

Visualizing Spacetime Instability in Theoretical Time Machines

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Abstract

The concept of the time machine opens up a number of research questions in the theory of relativity. Namely, time travel to the past introduces severe challenges to causality through logical paradoxes and structural instability. This paper presents a simulation-based conceptual study that reviews relativity concepts such as closed timelike curves (CTCs), black hole theory, and the Gödel model. Using MATLAB, this study generates simplified visualizations of these models to highlight properties of stable and paradoxical paths within spacetime. These visual models illustrate that time loops, although permitted in certain theoretical spacetime geometries, are highly unstable and inevitably collapse to paradoxes. Ultimately, the study concludes that instability remains the primary theoretical barrier to time travel, demonstrating that while theoretical frameworks allow for CTCs, mechanisms such as the Novikov self-consistency principle are required to maintain causal stability.

Keywords: Time machine, Closed timelike curve, Black holes, Gödel model

1. Introduction

Time travel has been a controversial and enigmatic topic for scientists and the public alike, appearing not only in science fiction but also in real theoretical physics. The meaning of time travel can be explained simply or through the lens of complex scientific principles. Broadly, time travel can be categorized into travel to the future and the past. Time travel to the past is a more controversial topic in physics due to the instability theories behind time machine concepts. This paper aims to explore these specific instability theories to better understand the barriers to retrograde time travel.

The basis of these theories is Einstein's special theory of relativity, which expresses time dilation according to the following equation:

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1)$$

In Equation (1), Δt represents the time measured by a stationary observer, while Δt_0 is the proper time measured by an observer moving with the object. The variable v is the velocity of the object, and c is the speed of light. As the velocity v increases and approaches the speed of light, the denominator becomes smaller, causing Δt to increase. This means that time passes more slowly for the moving object compared to the stationary observer. This effect is known as time dilation.

The Russian cosmonaut Gennady Padalka, who spent approximately two and a half years in space, found that his clock had been ticking at a slower rate than the Earth, a phenomenon that can be explained by general relativity and special relativity (Smart, 1963). After that time in space, his clock had moved him 21 milliseconds into the future. Even though this is a minuscule number, Gennady Padalka's experience demonstrates that time travel into the future is theoretically possible. However, time travel to the past remains severely restricted to the current framework of

physical laws, which inevitably lead to issues with stability and causality. This work discusses and explores these theories to examine the arguments surrounding the possibility of time travel. Ultimately, this paper serves as a simulation-based conceptual study that reviews theoretical models, such as closed timelike curves, black holes, and the Gödel model, and utilizes simplified mathematical visualizations to examine the instability and causality concerns that challenge time-machine theories.

1.1 Prior Art

The concept of time travel first gained widespread popularity through H.G. Wells' 1895 novel, *The Time Machine*. While it began as science fiction, the idea gained scientific credibility in the early 20th century with the development of Einstein's theories of relativity (Aerts & de, 2024). The Special Theory of Relativity (1905) demonstrated that time is not absolute and can flow at different rates. Later, Albert Einstein expanded his idea by describing gravity as the curvature of spacetime, allowing the possibility of closed timelike curves (CTCs). Several works in the scientific literature conclude that time machine theories allow for the possibility of time travel. A few of them are discussed in this paper.

Research by Smart introduces the Schwarzschild metric and related concepts, which mathematically permit the formation of a spacetime loop by bridging a black hole and a theoretical white hole (Smart, 1963). Such geometries arise as exact solutions to Einstein's field equations of general relativity. The author explores several key factors in the context of black hole theory, such as the singularity and the parallel universe. This study considers this work as the base theory and primarily analyzes instability aspects based on the learnings from this paper.

Several works illustrate how instability emerges with time travel to the past. For instance, Gertsenshtein utilizes the framework of the theory of general relativity to study the possibility of the existence of a time machine (Gertsenshtein, 1998). The article states that there are two types of time machines: the Gödel type and the Wells type. The paper mainly focuses on the Gödel-type time machine and related proofs, which demonstrate instability in the solution. This instability leads to the breakdown of causality, where present events could affect the past. An open avenue of research remains to investigate if time travel to the past is possible, or if alternative theories of gravity could be the underlying concepts governing these phenomena

To contextualize these constraints, it is useful to examine the contrasting physics of forward directed time travel. A study by Dixit provides a view on time dilation based on special relativity principles from the perspective of future time travel (Dixit, 2025). Dixit explains that time moves more slowly for the traveler while traveling near the speed of light. To put this into perspective, the fastest object humans have ever created, the Parker Solar Probe, travels at 192,200 m/s—a speed that is still only 0.064% of the speed of light. Expanding on these macroscopic limitations, the foundational review by Smart synthesizes broad physical concepts across relativity, gravitational waves, wormholes, and closed timelike curves (Smart, 1963). It highlights relevant theories in the directions of relativity, black holes, gravitational waves, wormholes, and closed timelike curves. Further, it concludes the challenges for time travel by showing different ways for nature to circumvent time travel possibilities based on mathematics.

In line with these geometric restrictions, a thermodynamic perspective offered in a related study by Volaris utilizes the second law of thermodynamics to explain that time only flows in one direction; even if time allows travel to the future, it prohibits travel to the past (Volaris, 2024). According to the Second Law of Thermodynamics, entropy of the universe is always increasing and can never decrease. This concept is illustrated by Maxwell's demon, a thought experiment introduced by James Clerk Maxwell in 1867. It imagines two chambers containing gas particles with different speeds. A hypothetical demon would control a trap door, sorting the particles by letting fast ones pass to one side and slow ones to the other, which would seemingly reduce entropy. If this were possible, time could, in theory, flow backward. However, it was later explained that the demon itself would create entropy by making measurements and using information, so the second law is never truly violated. This shows that entropy of the universe always increases, and explains why time only flows forward and not backward.

