A new topology for curved space–time which incorporates the causal, differential, and conformal structures

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A new topology is proposed for strongly causal space-times. Unlike the standard manifold topology (which merely characterizes continuity properties), the new topology determines the causal, differential, and conformal structures of space–time. The topology is more appealing, physical, and manageable than the topology previously proposed by Zeeman for Minkowski space. It thus seems that many calculations involving the above structures may be made purely topological.

1. INTRODUCTION

In 1964 Zeeman published a paper showing that the causal structure of Minkowski space $M$ already implied its linear structure. Causality was defined by means of a partial ordering on $M$, and it was shown that the group of automorphisms of $M$ preserving the ordering is generated by the inhomogeneous Lorentz group and dilatations. (This is the homothetic group $H$ of $M$, comprising all affine automorphisms which preserve the Lorentz metric up to a constant factor.) He then proposed that the conventional (positive definite) metric topology $H$ of $M$ should be replaced by a new topology $\mathcal{J}$ (the fine topology) which is related to the causal structure. $\mathcal{J}$ has the following properties:

1. $\mathcal{J}$ is defined to be the finest topology on $M$ which induces the one-dimensional Euclidean topology on every straight timelike line, and the three-dimensional Euclidean topology on every spacelike hyperplane. Thus $\mathcal{J}$ is finer (and, in fact, strictly finer) than $H$.

2. $\mathcal{J}$ incorporates the (homothetic) Lorentz structure at the primitive level of topology (rather than, as is conventional, after imposing linear structure); the homeomorphism group of $\mathcal{J}$ is $H$.

3. If the path of a particle is interpreted as a $\mathcal{J}$-continuous map $\gamma$ of the unit interval $I$ into $M$ such $\gamma$ preserves order, the image of $\gamma$ is piecewise linear, consisting of a finite number of straight timelike line segments, like the path of a free particle undergoing a finite number of collisions.

4. $\mathcal{J}$ is Hausdorff, connected and locally connected, but not normal, locally compact or first countable.

This new topology obviously has several advantages over the standard one, which merely characterizes the continuity of $M$. Its very definition (1) is more intuitive—appealing than that of $H$, since it requires a set to be open when (a) every inertial observer “times” it to be open, and (b) every section of time simultaneity intersects it in an open set. The definition of $H$ involves 4-spheres in space–time, which have no particular physical meaning. The idea of (2) incorporating causal, linear and even homothetic structure already in a topology $H$ is certainly physically appealing, and the idea (3) that the requirement of continuity of a curve should already restrict it to be physically meaningful is fascinating. However, there are disadvantages:

1. A 3-dimensional section of simultaneity has no meaning in terms of physically possible experiments. Also, the use of straight timelike lines in defining $\mathcal{J}$ suggests that $\mathcal{J}$ from the beginning has been equipped with information involving inertial observers, so that the emergence of linear structure in (2) is less surprising. (Though in fact this is not the reason for its emergence.)

2. While the isometry and conformal groups of $M$ are certainly significant physical, it is not necessarily clear that this is so for the homothety group of $M$.

3. The set of $\mathcal{J}$-continuous paths does not incorporate accelerating particles moving under forces in curved lines.

4. $\mathcal{J}$ is technically complicated. In particular, the fact that no point has a countable neighborhood basis makes $\mathcal{J}$ hard to calculate with.

Zeeman suggests that criticism (3*) could be overcome by generalizing his theory to general relativity, where the image of $\gamma$ should become piecewise geodesic (thus accounting for gravitational forces). This generalization has recently been carried out by Göbel who, for strongly causal space–time manifolds, replaced (1) by replacing “time axis” and “spacelike hyperplane” by “timelike geodesic” and “spacelike hypersurface.” He then proves that Zeeman’s conjecture about the generalization of (3) is correct, and, with the help of a theorem of Hawking relating causal to differential structure, that the homeomorphism group is again the homothety group.

However, even in general relativity, particles need not move along geodesics since, for example, they may be charged and an electromagnetic field may be present (and this applies in special relativity also). Thus the generalization to general relativity of the topology $\mathcal{J}$
(we also call the generalizations \( \mathcal{J} \)) only partially answers (3*), and leaves the other criticisms (1*), (2*) and (4*) as before.

In this paper, we propose a new topology \( \mathcal{P} \) for strongly causal space—times \( M \) which share the attractive features of the topologies \( \mathcal{J} \), but which also answer some of the above criticisms and have additional attractive physical features. The topology \( \mathcal{P} \), the path topology, has the following properties:

1) \( \mathcal{P} \) is defined to be the finest topology on \( M \) which induces the Euclidean topology on arbitrary (not necessarily smooth) timelike curves.

2) The topology \( \mathcal{P} \) incorporates the causal, differential, and smooth conformal structure; the homeomorphism group of \( \mathcal{P} \) is the conformal group.

3) The set of \( \mathcal{P} \)-continuous paths incorporates all timelike paths. In fact, the set consists of all “Feynman paths” (described below).

4) \( \mathcal{P} \) is still technically complicated, but less so than \( \mathcal{J} \). Indeed, \( \mathcal{P} \) is Hausdorff, connected and locally connected, but not normal or locally compact. However, every point has a countable neighborhood basis, and this makes \( \mathcal{P} \) much easier to deal with than \( \mathcal{J} \).

The definition (1') has an immediate physical interpretation which is more appealing than (1): a set is open whenever every observer (accelerated or not) “times” it to be open. No nonphysical experiments are required. Also, (1') does not require any smoothness properties to define \( \mathcal{P} \), so that the emergence of smooth and conformal structure is more surprising. Again, (2') answers criticism (2*), and (3') shows that all possible observers, accelerated or not, are described by \( \mathcal{P} \)-continuous curves. The fact that \( \mathcal{P} \) has a countable neighborhood basis at each point makes it much easier to deal with than \( \mathcal{J} \). Thus the computation of the set of all \( \mathcal{P} \)-continuous paths becomes relatively easy (Zeeman only finds the order preserving paths for \( \mathcal{J} \)).

