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Formulation and Justification of the Wheeler–Feynman Absorber Theory

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The "absorber theory" of Wheeler and Feynman is supposed to justify the use of retarded potentials in ordinary electromagnetic calculations despite a fundamentally time symmetric interaction. We restate the thesis of absorber theory as follows: here exist causal solutions of time symmetric electrodynamics. In our formulation, absorption need only take place in one direction of time (the future) rather than both, as seems to be required by Wheeler and Feynman. Even with complete absorption, however, the effects of advanced interactions are not entirely eliminated and a residual field may introduce a degree of indeterminacy into particle trajectories obtained using retarded potentials alone.

1. INTRODUCTION

Although time symmetric electrodynamics (TSE) appears to have a number of aesthetic virtues, it seems so at odds with ordinary experience that even the efforts of Wheeler and Feynman some 30 years ago seem to have made little impression. Wheeler and Feynman[1,2] noted that ordinary (retarded) and time symmetric electrodynamics differ only by a homogeneous solution of the Maxwell equations, and claimed that this homogeneous solution was in fact zero because of the absorption of the universe. Admitting this claim leads to connections between thermodynamics, electrodynamics, and cosmology.[3–5]

This paper is concerned with two problems that arise in Wheeler and Feynman's fourth proof of the absorber theory[1] (the fourth proof is the simplest and the most often quoted). The first problem is that Wheeler and Feynman require absorption of advanced waves and this is without

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experimental or theoretical justification. The second problem is that their proof involves a region "outside the system" and in any reasonable cosmology there is no such region.

We solve the first problem by making a careful statement of what it is we are proving. Having done this, the proof itself is trivial and the fourth proof of Wheeler and Feynman goes through with no assumptions about absorption of advanced radiation. We have no clear way out of the second problem and even with complete absorption distant matter may affect local electromagnetic phenomena. Calculation of the size of such effects is not undertaken in this paper.

In Section 2 we establish notation and criticize in more detail the "fourth proof." In Section 3 the thesis of the absorber theory is cast in the following forms: (1) a solution of retarded electrodynamics without external fields is also a solution of TSE; (2) there are causal solutions of TSE. The proofs of these statements are shown to depend on the absorption capabilities of the universe in the forward light cone. We also find that for reasonable cosmological models the effects of the advanced field are not entirely eliminated. Although this residual field introduces an element of indeterminacy into calculations using retarded potentials, when complete absorption obtains there is no violation of causality. In Section 4 the problem of incomplete absorption is taken up. We include here a comment on the indeterminacy due to the residual field and its possible relation to various classical "explanations" of quantum mechanics. Section 5 contains our conclusions as well as some remarks on various arrows of time.

2. ABSORBER THEORY AND THE CHARACTERIZATION OF TSE SOLUTIONS

2.1. Notation and Statement of the Boundary Value Problem

Consider N particles whose spacetime positions are given by $x_i^{\mu}(\tau_i)$ where τ_i is the proper time of particle i. Electromagnetic interactions among the particles can be derived by a variational principle based on the action

$$S = -\sum_{i=1}^{N} m_i \int [dx_i^{\mu}\, dx_{i\mu}]^{1/2} - \sum_{i<j} e_i e_j \iint \delta[(x_i(\tau_i) - x_j(\tau_j))^2]\, dx_i^{\mu}\, dx_{j\mu} \quad (1)$$

where m_i, e_i are, respectively, the mass and charge of the ith particle and the integrals are taken along the world lines of the particles. To define S we pose the variational principle as a boundary value problem. Suppose we wish the solution between two space-like surfaces σ_I (initial) and σ_F (final).

