Interference and Explanation in Time-Symmetric Quantum Mechanics

1. Wavefunction Epistemicism

The quantum wavefunction naturally suggests an epistemic interpretation, primarily because of the way it is connected to probability. The intensity (squared amplitude) of the wavefunction yields the probabilities of obtaining the various possible measurement outcomes on observation. Furthermore, during observation, but not otherwise, the wavefunction (apparently) collapses discontinuously to an eigenstate corresponding to the observed outcome. These features are straightforwardly explained under an epistemic approach; the wavefunction is regarded as a statistical summary of our knowledge of the underlying local physical properties of the particles involved, so its connection to the probabilities of observed outcomes is built-in, and wavefunction collapse on observation simply reflects our coming to know the relevant measurement outcome.

However, the epistemic interpretation is widely regarded to be a non-starter; hence the proliferation of realist approaches that take the wavefunction to be a physical entity. One cannot simply impose a realist interpretation of standard (Copenhagen) quantum mechanics (QM), or one is left with no explanation of wavefunction collapse (the measurement problem). A number of wavefunction-realist solutions to the measurement problem have been proposed, including Everett's relative-state approach, Bohm's pilot-wave approach and the GRW collapse approach.

It would be nice if we could avoid this explanatory burden, and recently some progress has been made in rehabilitating wavefunction epistemicism by appealing to time-symmetric, retrocausal or atemporal explanation. The twin mysteries of QM are non-separability and interference, and both seem to stand in the way of an epistemic interpretation of the wavefunction, non-separability because of Bell's Theorem, and interference because wavefunction realism is apparently required by our causal explanations. However, a time-symmetric interpretation of QM has been shown to provide a plausible way of exploiting a loophole in Bell's theorem, reopening the possibility of interpreting the wavefunction epistemically (Price 1996). More precisely, if the states of the particles on emission can depend on the setting of the detectors they will later encounter, then Bell's theorem does not go through, and hence is no barrier to interpreting the wavefunction as a statistical summary of our knowledge of the underlying properties of the particles. That is, Bell’s Theorem does not rule out a local hidden variable theory.

But what of the second mystery? According to wavefunction-realist approaches the two mysteries are connected, since both non-separability and interference are explained in terms of superpositions of distinct wavefunction terms. But wavefunction-epistemic approaches cannot take this route, since superpositions simply reflect an observer's knowledge, and so cannot ground a physical explanation of either phenomenon. Indeed, the standard wavefunction-epistemic explanation of EPR-Bell correlations makes no mention of superposition, but simply appeals to the properties of the particles, the measurement settings and time-symmetric causation. Without superposition, interference phenomena become problematic, since interference is prima facie a physical interaction between the various superposed branches. Can a time-symmetric perspective help here too?

2. Time-Symmetric Explanation of Interference with Particles and Fields

Consider a Mach-Zehnder interferometer (MZI), as shown in Fig. 1. The standard wavefunction-realist analysis is as follows: The wavefunction intensity associated with an incoming particle is split into two equal components by beam-splitter A, and half the intensity follows each path through the interferometer, ABD and ACD. The two components of the wavefunction intersect at beam-splitter D; if the two components are exactly in phase, then all the intensity exits the interferometer through path E (because the waves along path F exactly cancel out), and if they are exactly out of phase then all the intensity exits though path F (because the waves along path E exactly cancel out). On the other hand, if all the wavefunction intensity takes path ABD (because the beam-splitter at A is removed), then no interference occurs at D; equal wavefunction intensities emerge along paths E and F. Initially, then, interference seems to rule

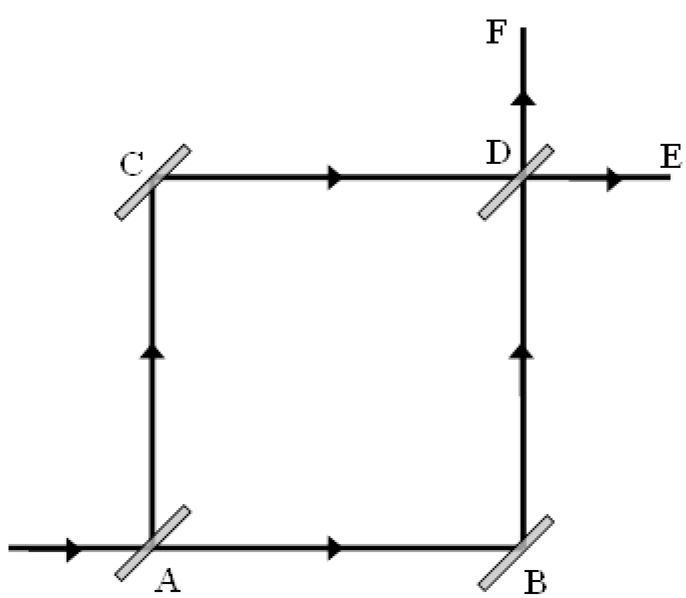


Figure 1: Mach-Zehnder Interferometer

out an epistemic approach, since the explanation of the phenomena depends on real waves travelling both paths and physically interacting at D. The time-symmetric approach is essentially a “hidden variable” approach, in that the wavefunction describes our state of knowledge concerning the actual underlying physical state of the system. If the intensity on each branch is 1/2, this suggests that there is a 50% epistemic probability that the actual physical state is a particle taking path ABD and a 50% probability that it is a particle taking path ACD. But if the actual physical system takes one path rather than the other, there is no physical interaction between entities taking the two paths at D, and the explanation of interference is lost.