These paths are (possibly accelerated) “Feynman paths” which zigzag with respect to time orientation, like the Feynman track of an accelerated electron. This same “basis” property makes it relatively easy to find the general properties of \( \mathcal{P} \). In fact, \( \mathcal{P} \) is path connected and locally path connected, but not regular or paracompact, in addition to having the properties mentioned above. The relative ease of calculations with \( \mathcal{P} \) suggest that it could be usefully applied to “practical” problems in general relativity. If one could show (using the basis property) that a space—time must admit a (local or global) \( \mathcal{P} \)-homeomorphism, this would mean that the space—time admits a (local or global) conformal diffeomorphism.

Thus we suggest that, while Zeeman’s topology and its general relativistic analogs represent a radical and fascinating departure from the conventional schemes, our topology \( \mathcal{P} \) has all of the required features, but is more intuitively appealing, manageable, and physical. Section 2 is devoted to standard results and definitions. In Sec. 3, timelike paths (not necessarily smooth) and Feynman paths are defined, and the topology is described. In Sec. 4 it is shown that \( \mathcal{P} \) is not comparable to \( \mathcal{J} \), and the important basis property is proved. This is used to show that the set of continuous paths is the set of Feynman paths, and to prove various general properties of \( \mathcal{P} \). In Sec. 5 it is shown that \( \mathcal{P} \) carries the chronological structure of \( M \), and in Sec. 6, that \( \mathcal{P} \) carries the causal, differential, and conformal structure of \( M \). The final theorem is that the homeomorphism group of \( \mathcal{P} \) is the group of conformal diffeomorphisms of \( M \).

The burden of the argument is as follows. First we show that \( \mathcal{P} \)-homeomorphisms take timelike curves to timelike curves. Then we show that this implies that \( \mathcal{P} \)-homeomorphisms preserve causal relations. This is used to show that they are diffeomorphisms preserving the null cones, that is, conformal diffeomorphisms.

2. STANDARD DEFINITIONS AND RESULTS

Space—time is taken throughout to be a connected, Hausdorff, paracompact, \( C^\infty \) real four-dimensional manifold \( M \) without boundary, with a \( C^\infty \) Lorentz metric (only a few orders of differentiability will actually be needed) and associated pseudo-Riemannian connection. \( M \) is taken to be time orientable throughout (that is, \( M \) admits a nonvanishing timelike vector field). For subsets \( A \) and \( B \) of \( M \), the chronological future \( \mathcal{J}^+(A,B) \) of \( A \) relative to \( B \) is the set of all points in \( B \) which can be reached from \( A \) by a future directed smooth (i.e., \( C^\infty \)) timelike curve in \( B \) of finite extent. The causal future \( \mathcal{J}^+(A,B) \) of \( A \) relative to \( B \) is the union of \( A \cap B \) with the set of all points in \( B \) which can be reached from \( A \) by a future directed smooth causal curve (i.e., nonspacelike curve) in \( B \). The future horismos \( E^+(A,B) \) of \( A \) relative to \( B \) is defined as \( J^+(A,B) \cap \mathcal{J}^+(A,B) \). These definitions have duals, often regarded as self evident, in which “future” is replaced by “past” and “+” by “-”.

If \( A \) is the singleton set \( \{p\} \) for a point \( p \in M \), we write \( \mathcal{J}^+(p,B) \) rather than \( \mathcal{J}^+(\{p\},B) \), for example, and \( \mathcal{J}^-(p) \) for \( \mathcal{J}^-(p,M) \). The relations \( p \in \mathcal{J}^+(q) \), \( p \in \mathcal{J}^-(q) \), and \( p \in E^+(q) \) will sometimes be written \( q < p \), \( q > p \), and \( q \sim p \), respectively. These last relations are respectively called, chronological, causal, and horismos relations. The definitions and results below will be needed in this paper. They are only stated in the generality needed:

1. If \( V \) is an open set, \( q \in \mathcal{J}^+(p,V) \) implies \( p \in \mathcal{J}^+(q,V) \), and conversely. Similar results hold for \( J \) and \( E \). \( \mathcal{J}^+(p,V) \) and \( \mathcal{J}^+(p,V) \) are open sets. In particular, these statements hold for \( \mathcal{J}^+(p) \) and \( \mathcal{J}^-(p) \).

2. If \( V \) is an open set, either

\[
q \in J^+(p,V), \quad r \in J^+(q,V) \quad \Rightarrow \quad r \in J^+(p,V).
\]

3. Let \( T^\infty_M \) denote the tangent space of \( p \in M \), and \( \exp: T^\infty_M \to M \), the exponential mapping. Then there is an open neighborhood \( N \) of the origin of \( T^\infty_M \) such that \( \mathcal{J} = \exp(N) \) is an open convex normal neighborhood of \( p \in M \). That is, every pair of points in \( \mathcal{J} \) can be joined by a unique geodesic curve in \( \mathcal{J} \), and geodesics in \( \mathcal{J} \) through \( p \) are the images of straight lines through the origin in \( N \subset T^\infty_M \). Further, \( p \) possesses a neighborhood basis of open convex normal neighborhoods.
Furthermore, the normal neighborhoods may be taken to be normal neighborhoods of every point in them. Let \( \epsilon > 0 \) be sufficiently small so that the Euclidean open ball \( B \) of radius \( \epsilon \), centered at the origin, is contained in \( N \). We define \( B(p, \epsilon) = \exp(B) \), and whenever such a set is referred to, it is assumed that \( \epsilon > 0 \) is sufficiently small.

2.4 Denote the normal coordinates of \( q \in \mathcal{U} \) by \( x^i(q) \), where \( i = 0, 1, 2, 3 \), and \( x^i \) is the time coordinate, \( x^1, x^2 \), \( x^3 \) the space coordinates. Then \( x^i(p_0) = 0 \) and

\[
J^p(p, l) = \{ q \in \mathcal{U} | (x^0(q))^2 - (x^1(q))^2 - (x^2(q))^2
\]

\[
> 0, \quad x^3(q) > 0 \},
\]

\( J^p(p, l) \) satisfies the same condition except that \( x^0(q) \leq 0 \), and \( \Gamma(p, l) \) are defined analogously, except that all inequations are strict. Define, for any open set \( \mathcal{V} \), the cones (possibly) with and without origin by

\[
C(p, \mathcal{V}) = \Gamma(p, \mathcal{V}) \cup \Gamma(p, \mathcal{V}),
\]

\[
K(p, \mathcal{V}) = C(p, \mathcal{V}) \cup \{ p \},
\]

and, for an open convex normal neighborhood \( \mathcal{U} \) of \( p \), define

\[
L_a(p, \epsilon) = B(p, \epsilon) \cap K(p, \mathcal{U}).
\]

Note that \( L_a(p, \epsilon) \) is nonempty [the point with coordinates \( \{ \epsilon, 0, 0 \} \) belongs to \( B(p, \epsilon) \) as is \( B(p, \epsilon) \) [take coordinates \( \{ 0,0,0 \} \)]]

2.5 A space-time \( M \) is chronological, if there is no closed smooth future (or past) directed timelike curves in \( M \). Equivalently, \( M \) is chronological, and if only if, \( \Gamma(p) \cap I^+(p) = \emptyset \) for all \( p \in M \). Analogously, \( M \) is causal, if there are no future (or past) directed causal curves.

