

**THE SIGNIFICANCE OF CAUSALLY COUPLED,  
STABLE NEURONAL ASSEMBLIES  
FOR THE PSYCHOLOGICAL TIME ARROW**

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**Abstract:** Stable neuronal assemblies are generally regarded as neural correlates of mental representations. Their temporal sequence corresponds to the experience of a direction of time, sometimes called the psychological time arrow. We show that the stability of particular, biophysically motivated models of neuronal assemblies, called coupled map lattices, is supported by causal interactions among neurons and obstructed by non-causal or anti-causal interactions among neurons. This surprising relation between causality and stability suggests that those neuronal assemblies that are stable due to causal neuronal interactions, and thus correlated with mental representations, generate a psychological time arrow. Yet this impact of causal interactions among neurons on the directed sequence of mental representations does not rule out the possibility of mentally less efficacious non-causal or anti-causal interactions among neurons.

**Keywords:** Causation – Coupled Map Lattices – Neuronal Assemblies – Psychological Time Arrow – Stability

## 1 Introduction

It was one of the great insights of Isaac Newton to disentangle the dynamical laws of nature from their initial and boundary conditions. The dynamical laws in all fundamental physical theories are time-reversal invariant. This is to say that any of their solutions describing the temporal evolution of a

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physical system in one direction of time has a time-reversed copy which is equally possible. This feature is distinctly at variance with the empirical experience of a distinguished, forward direction of processes in time from past to future, observed in thermodynamics, electrodynamics, quantum mechanics and cosmology. The standard attempt to resolve this apparent contradiction is to ascribe the directedness of time to particular initial or boundary conditions (cf. [1]).

Another option to enter and entertain this debate uses the relation between causation and the direction of time. Based on arguments presented earlier by Reichenbach [2], such an approach has been developed in detail by Price [3]. He emphasizes that an intuitive, subjective causal asymmetry, associated with a psychological arrow of time, needs to be properly distinguished from objective causation and a corresponding arrow of time of the physical world. Price argues that, in an important way, “the asymmetry of causation is a projection of our own temporal asymmetry as agents in the world” ([3], p. 264). Pruning off this anthropocentric element revitalizes the idea to take bidirectional (forward and backward) causation in the physical world seriously.

Broadly speaking, the notion of a psychological arrow of time stands for the experience that the flow of consciousness is directed from the past to the future, such that past events can causally influence future events (in the sense of efficient causation), but not *vice versa*. This means that the temporal sequence of thoughts, emotions, volitions and other conscious experiences has a distinguished direction in which past experiences precede future experiences.

There is a huge amount of literature on time and consciousness which cannot be comprehensively reviewed here. A fairly recent and compact overview concerning philosophical views and psychological evidence is due to Treisman [4]. An earlier account by Dennett and Kinsbourne [5], focusing on the neurobiological basis of time in the brain, is also readable, especially since it is published together with a number of controversial commentaries. Physical, neurobiological and psychological notions of time have been addressed by Ruhnau [6].

In this paper we present arguments and results intended to explicate a particular variant of Price’s proposal. Our approach is based on a broadly assumed intrinsic relationship between material brain states and mental subjective states, often expressed by the term “neural correlates of consciousness”. Although correlations between brain states and mental states should in general not be considered one-to-one, they may nevertheless be

used to analyze the relationship between the properties of brain states and mental states to some degree (cf. [7]). In particular, we will be interested in this relationship as far as causal and temporal asymmetries in the dynamics of brain states and of mental states are concerned.

For this purpose, section 2 introduces a class of formal models for neuronal assemblies that are usually assumed to be correlated with mental representations. The model is essentially a lattice of coupled maps, whose parameters can be set such that they mimick the neurobiological situation as good as possible. Section 3 discusses numerical and analytical results for these lattices under different kinds of causation (forward, simultaneous, backward) for interactions among individual sites (neurons) in the lattice (assembly). Section 4 extends the discussion to genuinely time-reversal invariant equations for coupled map lattices. Finally, the basic results and some consequences will be summarized in section 5.