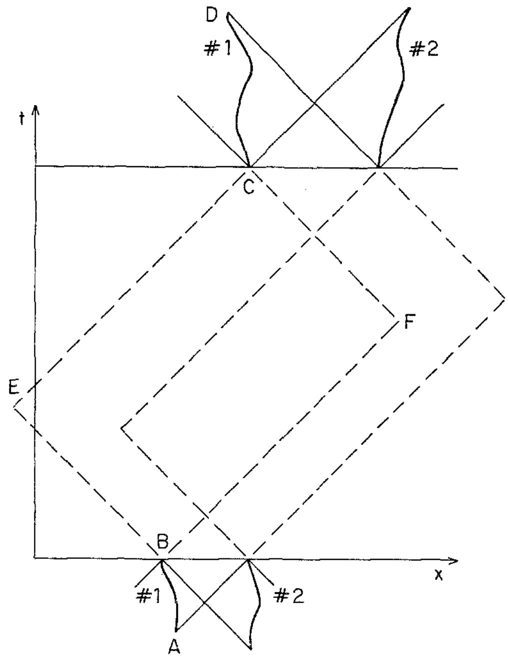

Fig. 1. Boundary conditions for two particles interacting through time symmetric electrodynamics. The data given are the indicated paths of particles 1 (*AB* and *CD*) and 2. This is sufficient, for, e.g., 1 does not depart from the rectangle *BECF* (light velocity is unity) and its light cones either intersect the boundary data for 2 or the path of 2 in its associated rectangle. For additional space dimensions the rectangle becomes an intersecting pair of cones.

Then as data we give the trajectories of the particles between σ_F and a surface σ_F' later than σ_F and between σ_I and σ_I' where σ_I' is earlier than σ_I. The surface σ_F' must be late enough so that the light cone out of $x_i(\tau_i)$ where it intersects σ_F meets the trajectory of $x_j(\tau_j)$ before σ_F', for every i and j. An analogous condition defines σ_I'. These conditions are illustrated in Fig. 1 (from Ref. 6) for the case of two particles.[2]

The condition $\delta S = 0$ yields

$$m_i\, d^2x_i^\mu/d\tau_i^2 = e_i F_\nu^{(i)\mu}(x_i)\, dx_i^\nu/d\tau_i\,, \qquad i = 1,\ldots, N \tag{2}$$

[2] In Ref. 6 these boundary conditions are shown to be appropriate for the linear problem and we conjecture their applicability in general. It is possible however that smoothness or the requirement of global existence would reduce the class of solutions. See Ref. 25.

where

$$F_{\mu}^{(i)}(x) = \sum_{j \neq i} F_{j\mu\nu}(x)$$

$$F_{j\mu\nu}(x) = \partial A_{j\nu}(x)/\partial x^{\mu} - \partial A_{j\mu}(x)/\partial x^{\nu}$$

and

$$A_j^{\mu}(x) = e_j \int_{\sigma_I'}^{\sigma_F'} \delta([x - x_j(\tau_j)]^2) \frac{dx_j^{\mu}}{d\tau_j} d\tau_j \tag{3}$$

The conditions defining σ_I' and σ_F' guarantee that for x on any particle trajectory between σ_I and σ_F, the δ-function in Eq. (3) will vanish at two points along the trajectory, yielding a half retarded, half advanced interaction. Other properties of TSE can be found in Refs. 1, 2, 4, 7, and 8.

The vanishing of the δ-function in Eq. (3) at two points gives rise to two contributions to A

$$\left.\begin{matrix} A_{Rj}(x) \\ A_{Aj}(x) \end{matrix}\right\} = e_j \int_{\sigma_I'}^{\sigma_F'} \frac{1}{|\mathbf{y}|} \delta(y_0 \pm |\mathbf{y}|) \frac{dx_j^{\mu}}{d\tau_j} d\tau_j \tag{4}$$

with $y = x - x_j(\tau_j)$. The expressions (4) are the retarded and advanced potentials and by the properties of the δ-function

$$A_j = \tfrac{1}{2}(A_{Aj} + A_{Rj}) \tag{5}$$

with A_j given in Eq. (3) above. The quantities F can similarly be broken into advanced and retarded contributions. A_R is the usual Lienard–Wiechert potential.