2.6 Denote the manifold topology of \( M \) by \( \mathcal{T} \). Consider the collection of all sets of the form \( \Gamma(p) \cap \Gamma(q) \) for \( p, q \in M \). These sets are open and (together with, possibly, the empty set \( \emptyset \) clearly form a basis for a topology on \( M \). The topology is called the Alexandroff topology \( \mathcal{A} \) of \( M \), and in general, is coarser than \( \mathcal{T} \).

2.7 A causality neighborhood \( D \) of a point \( p \in M \) is an \( \mathcal{A} \)-neighborhood of \( p \) that, whenever \( \gamma: F \to M \) is a smooth causal path, \( \gamma^{-1}(D) \) is connected. (Here \( F \) is a connected interval of the real line \( R \).) \( M \) is strongly causal at \( p \), if and only if, \( D(p) \) is a causality \( \mathcal{T} \)-neighborhood. \( M \) is strongly causal, if it is strongly causal at each point. Another useful characteristic of this property is given by the following consequence:

\[
M \text{ is strongly causal } \iff \mathcal{A} \text{-Hausdorff } \iff \mathcal{A} = \mathcal{T}.
\]

2.8 If \( \mathcal{V} \) is an open convex normal neighborhood of \( p \in M \), \( \mathcal{E}(p, \mathcal{V}) \) consists of future directed null geodesics in \( \mathcal{V} \) from \( p \), and \( \mathcal{E}(p, \mathcal{V}) \cup \mathcal{E}(p, \mathcal{V}) \) is the image of the null cone \( N \cap N_c \subset T(M) \) in the neighborhood \( N \) of the tangent space \( T(M) \) under exp.

2.9 The metric \( g \) at \( p \in M \) is determined up to a constant by the tangent null cone \( N_c \subset T(M) \).

2.10 The isometry, homothecy and conformal groups of \( M \) are those groups of \( C^\infty \) diffeomorphisms of \( M \) which preserve, respectively, the metric tensor, the metric tensor up to a constant factor, and the metric tensor up to a (possibly variable) factor.

3. The topology \( \beta \)

3.1 Let \( \beta \) be a connected interval of the real line \( R \). (The singleton closed set \( \{ x, \beta \} \) is excluded. For our purposes we may take \( \beta \) to be bounded, for there is an order preserving \( C^\infty \) diffeomorphism \( \tau: (x, \beta) \to (x, \beta) \). Thus \( F \) is a finite, closed, open, or half open half closed interval.) A map \( \gamma: F \to M \) is called a path, and its image a curve (the same symbol \( \gamma \) often being used for either, it being clear from the context which is meant). A path \( \gamma \) is continuous if \( \gamma \) is continuous with respect to \( \mathcal{T} \) and the topology on \( F \) induced from the standard one on \( R \). A point \( q \in M \) is said to be an initial end point of a continuous path \( \gamma : F \to M \), if for every neighborhood \( N \) of \( q \) there is a \( l_q \in F \), such that \( l_q < l \) implies \( \gamma(l) \in N \). If a continuous path \( \gamma \) has an initial end point \( q \in \gamma(F) \), one may find a new continuous path \( \gamma' : F \cup \{ l_q \} \to M \) such that \( \gamma'(l) = \gamma(l) \) and \( \gamma'(l_q) = q \) where \( l_q \) is the greatest lower bound of \( F \). We shall therefore assume without loss of generality that continuous paths contain both their initial and final endpoints if they have them.

3.2 A path \( \gamma : F \to M \) is called a future directed and timelike at \( t_0 \in F \), if and only if \( \gamma \) is continuous and there is a connected neighborhood \( U \) of \( t_0 \) in \( F \), and an open convex normal neighborhood \( \mathcal{U} \) of \( p \) such that \( t \in U \) and \( t < t_0 \) implies \( \gamma(t) \in N \). If a continuous path \( \gamma \) has an initial end point \( q \in \gamma(F) \), one may find a new continuous path \( \gamma' \) such that \( \gamma'(l_q) = \gamma(q) \) and \( \gamma'(t) \equiv q \) where \( t_q \) is the greatest lower bound of \( F \). A path is called future directed and timelike, if it is future directed and timelike at each \( t_0 \in F \). Similar definitions hold for "past directed." A path is timelike at \( t_0 \), if it is either future or past directed and timelike at \( t_0 \), and timelike, if it is either everywhere future directed, or everywhere past directed and timelike. A curve is timelike, if it is the image of a timelike path.

Proposition 3.3: Let \( \gamma : F \to M \) be a continuous path which is timelike at each \( t_0 \in \text{int} \mathcal{F} \). Then \( \gamma \) is a timelike path.

Proof: Suppose \( \gamma \) is future directed at \( t_0 \in \text{int} \mathcal{F} \). Let \( \mathcal{U} \) and \( \mathcal{V} \) be as above. Suppose there were a \( t_0 \in \mathcal{U} \) with \( t_0 > t_0 \) such that \( \gamma(q) \) was past directed at \( t_0 \). The coordinate \( x^0(\gamma(t)) \) will be a continuous function of \( t \). Thus there will be some \( t_0 \) such that \( x^0(\gamma(t)) \) is the maximum value of \( x^0(\gamma(t)) \). Since \( \gamma \) is future directed at \( t_0 \), \( t_0 \) must be greater than \( t_0 \). Similarly, \( t_0 \) would have to be less than \( t_0 \). Consider the point \( q = \gamma(t_0) \). On \( \gamma'(t_0) \) the coordinate \( x^0 \) would be greater than its value at \( t_0 \). This would mean that \( \gamma(\mathcal{U}, t_0) \) could not be timelike at \( t_0 \).