## 2 Coupled Map Lattices as Models for Neuronal Assemblies

In much current literature, conscious experiences are expressed as contents of mental representations. In this framework, the psychological arrow of time corresponds to the temporal sequence of mental representations. From a neurobiological point of view, mental representations are usually addressed in terms of their neural correlates. It is generally agreed that these correlates are to be found at a mesoscopic level of description referring to assemblies of several thousand functionally cooperating neurons.<sup>c</sup> In order to be a neural correlate of a mental representation, it is essential that the behavior of a neuronal assembly is stable.

A convenient way to investigate the stability of neuronal assemblies uses plausible models of such assemblies. A specific class of such models, particularly proposed for brain studies by Kaneko and collaborators [10], is called coupled map lattices (CMLs). In the remainder of this section we will briefly introduce their main features and, in the following section, summarize recent results [11] of a surprising relation between their stability and the extent to which their internal interactions are causal in the sense that past events effectuate future events. Insofar as (1) this neurobiological causality is necessary for stable neuronal assemblies, and (2) the stability of neuronal assemblies is necessary for them to be correlates of mental

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<sup>c</sup>Although these assemblies, or networks, are constituted by neurons, they have properties which are not derivable from the microscopic level of individual neurons alone. As indicated recently [8, 9], the scheme of contextual emergence is a good candidate to describe such micro-meso relations already within the neurobiological domain.

representation, it will be argued that a psychological arrow of time emerges from the neurobiological level of description.

A compact characterization of a CML with one time parameter is given by

$$u(n+1, x) = (1 - \epsilon)f(u(n, x)) + \frac{\epsilon}{n_x} \sum_{y \sim x} g(u(n, y)) , \quad (1)$$

where  $x$  represents the sites of the lattice,  $x = 1, \dots, N_{tot}$ , and  $n$  represents the time step of the iteration. The parameter  $\epsilon$  specifies the coupling between each cell and its neighborhood. It is here considered as constant over time and space, disregarding neural plasticity. The sum over  $y \sim x$  is the sum over all  $n_x$  neighbors  $y$  of vertex  $x$ . The function  $g$  characterizes the interaction of a vertex with its neighborhood and will be explained below.

As in many other studies of CMLs,  $f(x)$  is the logistic map on the unit interval,

$$f(x) = rx(1 - x) ,$$

with  $0 \leq r \leq 4$ . For  $r \geq 1$  the logistic map has a critical point at  $\frac{r-1}{r}$  which is unstable for  $3 < r \leq 4$ . The relevance of maps with quadratic maximum (such as the logistic map) for models of neurobiological networks was recently substantiated by novel results concerning a non-monotonic (rather than sigmoid) transfer function for individual neurons [12].

For  $\epsilon \rightarrow 0$ , there is no coupling at all; hence, local neighborhoods have no influence on the behavior of the CML. This situation represents the limiting case of  $N_{tot}$  independently operating local objects at each lattice site. In the general case  $0 < \epsilon < 1$ , the independence of individual cells is lost and the lattice behavior is governed by both local and global influences, depending on the chosen neighborhood. CMLs with a maximal neighborhood,  $n_x \approx N_{tot}$ , are often denoted as globally coupled maps. Their behavior is determined by global properties alone (mean field approach).

The function

$$g(x) = \alpha x + \beta f(x) + \gamma f(f(x)) , \quad (2)$$

with

$$\alpha + \beta + \gamma = 1 \quad \alpha, \beta, \gamma \geq 0 ,$$

allows us to treat the interaction between each vertex and its neighborhood in different ways, depending on its time scale  $\Delta t$ . If the interaction can be regarded as instantaneous,  $\Delta t \approx 0$ , the situation can be approximated by  $\alpha = \gamma = 0$  and  $\beta = 1$ . Such a type of coupling, sometimes called “future coupling” [13], will be referred to as *non-causal coupling* [11] in

the following, since the simultaneity of the interaction between vertex and neighbors makes the distinction of cause and effect impossible.