2.2. The Absorber Theory

The theory presented so far appears to contradict experience both in having advanced interactions and in not having radiation reaction. The Wheeler–Feynman absorber theory[1] proposes to solve both these problems at once. According to this theory the universe at large absorbs the advanced radiation (A_A) at the same time doubling the retarded component [eliminating the factor $\frac{1}{2}$ in Eq. (5)] leaving over a self-interaction interpreted as radiation reaction. We now present proof number IV from Ref. 1.

The physical property of absorption means that a disturbance within the system is not felt outside. This implies, according to Wheeler and Feynman, that for all times

$$\tfrac{1}{2} \sum_{k=1}^{N} (F_{Rk} + F_{Ak}) = 0 \qquad \text{outside the system} \tag{6}$$

("R" and "A" have the same meaning as for the vector potential). For a sum of incoming and outgoing waves to vanish in a region, they must vanish individually, so that

$$\tfrac{1}{2} \sum_{k=1}^{N} F_{Rk} = 0 \qquad \text{outside the system} \tag{7}$$

$$\tfrac{1}{2} \sum_{k=1}^{N} F_{Ak} = 0 \qquad \text{outside the system} \tag{8}$$

It follows that the difference

$$\tfrac{1}{2} \sum_{k=1}^{N} (F_{Rk} - F_{Ak}) \tag{9}$$

must also vanish outside the system for all times. But the sources of F_R and F_A are the same, so that the difference (9) is a solution of the homogeneous Maxwell equations. Since this difference vanishes for all times outside the system, it must vanish everywhere.

Consider the field seen by particle j. According to TSE it is

$$F^{(j)} = \tfrac{1}{2} \sum_{k \neq j} (F_{Rk} + F_{Ak})$$

This can be rewritten identically as

$$F^{(j)} = \sum_{k \neq j} F_{Rk} + \tfrac{1}{2} \sum_{k} (F_{Ak} - F_{Rk}) - \tfrac{1}{2}(F_{Aj} - F_{Rj}) \tag{10}$$

The first term on the right of Eq. (10), $\sum F_R$, is the ordinary Lienard–Wiechert retarded potential. The third term, $\tfrac{1}{2}(F_{Aj} - F_{Rj})$, was the subject of Dirac's analysis[1] in 1938 and was found to yield—when singularities are property evaluated—the usual radiation reaction term. The second term on the right of Eq. (10), $\tfrac{1}{2} \sum (F_{Ak} - F_{Rk})$, is just what was analyzed above and found to vanish by virtue of the absorber hypothesis. It follows that with the absorber hypothesis the time symmetric fields can be replaced by retarded fields, together with radiation reaction.

2.3. Criticism of the Absorber Theory

(I) If the difference (9) vanishes, one can also write $F^{(j)}$ in terms of advanced fields alone and an opposite radiation reaction. Thus if this demonstration says anything about an electromagnetic arrow of time it only says that such an arrow is possible, but nothing about the direction in which the arrow points. Wheeler and Feynman discuss this question at length.

(II) The proof required a region "outside the system" in which no matter is present. Even with the flat space Wheeler and Feynman consider that this does not seem a natural demand. Certainly few realistic cosmologies have such regions. Also there is the question of advanced effects for particles near the edge of their "system."

(III) The most serious problem is the assumption Eq. (6) and its consequence, Eq. (8). Absorption is a familiar irreversible process derivable from the usual assumptions of statistical mechanics. These assumptions are usual and familiar and applicable only to the retarded fields (i.e., for radiation emitted subsequent to a charge's acceleration). There is no reason to believe that advanced fields would be absorbed and in fact earlier in the same paper (in derivation I) the authors remark on the inappropriateness of using an index of refraction for advanced fields. We are thus prepared to accept Eq. (7) on physical grounds, but not Eq. (8).