But it is important to note that the time-symmetric approach does not require that the “hidden variables” take the form of particle properties. Indeed, several proponents of the time-symmetric approach take the wavefunction to describe our knowledge of fields rather than our knowledge of particles, and they do so precisely so as to give a physical account of interference. Consider, for example, Cramer's (1986) transactional interpretation. According to this approach, the wavefunction should not be regarded as a physically real field inhabiting a 3N-dimensional configuration space; rather, what is real is a transaction, which is a field in ordinary 3-dimensional space. Nevertheless, one can as a matter of convenience take the wavefunction as a summary of our knowledge of the transactions at a time, yielding the probability that each possible transaction is actual via the Born rule.

In non-interference situations, a transaction forms along a determinate spatial trajectory. For example, suppose the beam-splitter at A is removed from the MZI. Then two possible transactions may form, one along ABDE and one along ABDF, and the traditional wavefunction intensities at E and F reflect the epistemic probability that each of these transactions is actual. However, in interference situations, a transaction forms along a disjoint trajectory. With the beam-splitter at A in place, and with path-lengths ABD and ACD chosen appropriately, a single transaction forms between A and E, split between paths ABDE and ACDE. This single transaction consists of a classical field that takes both paths through the interferometer, and hence the physical interaction between the field amplitudes arriving at D from B and from C can explain the interference effect.

Wharton (2010) takes a related approach, in that he also takes the quantum wavefunction to be of merely epistemic significance, where the true underlying state of a quantum system is characterized in terms of a classical field evolving between an initial boundary condition (preparation) and a final boundary condition (detection). Wharton takes a Feynman-path approach to the field between the two boundaries, interpreting it as a sum over all possible paths. As in the transactional approach, for the MZI without interference (beam-splitter at A removed) the field forms either along path ABDE or along ABDF, and in the interference case (beam-splitter present) the field forms along both paths ABDE and ACDE simultaneously.

The transactional interpretation has been criticized on a number of fronts; in particular, since transactions form between particle emission events and particle absorption events, the theory has difficulty accommodating situations where the absorbers do not occupy fixed space-time points, but move in response to the actual path taken by the transaction (Maudlin 1994, 200). Such difficulties can perhaps be accommodated within the transactional interpretation by explicitly incorporating the absorbers into the transactional analysis (Lewis 2011). Even so, identifying the ends of a transaction with particle emission and absorption points remains problematic. The assumption seems to be that all measurement outcomes are particle absorptions, since it is particle absorptions that are made determinate by the transactional approach. But this is far from obvious. Indeed, QM necessarily models measurement without particle absorption, typically as the correlation between a microscopic system and a macroscopic "pointer". There is no reason why a transaction should make such a measurement event determinate, rather than being a superposition of classical waves passing through various different measurement outcomes. Perhaps Wharton's approach can be more flexible in this regard; perhaps it need not take particle destruction as the only future constraint on the classical field. But note that a dilemma threatens. If the future constraint is tied to a particular kind of physical process, then we need some reason to think that all measurements will be instances of this process, otherwise measurement outcomes need not be made determinate. But if the future constraint is not tied to a particular kind of physical process, but is simply whatever constitutes a measurement, then the measurement problem reemerges. That is, if all that distinguishes the future constraint on the field from other physical processes is that it constitutes a measurement, then stipulating that the field converges to this point is arbitrary, since measurements are just physical processes too.

The basic worry here is that the field-based time-symmetric approaches are unstable hybrids. On the one hand, they seek to interpret the wavefunction epistemically rather than ontically, such that preparations and measurements are merely points at which we have a particularly detailed knowledge of the quantum system. On the other, they retain the field-like behavior of the wavefunction at the ontic level, with a wave that spreads out from the preparation point and converges to the measurement point. Even if the above dilemma is not convincing, there is a feeling of redundancy about it; as Price has remarked, the time-symmetric approach promises to restore discrete trajectories to QM, so to back away from discrete trajectories at this point "misses the true potential" of the approach (1996, 283).