The situation of a finite interaction time  $\Delta t > 0$  can be properly modeled by  $\beta = \gamma = 0$  and  $\alpha = 1$ . In this way, past states in the neighborhood of a vertex are considered to act on the present state of the vertex with limited signal speed, so that the effect of an interaction is delayed with respect to its cause. Such a type of coupling will therefore be denoted as *causal coupling* in the following [11].

A third, somewhat exotic possibility arises for  $\alpha = \beta = 0$  and  $\gamma = 1$ . This case reflects the idea to model the action of future states of a vertex neighborhood on a present vertex state. More precisely, this refers to *locally extrapolated* future states and is justified for small  $\epsilon$  since then  $u(n+1, y) \approx f(u(n, y))$ . In this interpretation, the case of non-vanishing  $\gamma$  is in contradiction with causality; thus we refer to such a situation as *anti-causal coupling*. Its investigation can be of particular interest from a fundamental point of view, where forward and backward directions of time result from a decomposition of a time-reversal symmetric, or briefly reversible, evolution into these two components.

Another important feature for the interpretation of Eq. (1) is the time interval  $\Delta\tau$  assumed for the updating mechanism, i.e. for the physical integration of signals from the neighborhood states with the state considered. If signals between cells are transmitted much slower than the time scale assumed for the updating mechanism,  $\Delta\tau \ll \Delta t$ , the updating can be implemented (almost) instantaneously, or synchronously. If this is not the case,  $\Delta\tau \gtrsim \Delta t$ , updating must be implemented in an asynchronous way. (In this case, an equation different from Eq. (1) has to be solved; see [14].) This entails the additional problem of determining a proper updating sequence, which can be random or depend on particular features of the situation considered.

Most of the work on CMLs (cf. [10]) was based on synchronous updating. However, asynchronous updating rules have been suggested as particularly relevant for neurobiological networks. For asynchronous updating, as first studied by Lumer and Nicolis [15], it was found that the behavior of CMLs differs strongly from that of CMLs with synchronous updating. As a common feature of asynchronous updating, it has been reported that it facilitates the synchronization and stabilization of CMLs decisively. In particular, Mehta and Sinha [13] demonstrated that the dynamics at individual lattice cells is strongly synchronized by coupling among cells. Atmanspacher and Scheingraber [11, 16] showed that unstable fixed points at

individual vertices can be inherently stabilized as a consequence of their coupling to neighboring unstable fixed points.

### 3 Causal, Non-Causal, and Anti-Causal Interactions

Following up on earlier investigations of CMLs using the logistic map at  $r = 4$  with synchronous and asynchronous updating for small neighborhoods, Atmanspacher and Scheingraber [11] presented numerical results for the stabilization of CMLs for different degrees of causal versus non-causal coupling. As mentioned above, the limiting cases are instantaneous interactions on the one hand ( $\alpha = 0$ ; non-causal coupling) and finite-time interactions on the other ( $\alpha = 1$ ; causal coupling). It was found both numerically [11] and analytically [14]<sup>d</sup> that the degree  $\alpha = 1 - \beta$  of causal versus non-causal coupling in a CML and its stabilization behavior are related in surprising ways.

- For *asynchronous updating*, the critical coupling strength  $\epsilon_{crit} = 0.5$  for stabilization onset is in general robust against variations of both the degree of causal coupling and the type and size of neighborhood. The von Neumann neighborhood of order 1 shows an additional destabilization in the regime of small causal coupling, which is not observed for all other neighborhoods.
- For *synchronous updating*, there is no stabilization at all for small causal coupling  $\alpha < 1/3$ . In the regime  $1/3 < \alpha < 1$ , the influence of causal coupling induces stabilization at different critical coupling strengths. For global coupling with a causal degree  $\alpha > 2/3$ , the stabilization onset coincides with that of asynchronous updating.

