2. The Time Arrow of Radiation

After a stone has been dropped into a pond, one observes concentrically diverging (‘defocussing’) waves. Similarly, after an electric current has been switched on, one finds a retarded electromagnetic field that is moving away from its source. Since the fundamental laws of nature, which describe these phenomena, are invariant under time-reversal, they are equally compatible with the reverse phenomena, in which concentrically focussing waves (and whatever was caused by the stone – such as heat) would ‘conspire’ in order to eject the stone out of the water. Deviations from the time reversal symmetry of the laws would modify this argument only in detail, as one merely had to alter the reverse phenomena correspondingly (cf. the Introduction). Such reverse phenomena have, however, never been observed in nature. The absence of focusing processes in high-dimensional configuration space may similarly describe the time arrow of thermodynamics (Chap. 3) or, when applied to wave functions, even that of quantum theory (see Sect. 4.6).

Electromagnetic radiation will here be considered as an example for wave phenomena in general. It may be described in terms of the four-potential \( A^\mu \), which in the Lorentz gauge obeys the wave equation

\[
-\partial^\nu \partial_\nu A^\mu (r, t) = 4\pi j^\mu (r, t) \quad \text{with} \quad \partial^\nu \partial_\nu = -\partial^2_t + \Delta ,
\]

with \( c = 1 \). Here, the notations \( \partial_\mu := \partial / \partial x^\mu \) and \( \partial^\mu := g^\mu_\nu \partial_\nu \) are used together with Einstein’s convention of summing over identical upper and lower indices. When an appropriate boundary condition is imposed, one may write \( A^\mu \) as a functional of the sources \( j^\mu \). For two well known boundary conditions one obtains the retarded and the advanced potential,

\[
\begin{align*}
A^\mu_{\text{ret}} (r, t) &= \int \frac{j^\mu (r, t - |r - r'|) d^3 r'}{|r - r'|} , \\
A^\mu_{\text{adv}} (r, t) &= \int \frac{j^\mu (r, t + |r - r'|) d^3 r'}{|r - r'|} .
\end{align*}
\]

These two functionals of \( j^\mu (r, t) \) are related to one another by a time reversal transformation (see (2.5) below). Their linear combinations are also solutions of the wave equation (2.1).

At this point, many textbooks argue somewhat mysteriously that ‘for reasons of causality’, or ‘for physical reasons’, only the retarded fields, derived
from the potential (2.2a) according to $F_{\text{ret}}^{\mu
u} := \partial^\mu A^{\nu}_{\text{ret}} - \partial^\nu A^{\mu}_{\text{ret}}$, may occur. This is evidently an independent condition, based on causal experience. It is added to the deterministic laws such as (2.1), which emerged historically from the traditional concept of causality. This example allows us to formulate in a preliminary way what seems to be meant by this intuitive notion of causality: correlated effects (that is, non-local regularities such as coherent waves) must always possess a local common cause (in their past). However, this asymmetric notion of causality is a major explanandum of the physics concerned with the direction of time. As pointed out in the Introduction, it cannot be derived from known dynamical laws.

The popular argument that advanced fields are not found in nature because of their improbable initial correlations is known from statistical mechanics, but absolutely insufficient (see Chap. 3). The observed retarded phenomena are precisely as improbable among all possible ones, since they contain equally improbable final correlations. Their 'causal' explanation from an initial condition would just beg the question.

Some authors have claimed that retarded waves represent emission, while advanced ones have to be used to describe absorption. However, this interpretation ignores the vital fact that absorbers give rise to retarded shadows (that is, to retarded waves that interfere destructively with incoming ones). In spite of the retardation, energy may thus flow from the electromagnetic field into an antenna. When incoming fields are present (as is the generic case), retardation does not necessarily mean emission of energy (see Sect. 2.1).

At the beginning of the last century, Ritz proposed a radical solution of the problem by postulating the exclusive existence of retarded waves as a law. Such time-directed action at a distance is equivalent to fixing the boundary conditions for the electromagnetic field in a universal manner. The field would then not possess any degrees of freedom.

This proposal, probably supported by many physicists at that time, led to a famous controversy with Einstein, who favored the point of view that retardation of radiation can be explained by thermodynamical arguments. Einstein, too, argued by means of an action-at-a-distance theory (see Sect. 2.4), which had played an important role historically because of its analogy with

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1 In the case of a finite number of effects (correlated future 'events') resulting from one local cause, this situation is often described as a 'fork' in spacetime (cf. Horwich 1987, Sect. 4.8). This fork of causality should not be confused with the fork of indeterminism (in configuration space and time), which points to different (in general global) potential states rather than to different events (see Footnote 7 of Chap. 3 and Fig. 3.8). The fork of causality ('intuitive causality') also characterizes measurements and the documentation of their results, that is, the formation and distribution of information. It is related to Reichenbach's (1956) concept of branch systems, and to Price's (1996) principle of independence of incoming influences (PI3). Insofar as it describes the cloning and spreading of information, it represents an overdetermination of the past by the future (Lewis 1986), observed as a consistency of documents about the macroscopic past. These correlations let the past appear 'fixed' (unaffected by local events), while complete documents about microscopic history would be in conflict with thermodynamics and quantum theory.