Of course, the choice of fields rather than discrete trajectories is not unmotivated, but is motivated by the desire to explain interference. What can a discrete approach do here? It is worth noting that the heart of the time-symmetric approach is that a system can bear the traces of future interactions, just as it can bear the traces of past interactions. In particular, the state of the system can depend on where and how it will be detected. In the case of the MZI, then, it is no mystery that, for suitable path-lengths, the particles always go to E, since their ending up at E is just as much a constraint on the particles as their starting out at A. That is, what one might typically take as the explanandum in the interference case is taken as part of the explanans in a time-symmetric treatment. Indeed, this brings to the fore the sense in which the transactional and Wharton approaches seem to incorporate a redundancy. Both of them presuppose in their analysis that there is a future constraint on the classical field as well as a past constraint, and the future constraint is absorption at E. But then in what sense does absorption at E call for an explanation, if it is one of the boundary conditions? And if it does not call for an explanation, why insist that the underlying reality consists of fields just so as to provide such an explanation?

The obvious answer is that absorption at E calls for an explanation in the sense that simple taking it as a boundary condition makes the explanation of interference trivial. Why is it that for this choice of path-lengths all the particles go to E? It hardly seems satisfactory to reply "because the particles bear traces of being absorbed at E"; this just presupposes what we are trying to explain. However, explanation is a tricky matter; perhaps the explanation just looks trivial because we are used to explanations that proceed from the past to the future, so that taking a future state as an explanans seems to our untutored intuitions like cheating. Indeed, as long as the detection point and the emission point do not constitute all the degrees of freedom for the system, then the potential for a substantive explanation of the remaining degrees of freedom remains.

To put the same point in a slightly different way, perhaps the accusation is that an explanation that takes the end-point as given is vacuous since any phenomenon could be "explained" in this way, so nothing is really explained. But such a complaint would be premature, since we have as yet given no laws or mechanisms for a discrete time-symmetric approach. The mere form of an explanation is typically vacuous; it is only the laws or mechanisms that constrain the connections between the explanans and explanandum that give the explanation content. Indeed, one might accuse explanations in classical physics that start with the initial state of a system of being vacuous, since anything can be explained in this way. Ironically, though, not everything can be explained from initial conditions; this is precisely the lesson that Price draws from EPR-Bell experiments. Hence one needs to broaden the explanans to include some final conditions as well as some initial conditions. One certainly hopes that doing so means every phenomenon can potentially be explained, given suitable laws or mechanisms; that is precisely the point.

Still, without a concrete candidate for a law or mechanism that can constrain discrete particle trajectories in the required way, the worry that the explanation of interference will remain trivial cannot be fully put to rest. So perhaps there is a third alternative in the time-symmetric camp that can avoid the problems facing both the alternatives canvassed so far. There is a sense in which neither the field-based nor the trajectory-based approach fully exploits the explanatory resources that are made available by the time-symmetric program, since both still explain phenomena primarily via possessed physical properties that are traced through time by the underlying ontology, whether that ontology is discrete or continuous. They also appeal to the initial and final boundary conditions, but the constraints imposed by these conditions are always mediated by the dynamical properties of the system. Perhaps more insight—and deeper explanations—can be had by concentrating on the global consistency conditions imposed by these constraints directly (Silberstein et al., 2008), where "global" is spatiotemporal, i.e., the experiment from initiation to termination (measurement outcomes). The hope is that by explaining the behavior of a system in a global, adynamical or timeless fashion, the explanation of interference can avoid both the problems of appealing to dynamic interaction between fields and the apparent triviality of explanations based on particle trajectories.

3. **Time-Symmetric Explanation of Interference with Acausal Global Constraints**

Herein we will provide an explanation of MZI interference utilizing acausal global constraints. Whether this is anything more than a toy-model remains to be seen, but hopefully it provides a proof in principle that such an explanation is possible. Let us begin with the standard QM description of the MZI. One starts with a directed Source and a pair of detectors D1 (ultimately on E of Figure 1) and D2 (ultimately on F of Figure 1) $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$, i.e., the Source is aimed at D1.

Now, there is some information assumed in this simple 2D vector, e.g., that the Source is turned on and that the detectors are in fact responding to this particular, active Source. We next introduce beam splitter A (Figure 1) between the Source and detectors. This changes the 2D vector as follows:

$\frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\ 1 & 1\end{pmatrix}\begin{pmatrix}1\\ 0\end{pmatrix}=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ 1\end{pmatrix}$. Next we introduce the pair of mirrors B and C (Figure 1) between A and the detectors, but this does nothing to the 2D vector, i.e.,

$\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}}\end{pmatrix}=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ 1\end{pmatrix}$. Finally, we introduce beam splitter D between the mirrors and detectors giving $\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ -1 & 1\end{pmatrix}\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}}\end{pmatrix}=\begin{pmatrix}1\\ 0\end{pmatrix}$.