These observations are summarized in Fig. 1, where symbols show numerical results and lines show analytical results. It is interesting to discuss the relation between stability and causality in terms of an interlevel scheme recently introduced under the notion of contextual emergence [8, 9] with particular emphasis on neurobiological and mental, or psychological, levels of description. The existence of assemblies at the neurobiological level of description is necessary but not sufficient to describe mental representations at the psychological level exhaustively. In addition, it is crucial that the neural correlates of mental representations be stable. This condition

<sup>d</sup>The analytical approach in [14] (similarly in [17, 18]) considers CMLs as graphs and analyzes their stability properties in terms of the spectrum of eigenvalues of their normalized adjacency matrix. See Sec. 4 for an explicit implementation of the approach for time-reversal invariant CMLs.

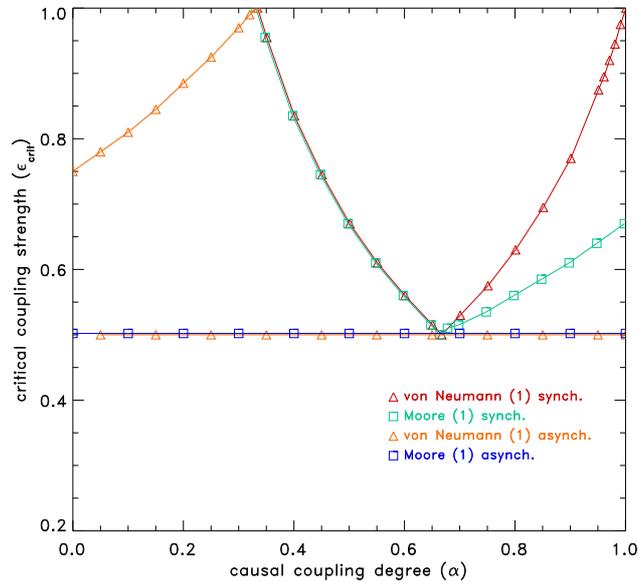


Figure 1: Critical coupling strength  $\epsilon_{crit}$  for stabilization onset as a function of the degree  $\alpha = 1 - \beta$  of causal coupling. Different symbols refer to different updating procedures and different neighborhoods as explained in the figure.

does not derive from the neurobiological level alone. It can only be reasonably motivated by features of mental representations at the psychological level. In this sense, stability conditions for neuronal assemblies represent a contingent context in addition to the neurobiological description. Only together with such an extra context is the neurobiological level of description sufficient to treat mental representations comprehensively.

The contingent context of *stable* neuronal activity is satisfied best if the coupling between interacting neurons is causal. Thus, forward causation at the neurobiological level of description is of crucial significance for mental representations as the key concepts at the psychological level. Insofar as this applies to their temporal sequence as well we can speak of an emergent arrow of time at this level. It should be emphasized that the contextual emergence of a psychological arrow of time consistent with forward causation does not imply that backward causation must be ruled out at the neurobiological level. Indeed, it is only possible to demonstrate forward causation as a selection criterion for stability if there are alternatives.

Since CMLs can be considered as discretized partial differential equations, our approach is a potential candidate for studying superpositions of advanced and retarded solutions of time-reversal invariant signal transmission in general. In addition to the non-causal alternative to causal coupling it was recently shown [14] that anti-causal interactions ( $\gamma \neq 0$ ) within neuronal assemblies obstruct their stability even more than non-causal interactions. However, as mentioned above, anti-causal interactions in that context have so far been implemented only in terms of local extrapolations in CMLs. An appropriate way to study time-reversal invariant equations in a truly symmetric way will be discussed in the following section.

#### 4 Time-Reversal Invariant Equations

So far the notions of “causal”, “non-causal”, and “anti-causal” interactions referred to specific implementations of interactions in Eq. (1), but not to its mathematical structure itself. The iterative Eq. (1) is always “causal” in the sense that it allows to determine the configuration  $\{u(n+1, x)\}$  at time-step  $n+1$ , given the configuration  $\{u(n, x)\}$  at time-step  $n$ . In this section, we study an equation which can be considered as a generalization of Eq. (1). Although it does not describe an actual “influence of the future”, it allows us to investigate the role of time-reversal invariance in more detail.