This means that \( \gamma \) must be future directed for all \( \mathcal{U} \in \mathcal{F} \) with \( t_0 > t_0 \). A similar argument shows that \( \gamma \) must be future directed for all \( \mathcal{U} \in \mathcal{F} \) with \( t_0 > t_0 \). Thus, the set of points at which \( \gamma \) is future directed is open in \( \text{int} \mathcal{F} \). Similarly, the set on which \( \gamma \) is past directed is open. Because \( F \) is connected, \( \gamma \) must be either everywhere future directed or everywhere past directed in \( \mathcal{F} \).

Assume, without loss of generality, that \( \gamma \) is future directed. Suppose that \( q = \gamma(t_0) \) is an initial endpoint.


Hawking, King, and McCarthy 176
Let $U$ be a connected neighborhood of $t_i$ in $F$ and let $U$ be a convex neighborhood of $q$. Let $t_{x_i}$ be the set in $U$ with $t_{x_i} \supset t_i$. Then $\gamma(t_{x_i}) \subset \Gamma(r_i(U))$, where $r_i$ is the radius. Therefore, by continuity $q_i \in \Gamma(r_i(U)) = \Gamma(U)$. Thus, $r_i \in J^+(U)$. However, by a similar argument one can find a $t_{x_i} \subset U$ such that $q_i \in J^+(U) \cap \Gamma(U)$. Therefore, by 2.2, $r_i \in J^+(U)$. Hence $\gamma$ is also future directed timelike at its endpoints. It follows from 2.2 and 3.2 that a timelike path is locally 1-1, that is, each $t_{x_i} \in U$ has a neighborhood $V$ such that $\gamma|_V$ is 1-1. Notice that timelike paths need not be smooth.

The point of this definition is that $F$ will be defined independently of smoothness properties, but nevertheless smooth structure will emerge from $\beta$ (Theorem 5). Curiously enough, a path may be timelike and smooth without being timelike. Let $\gamma: R \to M$ be the path defined in Minkowski space (usual coordinates) by $y(t) = (t, \sin t, 0, 0)$. Then $\gamma$ is timelike and smooth, but not smooth timelike, since it is null at the points $t = \pi n$ for integral $n$. However, $\Gamma(A, B)$ and $\Gamma(A, B)$, as defined by smooth timelike curves, agree with $\Gamma(A, B)$ and $\Gamma(A, B)$ as defined by timelike curves.

3.4 We now define a class of paths which are similar to timelike paths, in that their curves are constrained to lie within light cones, but which may zigzag with respect to time orientation. A path $\gamma: R \to M$ is a Feynman path, if $\gamma$ is continuous and, for each $t_0 \in U$, there is an open connected neighborhood $U$ of $t_0$ and an open convex normal neighborhood $\mathcal{U}$ of $\mathcal{U}$ such that $y(t) \subset \Gamma(p(t))$.

A locally 1-1 Feynman path will be called a Feynman path. Suppose $\gamma$ is a Feynman path, 1-1 in a neighborhood $V$ of $t_0$. Let $W$ be an open connected neighborhood of $t_0$ in $V \cap U$. Then, using the fact that $W$ is connected, and that $\gamma|_W$ is 1-1 and continuous, it is easily shown that $\gamma$ is either timelike at $t_0$ or $\gamma(W) \subset \Gamma(p(t)) \cup \{p_0\}$, or $\gamma(W) \subset \Gamma(p(t)) \cup \{p\}$. Obviously timelike paths are Feynman paths, but there are many non-timelike Feynman paths.

3.5 Suppose $y_1$ is a timelike curve with future endpoint $q_1$, and $y_2$ is a timelike curve with past endpoint $q_2$. Evidently the union $y_1 \cup y_2$ is also a timelike curve, which may be parametrized as a future or past directed timelike path. Any such path will be called a product path $y_1 \times y_2$ and qualified with "future directed" or "past directed," according to the choice of the direction of the parameter. If $y_1$ is as before, but with $y_2$ now with future endpoint $q_1$, we may similarly define product paths, denoted $y_1 \times y_2$, which are timelike everywhere at $\gamma(q)$. However, $y_1 \times y_2$ is always a Feynman path.

3.6 Define a new topology (the path topology) $\beta$ of $M$ by specifying the collection $\beta$ of open sets of the topology as follows: $\beta$ is the finest topology satisfying the requirement that the induced topology on every timelike curve coincides with the topology induced from $M$. Thus, if a set $E \subset M$ is $\beta$-open, for every timelike curve $\gamma$ there is an $O \subset \gamma$ with $E \cap O \subset O \cap \gamma$.

Conversely, if $\gamma$ satisfies this condition, it is $\beta$-open, and $\beta$ is the largest collection of such sets. Obviously $O \subset M$ implies $O \subset \beta$, so $\beta$ is finer than $\gamma$. We shall see below that it is strictly finer, and that $\beta$ is not comparable to the general relatively analogous $\beta$.

4. GENERAL PROPERTIES OF

Here we show that $\beta$ is strictly finer than $\gamma$, but not comparable to $\beta$, and find an explicit neighborhood basis for $\beta$. Then we show that the $\beta$-continuous paths are Feynman paths, and various general properties of $\beta$ are proved.

Proposition 4.1: Let $\gamma: F \to M$ be a path. If $\gamma$ is $\beta$-continuous, $\gamma$ is $\gamma$-continuous. If $\gamma$ is timelike, $\gamma$ is $\beta$-continuous.

Proof: The first assertion follows since $\beta$ is finer than $\gamma$. For the second, note first that $E \subset \gamma$ implies $E \cap \gamma = O \cap \gamma$ for some $O \subset \gamma$. Hence $\gamma^{-1}(E) = \gamma^{-1}(E \cap \gamma) = \gamma^{-1}(O \cap \gamma) = \gamma^{-1}(0)$. But $\gamma$ is timelike and so, in particular, continuous. Therefore $\gamma^{-1}(0) = \gamma^{-1}(0)$ is open.

Proposition 4.2: Sets of the form $K(p)$, $K(p, t)$, and $L(p,t)$ are $\beta$-open.