According to the adynamical global constraint model elaborated herein, the fundamental explanation for the MZI interference (D1 triggers but not D2) has nothing to do with the dynamics of particles or fields. Rather, the functioning MZI and its outcomes are viewed as one system, explained in its entirety via acausal global constraints (which will be given in terms of graphical boundary operators below). As explained in the previous section, psi-epistemic accounts utilizing both fields and future boundary conditions to obtain wave-like behavior, make for a potentially unstable combination because one must presuppose what one is trying to explain—interference in this case. However, we believe the problem stems from assuming that the pattern of explanation is still fundamentally dynamical however retrocausal or time-symmetric it may be. Wharton (2010) seems to assume this as well in spite of the fact that he utilizes the path integral or "Lagrangian" approach, as do we. On the other hand, if you take seriously the idea that the path integral-type explanation is the most fundamental, it opens up the possibility of fundamental explanation via acausal global constraints, i.e., this is an adynamical interpretation of the Lagrangian approach. On this approach, the fundamental answer to the question, why the interference pattern, is adynamical and acausal. It is a principle or rule underlying the spatiotemporal configuration of the experiment as whole that determines the outcomes (e.g., the interference pattern) and not "constructive" entities with dynamical histories (a la Einstein). We are advocating for a "principle" explanation as fundamental, again a la Einstein. However, unlike Einstein and many others, we reject the idea that fundamental explanation in physics is always ultimately constructive or dynamical (Brown, 2005).

It is sometimes pointed out that principle explanation is most clearly understood by considering examples from special relativity (SR), examples such as the well-known relativistic phenomena of length contraction and time dilation. Viewed as a "principle" theory, following Einstein's famous remarks, SR introduces, as Jeffrey Bub put it, "abstract structural constraints that events are held to satisfy" (1974, 143 as cited in Hughes 1989). The crucial point here is that causality and dynamical laws do not figure into the analysis of length contraction. The two principles at work in SR that constrain dynamics are the relativity principle and the light principle. Principle explanation has some precedent in the interpretation of quantum theory (see, for example, the discussion in Hughes 1989, 256 ff.), but the dynamical bias is impossible to shake for most people. However, unlike the case of SR, we seek a global self-consistency principle or rule that is *fundamental* to QM understood dynamically or constructively. We call this rule the self-consistency criterion (SCC), since it correlates the properties of space, time and matter on a graph in the spirit of general relativity (GR).

That is, in GR momentum, force and energy all depend on spatiotemporal measurements (tacit or explicit), so the stress-energy tensor cannot be constructed without tacit or explicit knowledge of the spacetime metric (technically, the stress-energy tensor can be written as the functional derivative of the matter-energy Lagrangian with respect to the metric). But, if one wants a "dynamic spacetime" in the parlance of GR, the spacetime metric must depend on the matter-energy distribution in spacetime. GR solves this dilemma by demanding the stress-energy tensor be "consistent" with the spacetime metric per Einstein's equations. Likewise, our fundamental rule for the construct of the Lagrangian difference matrix $\bar{\bar{K}}$ and source vector $\vec{J}$, which are ultimately responsible for interference, is based on the self-consistent construct of a relational graph, i.e., graphical links and their properties to include the spacetime metric. A classical analogy is Regge calculus (Misner et al., 1973, 1166), a discrete graphical approximation to GR. In Regge calculus, the spacetime manifold is replaced by a lattice geometry where each cell is Minkowskian (flat). Curvature is represented by "deficit angles" (Figure 2) about any plane orthogonal to a "hinge" (triangular side to a tetrahedron, which is a side of a simplex). The

Hilbert action for a 4D vacuum lattice is $I_R = \frac{1}{8\pi}\sum_{\sigma_j \in L}\varepsilon_i A_i$ where σ_i is a triangular hinge in the lattice L, A_i is the area of σ_i and ε_i is the deficit angle associated with σ_i. The counterpart to Einstein's equations is then obtained by demanding $\frac{\delta I_R}{\delta \ell_j^2} = 0$, where ℓ_j^2 is the squared length of the jth lattice edge , i.e., the metric. To obtain equations in the presence of matter-energy, one simply adds the appropriate term $I_{M\text{-}E}$ to I_R and carries out the variation as before to obtain $\frac{\delta I_R}{\delta \ell_j^2} = -\frac{\delta I_{M-E}}{\delta \ell_j^2}$. One finds the stress-energy tensor is associated with lattice edges, just as the metric, and Regge's equations are to be satisfied for any particular choice of the two tensors on the lattice. Thus, Regge's equations are, like Einstein's equations, a self-consistency criterion for the stress-energy tensor and metric. Likewise, we are proposing that the explanation of interference resides not in dynamical wave-like entities, but in a global self-consistency criterion.

In what follows we will present a candidate for the global self-consistency criterion (SCC) in a discrete graphical formalism fundamental to both QM and QFT. In order to build up the graphs that yield the right probabilities, we will indeed presuppose the entire spatiotemporal profile of the MZI experiment to include outcomes, i.e., we use the path integral approach.