The most straightforward way to extend Eq. (1) to a time-reversal invariant equation is to add a “future term” in the following way:

$$u(n, x) = \tau \left( (1 - \epsilon)f(u(n-1, x)) + \frac{\epsilon}{n_x} \sum_{y \sim x} g(u(n-1, y)) \right) + (1 - \tau) \left( (1 - \epsilon)f(u(n+1, x)) + \frac{\epsilon}{n_x} \sum_{y \sim x} g(u(n+1, y)) \right). \quad (3)$$

For  $\tau = 1$  one recovers Eq. (1), and for  $\tau = \frac{1}{2}$  the equation is invariant under time reversal, i.e., for any solution  $\{u(n, x)\}$   $\{u(-n, x)\}$  is a solution as well. Although we may use Eq. (3) to *check* whether or not a given series  $\{u(n, x)\}$  of configurations is indeed a solution, we cannot use this equation to *construct* such a solution unless we are able to solve Eq. (3) for  $u(n+1, x)$ . In this sense Eq. (3) does not represent an “algorithm” but only a necessary and sufficient constraint.

Another way to construct a time-reversal invariant form of Eq. (1) is given by:

$$\tau u(n+1, x) + (1 - \tau)u(n-1, x) = (1 - \epsilon)f(u(n, x)) + \frac{\epsilon}{n_x} \sum_{y \sim x} g(u(n, y)). \quad (4)$$

Again, we recover Eq. (1) for  $\tau = 1$ , and the equation is time-reversal invariant for  $\tau = \frac{1}{2}$ . This time, however, it is easy to solve Eq. (4) for  $u(n+1, x)$  and, thus, use it as an algorithm to generate solutions.

Both Eqs. (3) and (4) contain convex combinations of terms that are confined to the unit interval  $(0, 1)$ . Therefore the combinations, representing weighted averages, are confined to the same interval. However, solving the equations for  $u(n+1, x)$ , the restriction of  $u(n+1, x)$  to  $(0, 1)$  is lost even if it still holds for  $u(n-1, x)$  and  $u(n, x)$  individually.<sup>e</sup> It would be a highly non-trivial task to choose initial configurations for  $u(0, x)$  and  $u(1, x)$  such that their iterations remain bounded in the unit interval.

Therefore, we relax the constraint on the domain of  $\{u(n, x)\}$  and use functions  $f$  and  $g$ , for which this constraint is not necessary. We can, for instance, interpret the logistic map “modulo 1”, or we can replace it by some analytic function such as  $f(x) = \sin^2 \pi x$ , which is known to be in the same “universality class” as the logistic map (the class of functions with quadratic maximum).

For technical reasons, we use a slightly modified version of Eq. (4) in the following discussion:

$$u(n+1, x) = (1-\epsilon)f(u(n, x)) + \frac{\epsilon}{n_x} \sum_{y \sim x} g(u(n, y)) + A(u(n, x) - u(n-1, x)). \quad (5)$$

The original Eq. (1) for CMLs is recovered for  $A = 0$ , while a time-reversal invariant equation is obtained for  $A = 1$ . It turns out that the conditions for stable constant solutions of this equation can be worked out analogous to the special case  $A = 0$ . This connection becomes more obvious if we first investigate the one-dimensional problem, i.e. the case of a simple iterative equation for a field defined on a single point.

#### 4.1 The One-Dimensional Problem

We consider the following second-order iterative equation:

$$u_{n+1} = f(u_n) + A(u_n - u_{n-1}). \quad (6)$$

This equation has the following properties:

- For  $A = 0$  it reduces to the simple first-order iterative equation:

$$u_{n+1} = f(u_n). \quad (7)$$

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<sup>e</sup>The average value  $\bar{a}$  of two numbers  $a_1$  and  $a_2$ , each confined to the unit interval, is always in the unit interval. If, however,  $a_1$  and  $\bar{a}$  are given in the unit interval, then  $a_2$  may be larger than 1.

- For  $A = 1$ , Eq. (6) is invariant under time reversal:

$$u_{n+1} + u_{n-1} = f(u_n) + u_n .$$

Rewriting this as

$$u_{n+1} - 2u_n + u_{n-1} = f(u_n) - u_n ,$$

one can easily recognize the second difference quotient on the left hand side.