As we shall see below, when the problem is properly formulated we shall need to invoke physical absorption processes in the future light cone, but not for advanced waves. It will still be true that $\sum F_A = 0$, but that will be because advanced radiation is cancelled by advanced waves from the distant absorber medium rather than by virtue of any "thermodynamic" absorption process.

3. JUSTIFICATION OF ABSORBER THEORY AND CAUSAL SOLUTIONS IN TSE

3.1. The Theorem and the Conditions for its Validity

We now provide a justification of the absorber theory that is free from the third objection raised in Section 2.3. First it will be proved that a retarded solution in which no incoming fields are present and in which the system (which can be the entire universe) absorbs is also a solution of TSE.

Imagine trajectories of N charged particles extending from $t = -\infty$ to $t = +\infty$. These trajectories are solutions of the coupled field–particle equations with the electromagnetic field at each point given by the retarded solutions, i.e., the retarded Green's function integrated over currents in the past light cone. No other fields are present. The field on some spacelike surface σ can therefore be written

$$F_{\text{Total}}(\sigma) = \sum_{j=1}^{N} F_{Rj} \tag{11}$$

We now consider this entire set of fields and trajectories to be a solution of the advanced equations. This can always be done so long as one includes an appropriate solution of the homogeneous equation which is interpreted as an outgoing wave at $t = +\infty$ which propagates back to σ. Thus on σ we also have

$$F_{\text{Total}}(\sigma) = \sum_{j=1}^{N} F_{Aj} + F_{\text{out}} \tag{12}$$

Equation (12) is a consequence of Green's theorem. An outgoing wave F_{out} at $t = +\infty$ represents radiation not absorbed by any particles. Let us now suppose that for the vast majority of initial conditions for the N-particle systems there is in fact no outgoing wave—i.e., we suppose there is complete absorption. Then F_{out} in Eq. (12) is zero and $\sum F_A = \sum F_R$. But this is exactly what is needed to show that the retarded solution is also a solution of TSE.

The assumption that the behavior of a single system is obtained by averaging over microstates that are consistent with the observed macrostate is the statement of the thermodynamic arrow of time. This assumption is valid for statements ("predictions") about the future of a system but not ("retrodictions") about its past. Thus in determining whether a given N-particle system is an absorber we are entitled to use ordinary statistical mechanics to demonstrate absorption of retarded radiation but could not use such theories for advanced radiation.[3] It follows that an actual demonstration of absorption has two components: (1) an assumption of a thermodynamic arrow and (2) a physical calculation showing that there is in fact enough of the right kinds of matter to absorb in the usual way. In this respect our demonstration of absorber theory takes a conservative view and does not try to obtain both a thermodynamic and radiative arrow in one fell swoop (in contrast to, e.g., Ref. 4).

The presence of nonelectromagnetic forces does not invalidate the foregoing derivation; their effect is to change particle trajectories and hence change the currents from which F_R and F_A are calculated.

3.2. Corollary on Causal Solutions of TSE

We show how a solution of TSE can give causal behavior. Boundary conditions (trajectories) are given in appropriate regions, and the solved boundary value problem yields paths $x_i(\tau_i)$, $i = 1,..., N$, between space-like surfaces σ_I and σ_F. The causality condition takes the form: let particle number 1 be acted upon by a nonelectromagnetic force at $t = t_0$ (between σ_I and σ_F), a force which did not act when the curves $\{x_i(\tau_i)\}$ were found. This perturba-

[3] Thus our proof fails in the opposite time direction, so that the first criticism of Section 2.3 does not apply.

tion leads to a perturbation in the solution of TSE. *Causality* means that there exist new solutions of TSE which differ from the old solutions only on and within the forward light cone of the perturbing event $(\mathbf{x}_1(\tau_1(t_0)), t_0)$. We must therefore exhibit boundary conditions coinciding with the old ones between σ_I' and σ_I (but not coinciding between σ_F and σ_F') such that particle trajectories are unchanged except in the forward light cone of the perturbation.