The fundamental element in our adynamical explanation is the "relation." To picture what we mean by relations consider a graphical depiction of connected worldlines, i.e., sets of vertical/time-like links (e_1, e_3, e_5, e_6 in Figure 3) connected by horizontal/spatial-like links (e_4, e_2, e_7 in Figure 3). Now, assign properties such as mass, energy, momentum, spatiotemporal length, etc., to each link. These property-endowed links represent relations and the graph represents trans-temporal objects (TTOs) involved in some process. Of course, a complete graphical depiction of the TTOs involved in the MZI would be prohibitively and unnecessarily complex. In addition, there are many different distributions of relations possible for a particular TTO, just as there are many different distributions of molecular velocities for a gas at some given temperature. Since we don't know exactly the relational composition of the TTOs, our predictions concerning their relational compositions are necessarily probabilistic. With this correspondence in mind, we understand that $\begin{pmatrix}1\\0\end{pmatrix}$ represents an active Source directed at one of a pair of corresponding detectors, but more importantly it also represents the fact that the active nature of the Source has established a "Source -- D1 relation" responsible for D1 clicks.

When one introduces beam splitter A, $\begin{pmatrix}1\\0\end{pmatrix} \to \begin{pmatrix}1/\sqrt{2}\\1/\sqrt{2}\end{pmatrix}$ per the matrix $\frac{1}{\sqrt{2}}\begin{pmatrix}1 & -1\\1 & 1\end{pmatrix}$ represents the fact that the active nature of the Source has established a "Source – A" relation which has subsequently established an "A – D1" relation and an "A – D2" relation of equal weight. The mirrors only serve to allow for the introduction of beam splitter D which now creates (essentially) the following set of relations: "Source – A" → "A up – D left" and "A right – D up" → "D – D1," as represented by $\begin{pmatrix}1\\0\end{pmatrix} \to \begin{pmatrix}1/\sqrt{2}\\1/\sqrt{2}\end{pmatrix} \to \begin{pmatrix}1\\0\end{pmatrix}$. To answer this question in complete formal detail exceeds the scope of this paper. However, we can briefly summarize the approach so as to convey some appreciation for the relevant result.

In order to compute the transition amplitude Z for the two-source graph (as depicted in Figure 3, but with N nodes), one must solve the eigenvalue problem for the matrix $\vec{\vec{K}}$ constructed from boundary operators on the graph, i.e., $\vec{\vec{K}} = \partial_1 \partial_1^T$ where

$$\partial_1 = \begin{bmatrix} -1 & 0 & 0 & -1 & 0 & 0 & 0 \\ 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

is the ∂_1 boundary operator for the graph in Figure 3. $\vec{\vec{K}}$ is essentially the difference matrix in the Wick-rotated discrete action of the free field of QFT, i.e., that for coupled harmonic oscillators. Also required for computing Z are the projections of the source vector $\vec{J}$ onto the eigenvectors of $\vec{\vec{K}}$. $\vec{J}$ is given by the ∂_1 boundary operator on the vector of graphical links, i.e., $\vec{J} = \partial_1 \vec{e}$, which automatically makes $\vec{J}$ divergence-free, i.e., $\sum_i J_i = 0$. Solving the eigenvalue problem for $\vec{\vec{K}}$ and projecting $\vec{J}$ onto the eigenvectors one obtains the probability amplitude for a direct source-to-source interaction. This is the graphical counterpart to the free field propagator in QFT, but in this application to QM we're coupling sources (oscillators) that are widely separated in space, as between Source and A in the MZI, rather than adjacent, as in the continuous sense of QFT (Stuckey et al., 2012). Combining two graphs (Figure 4) then serves to model the twin slit experiment. Adding the respective probability amplitudes and squaring (Born rule) shows that interference is given by the difference in the square of spatial links, i.e., the phase goes as $e_x^2 - \tilde{e}_x^2$. That is to say, the square of spatial links corresponds to spatial distance and the interference pattern is associated with different spatial path lengths between sources, just as in geometric optics. Of course, in this picture, the explanation of interference doesn't involve the "cancellation" or "enhancement" of "wave-like motion." Rather, Z simply provides a continuous probability of 0 → 1 for each detector as you change the MZI spatial lengths by virtue of the phase difference between sources obtained from $\vec{\vec{K}}$ and $\vec{J}$. So, we assumed an outcome location (along with MZI configuration) to build the graph, but that outcome (squared) could be anything from 0 to 1, so we did not assume an interference pattern. Rather, as in Regge calculus, the values of spacetime length and energy-momentum associated with a given graphical link obtain by virtue of the fact that they satisfy the relevant global self-consistency equation, such as Regge's equations.