- The constant solutions  $\bar{u}$  of Eq. (6) are independent of  $A$  and, therefore, the same as for the first-order iterative equation (7).

We can now express the “second-order” version of Eq. (6) as a coupled system of “first-order” equations in the variables  $u_n$  and  $p_n$ :

$$\begin{aligned} u_{n+1} &= f(u_n) + A(u_n - p_n) \\ p_{n+1} &= u_n . \end{aligned}$$

Small variations of  $u$  and  $p$  around the constant solution  $u_n = \bar{u}$  and  $p_n = \bar{u}$  yield in linear approximation:

$$\begin{aligned} \delta u_{n+1} &= f'(\bar{u})\delta u_n + A(\delta u_n - \delta p_n) \\ \delta p_{n+1} &= \delta u_n , \end{aligned}$$

or:

$$\begin{pmatrix} \delta u_{n+1} \\ \delta p_{n+1} \end{pmatrix} = \begin{pmatrix} f'(\bar{u}) + A & -A \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \delta u_n \\ \delta p_n \end{pmatrix} . \quad (8)$$

For simplicity we define

$$f' := f'(\bar{u})$$

and obtain for the eigenvalues of the matrix in Eq. (8):

$$\lambda_{1/2} = \frac{f' + A}{2} \pm \frac{1}{2} \sqrt{(f' + A)^2 - 4A} .$$

The constant solution is stable if the absolute values of both of these eigenvalues are smaller than one. This leads to the following stability conditions:

- For  $f' > 1$  or  $f' < -3$  the system is unstable for all  $0 \leq A \leq 1$ .
- For  $0 \leq A < 1$  the constant solution is stable, if

$$-2A - 1 < f' < 1 .$$

- For  $A = 1$  (the case of time-reversal invariance) the system is at the margin of stability (provided that  $-3 < f' < 1$ ), i.e., the absolute values of the eigenvalues of the matrix in Eq. (8) are 1.

**4.2 The CML Problem**

We now consider the case of an iterative mapping on a graph with  $N$  vertices. The general equation reads

$$u_{n+1}(x) = F(x; \{u_n(z)\}_{z=1, \dots, N}) + A(u_n(x) - u_{n-1}(x)) \quad (9)$$

for all  $x = 1, \dots, N$ ,

where  $F$  depends on the adjacency matrix of the graph and is some functional of the fields.

For  $A = 0$  we obtain an iterative equation of “first order”, and for  $A = 1$  the equation is time-reversal invariant. We assume the existence of constant solutions (constant with respect to the vertices and with respect to time):

$$u_n(x) \equiv \bar{u} .$$

These solutions are independent of  $A$ .

As we in the one-dimensional case we rewrite Eq. (9) as a coupled system of first-order equations:

$$\begin{aligned} u_{n+1}(x) &= F(x; \{u_n(z)\}_{z=1, \dots, N}) + A(u_n(x) - p_n(x)) \\ p_{n+1}(x) &= u_n(x) . \end{aligned}$$

Let

$$\Phi(x, y) = \left. \frac{\partial F(x; \{u(z)\}_{z=1, \dots, N})}{\partial u(y)} \right|_{\{u(z)\} \equiv \bar{u}}$$

be the first derivative of  $F(x; \{u(z)\})$  with respect to  $u(y)$ , evaluated at the constant solution  $\bar{u}$ , and let  $\Lambda_k$  be the eigenvalues of the matrix  $F$ . The stability analysis leads to the same conditions as for the one-dimensional case, where now  $f'$  has to be replaced by  $\{\Lambda_k\}$ . In particular, for  $0 < A < 1$  the constant solution is stable only if

$$-2A - 1 < \Lambda_k < 1 \quad \text{for all } k ,$$

and for  $A = 1$  the system is at the margin of stability, as in the one-dimensional case. (If some of the eigenvalues  $\Lambda_k$  are outside the interval  $(-3,1)$ , the constant solution is unstable.)