Proof: Let $\gamma$ be any timelike curve. Suppose first that $p \subset \gamma$. Then by definition, $\gamma \subset \Gamma(p) \cup \{p\} = \Gamma(p)$. Thus, next that $p \subset \gamma$. Then $\gamma \subset \Gamma(p) = \gamma \subset \Gamma(p) \cup \{p\}$. In either case, $\gamma \subset \Gamma(p) \cap \{p\}$, which is open for some $O \subset \gamma$. The proof that $K(p, t)$ is $\beta$-open is similar. Replace $M$ by $\gamma$, and the proof for $L(p, t)$ follows because $B_s(p, t)$, being $\gamma$-open, is an open intersection with $\gamma$, as will any spacelike hypersurface. Therefore $R$ is $\beta$-open. However, $\gamma$ is not $\beta$-open since $R = \gamma(p, t)$, which is closed. On the other hand, $K(p, t)$ is $\beta$-open but not $\beta$-open, since the intersection of any spacelike hypersurface containing $p$ with $K(p, t)$ is $\gamma(t)$.

Theorem 1: Sets of the form $L(p, t)$ form a basis for the topology $\beta$.

Proof: We must show that, for any $\beta$-open set $E$ and any $p \in E$, there is a $\beta$-open neighborhood of $p$ of the form $L(p, t)$ contained entirely in $E$. Suppose it to be false. Then there is an open convex normal neighborhood $\mathcal{U}$ of $p$ such that, for every ball $B_s(p, t) \subset \mathcal{U}$ and corresponding $L(p, t)$, there is a $q \in L(p, t)$ with $q \not\in E$. Fix such a set $L(p, t)$ and assume, without loss of generality, that it contains a $q_1$ not in $E$, with $q_1 \in \Gamma(p, t)$. If there is no such $q_1$, all points of the required type lie in $\Gamma(p, t)$, and the proof is as before with $\Gamma$ and "sufficient" and "past" interchanged. Since $p$ belongs to the open set $\Gamma(p, t)$, we can find a $\epsilon > 0$ with $B_\epsilon(p, t) \subset \Gamma(p, t)$. Let $\epsilon$ be any positive number satisfying $\epsilon < \min(\epsilon_1, \epsilon_2)$. There is a $\epsilon_2 \in L(p, t)$ with...
Then easy to approximate $\gamma(I)$ by a Feynman path, showing that $M$ is $\beta$-path connected. Before proving further general properties, we need:

Proposition 4.3: $L(B_{\beta}(p_{0},e)^{\beta}) \subset L(B_{\beta}(p_{0},e) \cap A(K(p,0)))$. (Here the left-hand side denotes the $\beta$-closure, and all other topological symbols refer to $\beta$.)

Proof: Certainly $L(B_{\beta}(p_{0},e)^{\beta}) \subset L(B_{\beta}(p_{0},e)$ since $\beta$ is finer than $\beta$. Now points $q \in B_{\beta}(p_{0},e) \cap A(K(p,0))$ have $\beta$-open neighborhoods of the form $L(B_{\beta}(q,0))$ which do not meet $B_{\beta}(p_{0},e)$, so $L(B_{\beta}(p_{0},e)^{\beta}) \subset L(B_{\beta}(p_{0},e) \cap A(K(p,0)))$. If $v \in M$ is in this latter set, every $\beta$-neighborhood of $v$ contains a $\beta$-neighborhood of the form $L_{\beta}(v,0)$ which is easily seen to meet $L_{\beta}(v,v)$. 

Theorem 3: $\beta$ is first countable and separable. $\beta$ is Hausdorff, path connected and locally path connected (and so a fortiori connected and locally connected). However, $\beta$ is not regular, normal, locally compact or paracompact.

Proof: The first sentence has been dealt with above. $\beta$ is Hausdorff because $\beta$ is finer than $\beta$. The connectivity properties have been dealt with above. To show that $\beta$ is not regular, consider the $\beta$-neighborhood $L_{\beta}(p_{0},e)$ and show that $\beta$ has no $\beta$-closed neighborhood $S$ contained in $L_{\beta}(p_{0},e)$, using the basis property and 4.3. To show that $\beta$ is not normal, consider the disjoint $\beta$-closed subsets $L_{\beta}(p_{0},e)^{\beta}$ and $L_{\beta}(p_{0},e) \cap A(K(p,0))$, and show, using the basis property, that these sets cannot have disjoint $\beta$-open neighborhoods. To show that $\beta$ is not locally compact, use the fact that closed subspaces of compact sets are compact, the basis property and 4.3, and note that $L_{\beta}(p_{0},e)^{\beta}$ is not $\beta$-closed, so certainly not $\beta$-compact, hence not $\beta$-compact, since $\beta$ is finer than $\beta$. $\beta$ cannot be paracompact because paracompact spaces are normal. 

5. $\beta$ AND CHRONOLOGICAL STRUCTURE

We wish to prove $\beta$-homeomorphisms $h$, take time-like curves to timelike curves. Obviously $h$ takes $\beta$-continuous curves to $\beta$-continuous curves, but, of course, $\beta$-continuous curves (Feynman paths) need not be timelike. We single out a subclass of $\beta$-continuous curves, by adding restrictions made only in terms of $\beta$. This subclass will coincide with timelike curves. This will enable us to prove that for strongly causal spacetimes $\beta$-homeomorphisms preserve or reverse causal relations.

Definition 5.1: A path $\gamma: F \to M$ is said to be regular, if and only if:

(A) $\gamma$ is $\beta$-continuous and locally 1-1.

(B) For every $t_{0} \in F$, there is a connected neighborhood $U$ of $t_{0}$ and a $\beta$-neighborhood $\Omega_{0}$ of $p = \gamma(t_{0})$, such that:

(1) $\gamma(U) \subset \Omega_{0}$

(2) Whenever $t_{0} \in \text{int} F$ (the interior of $F$) and $a,b \in U$ satisfy $a < t_{0} < b$, every $\beta$-continuous curve in $\Omega_{0}$ joining $\gamma(a)$ to $\gamma(b)$ contains $p = \gamma(t_{0})$.

Proposition 5.1: A $\beta$-homeomorphism takes regular paths to regular paths.
Proof: The definition of regularity only set theoretical and $\beta$-topological notions. Since $h$ is a $\beta$-homeomorphism, it preserves all required properties.