For example, suppose in the context of Regge calculus, you asked, "Why does link X have 5.00 kg·m/s of momentum on it?" The answer would be, "Because 5.00 kg·m/s of momentum on link X satisfies Regge's equations when used in conjunction with the values given on all the other links for the stress-energy tensor and spacetime metric." Nothing "makes" the link "acquire" a momentum of 5.00 kg·m/s in a "dynamical" sense. The reason it has that value is per its role in the global solution of Regge's equations corresponding to the process being modeled. In our case, the process being modeled is an MZI in a particular configuration (specific path lengths on arms) with a particular outcome (D1 click). We get a probability for that graph via adynamical global constraints. Another example of this type of adynamical time-symmetric thinking is the Helsinki model (Price, 2008). Therein, rules govern the manner in which a graph is built by restricting properties that adjacent nodes and links can possess. If one then associates links with particle worldlines and nodes with interactions, a graph depicts various combinations of pair annihilation and creation. So, what are our counterparts to Regge's equations for $\vec{\vec{K}}$ and $\vec{J}$, and the rules of the Helsinki model?

Omitting the gory details, the definitions of $\vec{\vec{K}}$ and $\vec{J}$ above yield $\vec{\vec{K}}\vec{v} = \vec{J}$ where $\vec{v}$ is the vector of graphical nodes. This relationship between $\vec{\vec{K}}$ and $\vec{J}$ follows tautologically per the boundary of a boundary principle ($\partial\partial = 0$), as do Maxwell's and Einstein's equations (Misner et al. 1973, 772). Given that $\vec{\vec{K}} = \partial_1\partial_1^T$ yields the difference matrix in the discrete action for coupled harmonic oscillators, $\vec{J} = \partial_1\vec{e}$ guarantees the source vector is divergence-free and resides in the row space of $\vec{\vec{K}}$, and $\vec{\vec{K}}\vec{v} = \vec{J}$ follows from the same topological principle underlying Maxwell's and Einstein's equations, we posit that $\vec{\vec{K}}\vec{v} = \vec{J}$ is the fundamental rule (SCC) responsible for the self-consistent construct of $\vec{\vec{K}}$ and $\vec{J}$, i.e., our counterpart to Regge's equations. Our counterpart to the rules of the Helsinki model are then:

1. $\vec{\vec{K}}$ and $\vec{J}$, whence the transition amplitude Z, must satisfy the SCC, $\vec{\vec{K}}\vec{v} = \vec{J}$.
2. Z gives the probability for a particular outcome in a particular experiment.
3. $\vec{\vec{K}} \cdot \vec{Q}_o = \vec{J}$ where $\vec{Q}_o$ represents the most probable values of the experimental outcomes.
4. Steps 2 and 3 are approximated in the continuum by quantum and classical field theory, respectively.

Conclusion

In utilizing discrete path integrals over graphs constrained by the SCC, we have shown that it is possible in principle to explain interference adynamically with spatiotemporal global constraints fundamental to QM and QFT clothed in their standard dynamical formulation. Whatever the merits or demerits of our specific proposal, we would urge others willing to take time-symmetric accounts of QM seriously to start thinking about the new explanatory space opened up by this perspective. While integral calculus or "Lagrangian" methods have been with us for some time, very few have spent much time in their interpretation. As Healey says, "While many contemporary physics texts present the path-integral quantization of gauge field theories, and the mathematics of this technique have been intensively studied, I know of no sustained critical discussions of its conceptual foundations" (Healey, 141, 2007). In this paper we have explored an adynamical interpretation of the path-integral approach in its discrete form. In so doing, we also hope to have shown that an epistemic interpretation of the wavefunction is a live option with many explanatory virtues.

While we applaud Wharton's commitment to a psi-epistemic interpretation and likewise his "Lagrangian" approach, we note that his insistence on classical fields to explain interference makes explanation of discrete outcomes and the Born rule quite difficult. Furthermore, in light of the Quantum Liar Experiment (QLE) attempts to use either particle trajectories or fields to explain EPR-Bell correlations becomes much more problematic. This is because in QLE, in neither the past nor the future, do the atoms interact with each other or the photon that entangles them. Since the worldlines of the atoms and photon do not intersect, one is not going to be able to easily tell the standard retrocausal story via time-like and null worldlines even when working with the outcomes (Silberstein et al., 2008). Retrocausalists such as Wharton and Price are hoping that when EPR-Bell correlations occur, there still can be a physical chain of influence stretching from one side to the other, however zig-zaggy backwards and forwards in spacetime these correlations maybe (e.g., a V or W). One certainly can connect two space-like related events by time-like paths if you're allowed to go backwards in time (zig-zag). The motivation that Wharton and Price have is clear, they think that preserving locality (no action-at-a-distance) *requires* that we shouldn't find correlations between two space-like separated points without a chain of contiguous correlations stretching (backwards and forwards) through spacetime between those points. The chain of correlations could be the worldlines of intersecting particles or a continuous chain of spacetime fields. However, unfortunately for Price, QLE provides a no-go theorem for particles with definite and intersecting worldlines (Silberstein et al., 2008), a fact that Wharton himself acknowledges. However, the photon-field can go down both paths irrespective of which measurement is made on the atoms. That is, there can be a continuous zig-zag path of null connections (EM fields in 'both' arms of the interferometer) and time-like connections (atom fields) to link all correlated outcomes. That is, retrocausalists absolutely need fields to explain both interference and EPR-Bell correlations, however weak or ad hoc that explanation may be.