For Eq. (5) we have:

$$\Lambda_k = (1 - \epsilon)f'(\bar{u}) + \epsilon\lambda_k g'(\bar{u}) ,$$

where  $\lambda_k$  are the eigenvalues of the adjacency matrix multiplied by the inverse of the valence matrix of the graph.

## 5 Conclusions

This contribution addresses the question of how a psychological arrow of time, i.e. a directed temporal sequence of mental representations, is related to the behavior of neuronal assemblies. At the neuronal level we approach this question in terms of coupled map lattices (CMLs) as models of neuronal assemblies with neurobiologically motivated parameters. The stability properties of CMLs are influenced by different types of interactions (forward causal, simultaneous, and backward causal) among individual maps.

A straightforward way to analyze the stability of constant solutions of CMLs against perturbations is presented in section 3. It allows us to implement forward causal and non-causal (simultaneous) interactions rigorously, but anti-causal (backward causal) interactions are treated only in terms of local extrapolations. This introduces a temporal asymmetry, which prohibits an interpretation of forward and backward causal components as a symmetric decomposition of a time-reversal invariant evolution. Nevertheless, there are indications that anti-causal interactions obstruct the stability of CMLs in a way similar to non-causal interactions. The comparison of forward causal and non-causal interactions shows convincingly that forward causation supports the stability of CMLs.

An analytical investigation of a rigorously time-reversal invariant evolution has been carried out in section 4. In this framework, time-asymmetric equations can be demonstrated to support the stability of constant solutions of CMLs against perturbations as compared to a strictly time-symmetric version. This result represents an intriguing application of a quotation by the 2004 physics Nobel laureate Frank Wilczek:<sup>f</sup> “The fundamental equations have the symmetry, but the stable solutions of these equations do not” [19].

Applying the obtained relation between causation and stability to the discussion of mind-brain issues yields an interesting argument with respect to the psychological arrow of time. This argument can be systematically expressed in five steps.

1. The psychological time arrow is related to the temporal sequence of mental representations.

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<sup>f</sup>The reader may recognize that we are slightly misusing Wilczek’s statement, which actually refers to symmetries and symmetry breakings in elementary particle physics. Although the mathematical details there are different from our scenario, the basic idea is the same.

2. Mental representations are correlated with the activity of stable neuronal assemblies.
3. The stability of neuronal assemblies is supported by causal neuronal interactions.
4. Causal neuronal interactions distinguish a forward direction of time.
5. As a consequence, the direction of the psychological time arrow coincides with the forward direction of time of causal neuronal interactions.

The converse of the argument, that the psychological time arrow implies forward causation at the neuronal level, would be wrong insofar as (2) does not exclude the possibility of non-causal or anti-causal neuronal interactions. Statement (2) simply says that causal interactions support the existence of mental representations. It does not say that non-causal or anti-causal interactions are impossible in principle. This result is in striking correspondence with Price's proposal [3] to take bidirectional causation seriously once the psychological time arrow is cleanly separated from the discussion.<sup>9</sup>

It is essential for the presented argument that properties at the mental level of description *emerge* from properties at the neuronal level of description and cannot be strictly reduced to that level. The key issue for the scheme of contextual emergence applied here [8, 9] is that a particular kind of stability condition is required, though not already given, as a contingent context at the neuronal level. Only if such a context were included in the "first principles" of the neuronal level, a strict version of reduction would be more plausible than emergence.

If neuronal assemblies are not stable enough, which is the case for non-causal (or anti-causal) neuronal interactions, then there are no mental representations whose temporal sequence could provide a psychological time arrow. We do not yet have a final answer to the interesting question of a psychological correlate of unstable (or marginally stable) neuronal behavior. Some speculative ideas may be found in the option of so-called *acategorical* mental representations [21] situated *between* the usual mental representations that are associated with stable behavior.

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<sup>9</sup>Price himself seems to be mainly interested in causal and temporal bidirectionality in quantum theory rather than invoking mind-brain relations directly. It is a current topic of controversial discussion whether or not quantum approaches may be relevant for brain dynamics [20].

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