If the paths $\{x_i\}$ are also retarded solutions and the setting is an absorbing universe then we find the needed boundary conditions as follows: solve the retarded equations with the same initial conditions as for $\{x_i\}$ but *with* the perturbation, to obtain trajectories $\{y_i\}$. Since $\{x_i\}$ are also retarded solutions, $\{x_i\}$ and $\{y_i\}$ differ only in the forward light cone of the perturbation. Since the universe is absorbing, $\{y_i\}$ are also symmetric solutions. Now take as boundary values for the causal TSE solution the values taken by $\{y_i\}$ subsequent to σ_F and sufficiently far into the future.

There are other circumstances under which causal final conditions can be found. For two particles TSE can be cast as an initial value problem by solving for the positions at the latest times and giving data on a double light cone (see Ref. 6). While this solution can be used to satisfy our causality condition detailed inspection reveals that it does this in a peculiar way. If the perturbation has the form of an addition $\lambda \int x_1(\tau_1)\, \delta(\tau_1 - \tau_1(t_0))\, d\tau_1$ to the action then the response of particle number 1 begins only at $t_0 + \Delta t$, with Δt the travel time to the nearest other particle and back. Furthermore, for $N\,(\geqslant 3)$ particles one cannot in general recast the time symmetric equations as an initial value problem since when one solves each of the N TSE equations for its latest argument some positions occur more than once and some not at all. (This is another demonstration of the naturalness of symmetric boundary conditions for TSE.)

As far as we know the only physically relevant situation in which causality (as here defined) holds for TSE is an absorbing universe.

3.3. There Is Nowhere "Outside the System"

In the second objection of Section 2.3 we mentioned the inappropriateness of having a region "outside the system" void of all matter. In our proof this is expressed as follows: Equation (12) is based on Green's theorem and "F_{out}" is the field on some surface in the future, brought back to the present (σ) by the appropriate field Green's function. Whether or not there is absorption of a wave excited locally, there is no reason to suppose that in the distant future no radiation will be passing between the particles in the vicinity of the future surface used for Green's theorem. Particles in the future may still be interacting electromagnetically and even if their trajectories are in no way affected by perturbations applied here and now (i.e., the absorber hypothesis holds) the field "F_{out}" is not zero. Moreover, one cannot simply remove these distant particles and their fields, appealing to the linearity of the electromagnetic field equations for justification. First, the particles coupled to the fields satisfy nonlinear equations. More important, suppose some outer layer of particles were removed; their coordinates no longer appear in the sum over j in Eq. (12). Then the radiation from the next inner layer is not fully absorbed. This now provides a new outgoing field F_{out}. It may still be the case that shaking our very distant electron does not affect this F_{out} either, but neither this F_{out} nor the previous one nor any other can be set to zero.

The foregoing observation puts a different face on the entire set of questions considered in this paper.

Nonzero F_{out} means inequivalence of retarded and TSE. Surprisingly it is still true that even with $F_{\text{out}} \neq 0$, provided the absorber hypothesis holds, TSE is causal. By "causal" we mean that if a perturbation takes place at $t = 0$, the electromagnetic field near the perturbation will give no evidence of this perturbation for $t < 0$. By the "absorber hypothesis" we mean that sufficiently far along on the future light cone of the neighborhood of a perturbation there is no change in either particle trajectories or in electromagnetic fields from their unperturbed values. As above, "perturbation" means two sets of solutions are being considered, in one of which an external force acts.