However, what we have shown with our acausal time-symmetric model is that EPR-Bell correlations can be explained locally without a chain of contiguous correlations stretching (backwards and forwards) through spacetime (Silberstein et al., 2008). Just as we explained interference, we can explain EPR-Bell correlations by means of graphical relations and the SCC. Think of the underlying discrete graphical theory as a conspiracy theory if you like, one that enforces such “spooky” correlations in spacetime regardless of the presence or absence of contiguous correlations. The idea that such a contiguous chain of correlations is needed to preserve locality or explain EPR-Bell correlations is a vestigial limb of “constructive” and dynamical fundamentalism. After all, if one takes the blockworld, time-symmetric picture seriously, what are fields but standing waves sandwiched between past and future boundary conditions. There is no “flow” or “exchange” of information in any strictly Newtonian sense, just correlations obtaining at various regions in spacetime.

Figure 2

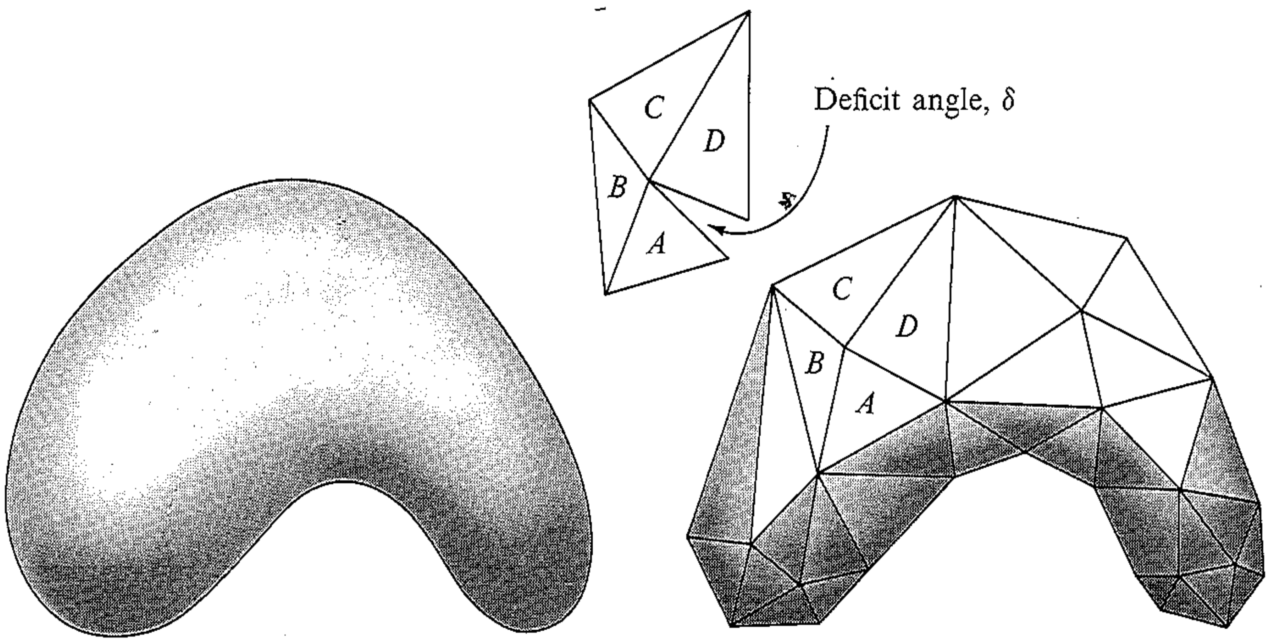


Figure 42.1.
A 2-geometry with continuously varying curvature can be approximated arbitrarily closely by a polyhedron built of triangles, provided only that the number of triangles is made sufficiently great and the size of each sufficiently small. The geometry in each triangle is Euclidean. The curvature of the surface shows up in the amount of deficit angle at each vertex (portion *ABCD* of polyhedron laid out above on a flat surface).

Reproduced from Misner, C.W., Thorne, K.S., Wheeler, J.A.: Gravitation. W.H. Freeman, San Francisco (1973), p. 1168.