Theorem 4: $\gamma: F \to M$ is timelike, if and only if, $\gamma$ is regular.

Proof: Suppose first that $\gamma$ is timelike and, for definiteness, future directed. By 4.1 $\gamma$ is $\beta$-continuous, so satisfies (A) of the regularity condition. For $t_0 \in \text{int}F$, let $U$ and $\bar{U}$ be as in 3.2. Set $\Pi_0 = K(p, \bar{U})$ where $p = \gamma(t_0)$. From 4.2, $\Pi_0$ is a $\beta$-neighborhood of $p = \gamma(t_0)$. Since $\gamma$ is future directed and timelike, $\gamma(U) \subseteq \Pi_0$.

Suppose next that $a, b \in U$ satisfy $a < t_0 < b$. Since $\gamma$ is future directed $\gamma(a) \in \Gamma(p, [a])$ and $\gamma(b) \in \Gamma(p, [b])$. Let $\xi = (r, s) \in \Pi_0$ be a $\beta$-continuous path with $\gamma(a) = \xi(r)$ and $\gamma(b) = \xi(s)$. Since $\xi$ is $\beta$-continuous, $\xi$ is, by 4.1, continuous, so $\xi([r, s])$ is connected. If $p \notin \xi([r, s])$, $\xi([r, s]) \subseteq \Gamma(p, [r]) \cap \Gamma(p, [s])$, then $\xi([r, s])$ is contained in a disjoint union of open sets, and meets both. This contradicts the connectivity of $\xi([r, s])$, so in fact, $p \in \xi([r, s])$ and $\gamma$ is regular. An analogous proof holds if $\gamma$ is past directed and timelike, so the first half of the proposition is proved.

Suppose next that $\gamma$ is regular, and that $\Pi_0$ is a $\beta$-neighborhood of $p = \gamma(t_0)$ satisfying the required conditions. Because $\gamma$ is $\beta$-continuous, $\gamma$ is continuous.

From Theorem 1, $p$ has a $\beta$-neighborhood of the form $L_{a, b}(p, \bar{U})$ contained in $\Pi_0$. Choose an open convex normal neighborhood $V$ of $p$ with $U \subseteq \bar{B}_a(p, \bar{U})$. Then $\beta$-neighborhood $K(p, \bar{U})$ of $p$ is contained in $L_{a, b}(p, \bar{U})$. Since $\gamma$ is $\beta$-continuous, $\gamma'$, $(K(p, \bar{U}))$, is a neighborhood of $t_0$.

Let $U \subseteq \gamma'(K(p, \bar{U}))$ be a connected neighborhood of $t_0$ such that $\gamma: U \to M$ is $1-1$. Then $\gamma(U) \subseteq K(p, \bar{U})$.

Assume now that $t_0 \in \text{int}F$, and choose $a, b \in U$ with $a < t_0 < b$. Since $\gamma$ is $1-1$ on $U$, both $\gamma(a)$ and $\gamma(b)$ lie in $\Gamma(p, [a]) \cup \Gamma(p, [b])$. Assume for definiteness that $\gamma(a) \in \Gamma(p, [a])$ and $\gamma(b) \in \Gamma(p, [b])$. Then $\gamma(b)$ cannot belong to $\Gamma(p, [a])$ either, since otherwise, in view of the $\beta$-path connectivity of $\Gamma(p, [a])$, there would be a $\beta$-continuous path in $\Gamma(p, [a])$ which joins $\gamma(a)$ to $\gamma(b)$ but which does not contain $p$ since $p \notin \Gamma(p, [a])$. Therefore, $\gamma(a) \in \Gamma(p, [a])$ and $\gamma(b) \in \Gamma(p, [b])$.

Let $U_0$ and $U_1$ denote the disjoint connected intervals $[a, b] \cap \{s \in \bar{U} \mid t_0 < s \}$, respectively. Since $\gamma$ is $1-1$, $\gamma(U_0)$ and $\gamma(U_1)$ both belong to the disjoint union $\Gamma(p, [a]) \cup \Gamma(p, [b])$ of open sets. But $\gamma$ is $\beta$-continuous, hence continuous, therefore $\gamma(U_0)$ and $\gamma(U_1)$ are connected. However, we have just shown that $\gamma(U_0)$ meets $\Gamma(p, [a])$ and $\gamma(U_1)$ meets $\Gamma(p, [b])$, so in fact $\gamma(U_0) \subseteq \Gamma(p, [a])$ and $\gamma(U_1) \subseteq \Gamma(p, [b])$, therefore $\gamma$ is future directed and timelike at $t_0 \in \text{int}F$ (or past directed and timelike at $t_0 \in \text{int}F$). Applying the same reasoning to each $t_0 \in \text{int}F$, we conclude that $\gamma$ is $1-1$ and timelike at each $t_0 \in \text{int}F$ and therefore, by proposition 3.3, $\gamma$ is a timelike path.

Here and henceforth, $M$ is always assumed chronological.

Proposition 5.3: A $\beta$-homeomorphism $h$ takes cones $C(p)$ bijectively onto cones, $h(C(p)) = C(h(p))$.

Proof: There is a timelike path $\eta$ joining $q$ to $p$ if and only if $q \in C(p)$. By proposition 5.1 and Theorem 4, the image path $h \eta$ is timelike, and it joins $h(q)$ to $h(p)$.

Therefore $h(q) \in C(h(p))$, and since $h$ is bijective, it maps $C(p)$ bijectively onto $C(h(p))$.

Proposition 5.4: For a fixed $r \in M$, a $\beta$-homeomorphism $h$ maps $\Gamma(r)$ (respectively $\Gamma'(r)$) bijectively onto either $\Gamma(r)$ (respectively $\Gamma'(r)$) or $\Gamma(h(r))$ (respectively $\Gamma(h'(r))$).