Assuming that TSE holds, the field seen by a particle (j) is

$$
\begin{aligned}
F^{(j)} &= \sum_{k \neq j} F_{Rk} + (\text{Radiation Reaction})_j + \tfrac{1}{2} \sum_{k} (F_{Ak} - F_{Rk}) \\
&= \sum_{k \neq j} F_{Rk} + (\text{Radiation Reaction})_j + \tfrac{1}{2}(F_{\text{in}} - F_{\text{out}})
\end{aligned}
$$

where F_{in} and F_{out} are the fields on surfaces in the distant past and future, respectively, and F_{in} has been included because unlike Eq. (11) we no longer assume the solution to be a retarded one. As before, to study causal effects of a perturbation for TSE we work within the context of a boundary value problem and assume the initial data are the same for both perturbed and unperturbed systems. Since F_{in} is calculated from past data, it is unchanged. F_{out} is calculated on a future surface but the absorber hypothesis says that if the surface is moved far enough into the future particle trajectories and hence the fields they determine are the same for perturbed and unperturbed systems. Since $\frac{1}{2}(F_{\text{in}} - F_{\text{out}}) \equiv \Phi$ is the same for both perturbed and unperturbed systems, there are no acausal effects.

4. COSMOLOGICAL AND INCOMPLETE ABSORPTION

4.1. The Field Φ and its Effects

Does the universe in fact absorb? Theoretically the answer does not seem to be clearcut and varies with the model.[4,10–13] Experimentally, no evidence has been found to contradict the assumption of complete absorption.[14]

Possible consequences of incomplete absorption were taken up by Wheeler and Feynman (and also by "Mr. X" in Ref. 5). They found (pp. 174–176, Ref. 1) two solutions for a dynamical situation (acceleration of a source) which ordinarily would yield an unambiguous answer. They seem to have felt that in one of their solutions at least no advanced effects are evident, but, in fact, in both solutions the acceleration of the source is anticipated. The difference between their solutions is in whether or not these anticipatory effects occur in the neighborhood of the source immediately preceding the acceleration.

From Section 3 it is evident that not just two but an infinity of motions is possible. The ambiguity can be catalogued either by means of the variety of final trajectories, thinking in terms of the boundary value problem for particles, or by the variety of fields $\Phi = \frac{1}{2} \sum (F_A - F_R)$ that could appear in the Cauchy problem for the coupled particle–field equations. Furthermore, by Section 3, the field Φ can be nonzero whether or not absorption is complete, the advantage of absorption being the elimination of acausal effects.

Suppose then that nature is described correctly by TSE, that Φ does not vanish, and that nevertheless we attempt to solve an initial value problem in electrodynamics using the retarded Lienard–Wiechert potential. The usual ways of handling retarded interactions require that we specify the particle trajectories as far back as a single light cone from the initial surface (just as σ_I' was specified in Section 2). The fact that the underlying theory is TSE means that this information is inadequate. Some information on the future trajectories of the particles must be given to specify the motion. Someone who nevertheless tried to do his electrodynamics with inadequate information would find some element of indeterminacy in his solutions. It is tempting to try to go further and relate the field Φ (which settles this indeterminacy) to the stochastic field that appears in various theories of "random electrodynamics."[15–23] In these theories a random Lorentz-invariant electromagnetic field of a certain strength can account for many of the phenomena of quantum mechanics. In principle our Φ should be calculable in a model cosmology and with various assumptions about particle motion. Although we are now exploring various approaches to this calculation, any detailed discussion would be premature. In Ref. 17 it was also suggested that the Wheeler–Feynman absorber theory might have something to do with a random background field; however, that suggestion is different from ours.[4]

It is also possible that the fate of the universe is to end as a gas of cold, distantly separated particles with mutual interaction so small that even blue shifting to the present does not bring Φ to any appreciable level. This then would supply the arrow of time to an expanding universe: not the fact that absorption would be incomplete towards the past (if appropriate statistical assumptions are made) but rather that the contracted phase of a universe has too much activity for its fields to be ignorable. Here, too, calculations more detailed and specific than those of the present paper would be needed to confirm or deny statements about the field Φ.

