendium of the foundations of classical statistical physics. In I. J. Butterfield & J. Earman (Eds.), *Philosophy of Physics* (pp. 923–1074). Amsterdam: Elsevier.

Watanabe, S. (1965). Conditional probability in physics. *Supplement of the Progress of Theoretical Physics*, 33–34, 135–160.