Proof: Suppose first that there is a $p \in \Gamma(r)$ with $h(p) \in \Gamma'(h(r))$ and let $q \in \Gamma'(r)$. Join $p$ to $r$ and to $q$ by past directed timelike paths $\eta_1$, respectively; and form a past directed product path $\eta \equiv \eta_1 \eta$. The image curves $h \eta_1$, $h \eta$, and $h \eta_2$ are timelike, and since $h(p) \in \Gamma(h(r))$, $h \eta_2$ is past directed. Therefore $h \eta_2$ is past directed and timelike. Hence, $h(q) \in \Gamma(h'(r))$ for every $q \in \Gamma'(r)$. A similar construction starting with a given $q \in \Gamma'(r)$ shows that $h(q) \in \Gamma'(h(r))$ for all $q \in \Gamma'(r)$. This completes the "either" part of the proof. If there is no $p \in \Gamma(r)$ with $h(p) \in \Gamma'(h(r))$, a similar construction gives the remainder of the proof.

Proposition 5.4: The previous proposition holds with "a fixed $r \in M" replaced by "every r \in M.""

Proof: Suppose that, for a given $r \in M$, $h$ preserved time orientation, $h(\Gamma(r)) = \Gamma'(h(r))$ and $h(\Gamma'(r)) = \Gamma'(h(r))$. Let $A \subseteq M$ be the set of points at which $h$ preserves time orientation. Then certainly $p \in A$ whenever $C(p) \cap C(r) \neq \emptyset$. We assert that $A$ is $\beta$-open. Indeed, choose a point $s \in \Gamma(r)$. Then $r \in \Gamma(s)$ and since $\Gamma(s)$ is open, there is an open neighborhood $U$ of $r$ with $U \subseteq \Gamma(s)$. Then for any $q \in U$, $\Gamma(q) \cap \Gamma'(r)$ contains $s$, so a fortiori $s \in C(q) \cap C(r)$. Therefore $q \in U \subseteq A$, and $A$ is $\beta$-open. The set $M-A$ of points at which $h$ is time orientation reversing is also open. But $M$ is connected and $\gamma \in A$, so $M = A$. If there is no $r \in M$ satisfying the above condition, every point satisfies the opposite condition.

Proposition 5.5: A $\beta$-homeomorphism is an $\alpha$-homeomorphism.

Proof: This follows immediately from 5.4 and the definition of the Alexandroff topology.

6. $\beta$ CAUSALITY, DIFFERENTIAL, AND CONFORMAL STRUCTURE

The fact that $\beta$-homeomorphisms preserve or reverse chronological relations enable us to prove that, for strongly causal space-times, they locally preserve or reverse causal relations. In particular, they preserve null geodesics. It is then shown that $\beta$-homeomorphisms are diffeomorphisms and, since they preserve null cones, conformal diffeomorphisms.

Proposition 6.1: Suppose now and henceforth $M$ is strongly causal. Then a $\beta$-homeomorphism $h$ is $\beta$-homeomorphism, and $h$ maps null geodesics to null geodesics curves.

Proof: Since $M$ is strongly causal, it is a fortiori chronological, hence $h$ is an $\alpha$-homeomorphism. Strong causality also implies $\alpha \beta$, so $h$ is an $\alpha$-homeomorphism. Let $D$ be a causality neighborhood of $r \in M$ and $\bar{D}$ an open convex normal neighborhood of $r$. Then causality relations restricted to $D$, agree with causality relations relative to $D$. Now, in $\bar{D}$ the horizons relations can be expressed in terms of chronology.
relations since, for \( p, q \in U \), \( q < p \) is and only if 
\[ q \notin p \text{ and } p = q \rightarrow q < p \]. Since \( b \) is a \( \beta \)-homeomorphism, \( h(U) \) and \( h(D) \) are \( \beta \)-open. Let \( U', D' \) be respectively, an open convex normal neighborhood and a chronology neighborhood of \( h(r) \) with \( U' \subset D' \subset h(U) \). In \( \gamma \cup \gamma \cap h^{-1}(U') \), \( h \) will preserve chronology (and hence horismos) relations or reverse them. Suppose \( \gamma \) is the unique null geodesic curve joining \( s, t \in U \cap h^{-1}(U') \). Then \( t < \gamma \) if and only if \( r < l = s \). Therefore \( h(t) \) satisfies \( h(r) = \varphi h(s) = h(s) \rightarrow h(r) = h(s) \), that is \( h(t) \) lies on a null geodesic joining \( h(r) \) to \( h(s) \). Hence, \( h(r) \) is a null geodesic curve in \( h(U) \). 

**Theorem 5:** A \( \beta \)-homeomorphism \( h: M \rightarrow M \), which takes null geodesic curves to null geodesic curves is a \( \beta \)-diffeomorphism.

**Proof:** (This is a theorem of Hawking\(^4\) which is given here in an improved form since it has never been published.) Let \( U \) be a convex normal neighborhood and \( \gamma_i; F_i \rightarrow U(i = 1, 4) \) be four \( \gamma \)-null geodesic paths such that:

1. For each \( i, i \in F_i \), there is a unique null geodesic curve \( \gamma_i; U \rightarrow U \) joining the point \( \gamma_i(l_i) \) to the null geodesic curve \( \gamma_i \).

2. For each \( t \in F \), there is a unique point \( q \in \lambda \), such that \( q \) and \( \gamma_i(l_i) \) lie on a null curve in \( U \).

3. For each point \( q \in \lambda \), there is a unique \( t \in F \), such that \( q \) and \( \gamma_i(l_i) \) lie on a null curve in \( U \).

4. The map \( \psi; F_1 \times F_3 \rightarrow F_4 \) defined by \( \psi(t_1, t_3) = t_4 \), where \( t_1, t_3 \) and \( t_4 \) are as in (1)–(3) above is \( C^\alpha \), and is such that \( \partial \psi/\partial t_1 \) and \( \partial \psi/\partial t_3 \) are nonzero.

For a sufficiently small neighborhood \( U \), the metric differs by an arbitrarily small amount from that of Minkowski space. Comparison with Minkowski space shows that \( \gamma \) can be chosen to satisfy the above conditions. Condition (4) cannot be satisfied in less than three dimensions.