4.2. Digression: Elastic Scattering and TSE

We consider another test to which one can subject the hypothesis of time symmetric electrodynamics. Suppose a world has but two electrons which come together and then move apart, always satisfying the coupled particle–field equations of electrodynamics. If the electrons move apart with less energy than they had initially we interpret this as the radiation of energy due to their mutual accelerations. Such an event is not a solution of TSE since there is no place there for an outgoing radiation field ending on no charged particle. Similarly, in our universe radiation that is never scattered, elastically or inelastically, would contradict TSE. In quantum terminology (used for convenience only), the question is, is a photon ever scattered? For small ω the principal scattering effect is Thompson scattering by free electrons. If they have density n, the mean free path for a photon is $\lambda = 1/n\sigma_T = (1.4 \times 10^{29}\ \text{cm})(n_0/n)$ where σ_T is the Thompson cross section and $n_0 = 10^{-5}$ electrons/cm^3. The density n_0 corresponds to about 10^{-29} gm/cm^3 for matter in the universe. This close agreement between the mean free path of a photon and the inverse of the Hubble constant (2×10^{28} cm) is equivalent to one of the large number "coincidences" and is mentioned by Harrison.[(24)] In the present context, the large number coincidence is what allows ambiguity in the selection of an electrodynamic Green's function.

[4] Braffort *et al.*[(17)] suggest that the stochastic force arises from fluctuations in the "absorber field." They argue that absorption is statistical and that although the absorber field averages to zero, it will necessarily have fluctuations and that these fluctuations are related to radiation reaction as well as provide the origin of the zero-point energy for oscillators. However, the fact that absorption is stochastic does not by itself require that fluctuations about the (zero) mean have any minimum value. For example, a particle with high initial velocity in a medium can have its velocity damped to any arbitrarily small velocity, depending on the temperature of the medium.

5. DISCUSSION

5.1. Arrows of Time

The fourth proof offered by Wheeler and Feynman for their absorber theory has always exerted a great attraction because of its simplicity and avoidance of details. In this paper we have noted that it is flawed by requiring an assumption that advanced waves be absorbed.

We find that there is no need to make such an assumption and that for a justification of the absorber theory one needs only ordinary considerations of thermodynamics and statistical mechanics.

The role of various arrows of time is now easier to unravel. We needed the thermodynamic arrow for absorption of $\sum F_R$. Thus, even if the universe is potentially an absorber both in the future and the past, our arguments cannot be turned around. If, on the other hand, absorption can only take place towards the direction of the universe's expansion, then one would have shown a correlation of cosmological, thermodynamic, and radiative arrows.

In a world with absorption we concluded with Wheeler and Feynman that $\sum (F_R - F_A)$ is zero. This leads to the observation that $\sum F_R +$ (Radiation Reaction) can be replaced by $\sum F_A -$ (Radiation Reaction), and that the world can as well be described by advanced interactions alone.

Such a description presents no problem. The possibility, in principle, of using microscopic equations of motion to work backwards from final conditions exists in mechanics even without electromagnetism. Our preference for one description over another is meaningful only when one considers averaging processes. With partial ignorance of microscopic initial conditions, using $\sum F_R$ will still give correct physical answers; using $\sum F_A$ will not. This justification for choosing $\sum F_R$ over $\sum F_A$ is valid because we have already specifically invoked the thermodynamic arrow and now we are simply using it again.

5.2. The Residual Field Φ

Even with complete absorption there may still be a residual field $\sum (F_R - F_A)$ due to electromagnetic interactions between particles in the distant future. In an absorbing universe these fields will provide indeterminacy but not acausality (i.e., there will be no anticipatory effects). If these fields are large they might serve as candidates for the random fields needed in "stochastic electrodynamics."[15–23] On the other hand, it may be that these fields are small because particles in the distant future will be isolated and noninteracting. Then one would find that the electromagnetic arrow of time is not due to preferential absorption (where sufficient matter is present for absorption in either direction) but rather because of the different properties of F_{in} and F_{out}. Specifically the arrow would point in such a way that F_{out} is small.

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