Figure 3

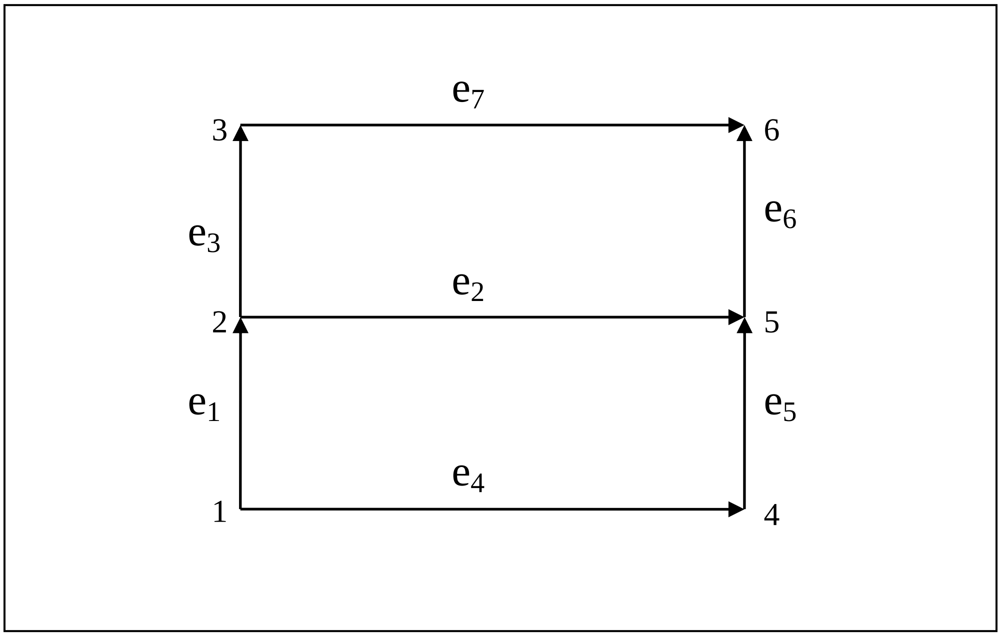
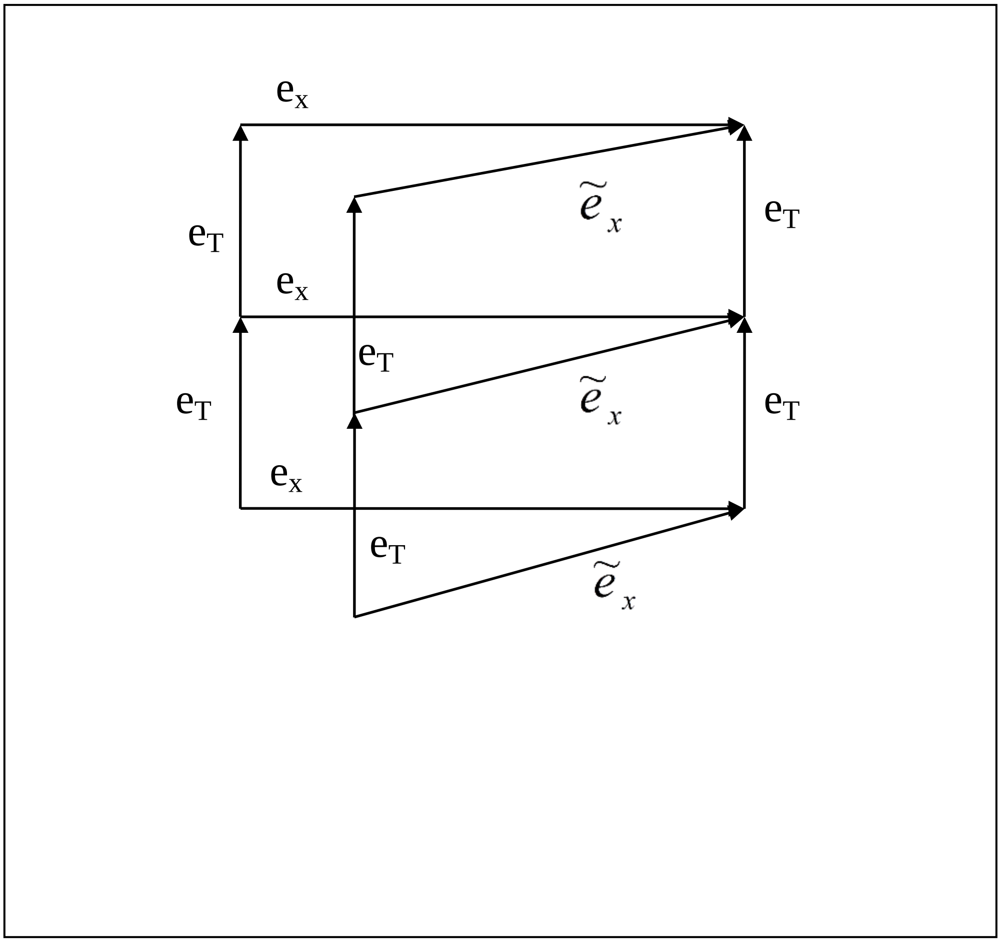


Figure 4



e$_x$
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$\tilde{e}_x$
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e$_x$
e$_T$
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