By the assumption of the theorem \( h(\gamma) \) will be four null geodesic curves contained in \( h(U) \). Thus one can find four \( \gamma \)-paths \( \gamma_i; F_i \rightarrow h(U) \) which define the same null geodesic curves as \( h(\gamma) \), but which may be parameterized differently. Let \( \tilde{h}_i; F_i \rightarrow F_4 \) be defined by \( \tilde{h}_i = \psi_i \gamma_i \). The maps \( \tilde{h}_i \) will be continuous and monotonic (because \( h \) preserves or reverses ordering). Therefore, by Lebesgue's theorem, they will be differentiable almost everywhere. Let \( \tilde{j}; F_3 \times F_3 \rightarrow F_3 \) be defined similarly to \( \psi \). Then

\[
\tilde{h}_i((l_1, l_3)) = \tilde{j}(\tilde{h}_i(l_1), \tilde{h}_i(l_3)).
\]  

(Differentiating (I) with respect to \( l_3 \) one has

\[
h_i((l_1, l_3)) \frac{\partial \tilde{j}}{\partial l_3} = \frac{\partial \tilde{h}_i}{\partial l_3} h_i(l_3).
\]  

Because \( \tilde{h}_i \) is differentiable almost everywhere, it follows from property (4) that \( \tilde{h}_i \) exists and is continuous. Similarly, by choosing different combinations of null geodesic paths one can show that each \( \tilde{h}_i \) is \( C^\alpha \).

Now, differentiating (II) with respect to \( l_3 \) gives

\[
\tilde{h}_i((l_1), \frac{\partial \tilde{h}_i}{\partial l_3} + \tilde{h}_i((l_1), \frac{\partial \tilde{h}_i}{\partial l_3} = \frac{\partial \tilde{h}_i}{\partial l_3} \tilde{h}_i(l_3).
\]  

Therefore, \( \tilde{h}_i \) is \( C^\alpha \). By repeating the above process, it may be shown that each \( \tilde{h}_i \) is \( C^\alpha \). In other words, \( h \) maps a \( C^\alpha \) parameter on a null geodesic curve to a \( C^\alpha \) parameter.

Let \( \gamma_i; F_i \rightarrow U \) be four \( \gamma \)-null geodesic curves, and \( W \rightarrow U \) be a neighborhood such that the map \( \Gamma; W \rightarrow \gamma \) [an open set of \( B^D \) defined by \( \Gamma(q) = \gamma_i(U(q), U) \) is a \( \gamma \)-diffeomorphism. (Comparison with Minkowski’s space shows that this is possible for \( W \) sufficiently small.) Pairs of the form \( (W, \Gamma) \) form a \( \gamma \)-atlas for \( M \) which is preserved by \( h \). Thus \( h \) is a \( \gamma \)-diffeomorphism.

**Corollary:** A \( \beta \)-homeomorphism is a \( \gamma \)-diffeomorphism.

**Theorem 6:** A \( \beta \)-homeomorphism \( h \) is a smooth conformal diffeomorphism.

**Proof:** Since \( h \) is a diffeomorphism which, locally, preserves null cones, and the metric \( g \) at \( p \in M \) is determined up to a constant by the tangent null cone, \( h \) preserves the metric up to a constant factor which must, since \( h \) is smooth, be smooth.

**Theorem 7:** The group \( \text{Homeo}(M, \beta) \) of \( \beta \)-homeomorphisms of \( M \) coincides with the group \( G \) of conformal diffeomorphisms of \( M \).

**Proof:** By Theorem 6, \( \text{Homeo}(M, \beta) \cdot G \), and it remains to prove the opposite inclusion. Suppose \( E \in \beta \), so that whenever \( \gamma \) is timelike, \( E \cdot \gamma = 0 \cdot \gamma \) for some \( O \in \beta \). Then if \( g \in E \cdot g(E) = g(E) = g(O) = \gamma \). But \( E \cdot \gamma \) is timelike because \( h \) is conformal, and \( E \in \beta \)-open. Therefore, \( gE \in \beta \), and \( g \) is \( \beta \)-open. Similarly, \( g \) is \( \beta \)-continuous so \( g \in \text{Homeo}(M, \beta) \).

It is instructive to give an example of a manifold for which \( G \) is strictly larger than the homothety group. This is not the case for Minkowski space because, though the infinitesimal conformal group is larger than the infinitesimal homothety group, the infinitesimal conformal group cannot be exponentiated to give a global action on Minkowski space. However, consider the manifold \( \mathcal{N} \) obtained by removing the following closed set \( S \) from Minkowski space \( M \).

\[
S = \{ q \in M \mid [x^\theta(q)]^2 - [x^\theta(q)]^2 - [x^\theta(q)]^2 \geq 0 \}.
\]

The conformal group of this manifold is generated by the homogeneous Lorentz group (including space, time, and space–time reversal), dilatations, and the inversion \( I \) given, in coordinates, by

\[
x^\theta(q) = \frac{x^\theta(q)}{[x^\theta(q)]^2 - [x^\theta(q)]^2 - [x^\theta(q)]^2},
\]

\[\mu = 0, 1, 2, 3.\]

In fact, infinitesimal conformal diffeomorphisms which are not infinitesimal isometries are rather rare. DeFrise-Carter\(^5\) has shown that the infinitesimal conformal diffeomorphisms of Lorentz manifolds are with two exceptions, essentially isometries. The exceptions are Minkowski space and the “plane wave” space–times. In the former, there are five linearly independent infinitesimal conformal transformations which are not isometries (the dilations and “accelerations”),
and in the latter, only one (the dilations). Only the homothecy group acts globally on Minkowski space, but \( N \) admits global conformal transformations which are neither isometries nor homotheties.

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\*F. C. Zeeman, Topology 6, 161 (1967).
\*Added in proof: We are grateful to Dr. M. Dobson for pointing out that the inverted commas on "times" are essential. The observer does not measure the length of a time interval—many experiments are required to determine whether a set is open.
\*Added in proof: Rüdiger Göbel informed us that he has a modification of the general relativity analog of \( \mathcal{F} \) which allows the effects of a fixed electromagnetic field to be incorporated. We feel it is preferable to use \( \rho \), thus allowing all timelike curves to be continuous (not just geodesics or particles with a fixed charge in a fixed field).
\*Added in proof: Actually the Zeeman topology, and Göbel's generalization admit spacelike curves as continuous curves.
\*Added in proof: We may also assume \( \mathcal{F} \) to be an open convex normal neighborhood of each of its points.

\*Added in proof: It may also be of interest to note that \( \rho \) is not metrizable, since it is separable but not regular, and neither can \( \mathcal{F} \) arise from a uniformity, since it is not regular, therefore certainly not completely regular.