Based on the learnings from the above literature, this article explores key theories with simplified simulations to visualize the stability concerns associated with the time machine. Moving beyond a generalized survey of these barriers, this current study focuses specifically on visually modeling the explicit instability concerns surrounding time

machine evolutions. The study uses these results to clarify and illustrate the current scientific understanding regarding the viability of time machines. Lastly, this analysis examines some of the mathematical solutions available to resolve the issues of instability.

2. Theories behind the time machine

2.1 Closed Timelike Curve (CTC)

A closed timelike curve (CTC) is a way to visualize the event's outcome in a loop with respect to time. Think of a closed timelike curve as a path through space and time that loops back onto itself, theoretically allowing a traveler to meet their past self. It is one of the solutions of Einstein's Field Equation that allows any object to loop back on itself. It can be considered as an indication that a particle or traveler could return to its own past (Gorjup, 2024), (Wu, 2024). In simple terms, a CTC is like an illustration of "loop in time" characteristics. The concept is important from the perspective of time machine theory because it shows how time travel to the past is possible in theory. However, it also further creates problems like paradoxes.

2.2 Black holes

Black holes are exact solutions of Einstein's field equations, where gravity bends spacetime so strongly that not even light can escape. In Einstein's general relativity, a non-rotating black hole is described by the Schwarzschild metric, one of the solutions of the field equation. This metric acts as a mathematical map describing how a perfectly still, spherical mass stretches the space and slows down time around it. It is written as:

$$ds^2 = -c^2 d\tau^2 = -\left(1 - \frac{r_s}{r}\right) c^2 dt^2 + \frac{dr^2}{1 - \frac{r_s}{r}} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \quad (2)$$

Equation (2) describes how space and time change around a very massive object. The spacetime interval ds^2 represents the combined separation between two nearby events in space and time. The variables t , r , θ , and ϕ describe time, distance from the center, and angular direction, while c is the speed of light. In this equation, r_s is the Schwarzschild radius, which defines the event horizon. This is the boundary beyond which nothing, not even light, can escape.

The factor $\left(1 - \frac{r_s}{r}\right)$ shows how gravity affects measurements near a black hole. When r is large, this factor is close to one and spacetime behaves normally. As r decreases, gravitational effects become stronger, changing how time and distance are measured. Each term in the equation has units of length squared, ensuring physical consistency.

A more complicated case concerns the Kerr black hole: a rotating black hole. Its geometry is more complex as the black hole spins, twisting spacetime around it. It does not just pull objects inward, but also drags the fabric of spacetime along with its rotation. If a non-rotating black hole is like a heavy bowling ball resting on a trampoline, a Kerr black hole is like a spinning bowling ball on a trampoline covered in thick syrup—everything nearby is forced to swirl around it. The mathematical form of the Kerr metric is shown below:

$$ds^2 = -dt^2 + \Sigma \left(\frac{dr^2}{\Delta} + d\theta^2 \right) + (r^2 + a^2) \sin^2 \theta d\phi^2 + \frac{2Mr}{\Sigma} (a \sin^2 \theta d\phi - dt)^2 \quad (3)$$

Equation (3) describes how space and time behave around a rotating massive object. Unlike the non-rotating case, rotation introduces additional terms that mix time and angular motion. This means that motion in time becomes linked to motion around the black hole.

In this equation, M represents the mass of the black hole, and a represents its spin. The terms Σ and Δ are functions of r and θ that simplify the expression of the metric and describe how spacetime curvature depends on position. The key feature of this metric is the presence of cross terms involving both dt and $d\phi$, which reflect the effects of rotation.

Because of the black hole's rotation, spacetime itself is dragged around the black hole. This effect is known as frame dragging. Similar to a spoon stirring thick honey, a spinning black hole pulls the very fabric of space and time

along with it. This property of a Kerr black hole results in an additional region called the ergosphere, where objects cannot remain stationary relative to distant observers. Everything inside the ergosphere must rotate in the same direction as the black hole, even if it does not initially have angular motion. This shows how rotation fundamentally changes the structure of spacetime compared to a non-rotating black hole.

2.3 Gödel model

The Gödel model was published by the Austrian-born logician and mathematician Kurt Gödel in 1949 as a solution to Einstein's field equations. This model imagines an entire universe that is constantly spinning, rather than just a single spinning object. In this condition, rotation causes closed timelike curves to appear naturally, meaning that an object theoretically returns to its own past. The Gödel metric is written as:

$$ds^2 = a^2 \left[(dt + e^x dy)^2 - dx^2 - \frac{1}{2} e^{2x} dy^2 - dz^2 \right] \quad (4)$$

In Equation (4), a is a constant related to the overall rotation of the universe in the Gödel model. The term $dt + e^x dy$ shows that time is mixed with spatial motion, which reflects the twisting of spacetime caused by rotation. Because time and space are coupled in this way, spacetime paths can form loops. This allows time to behave differently from ordinary forward progression and makes closed timelike curves mathematically possible in this model.

Although the Gödel model allows time loops mathematically, it does not describe the observable universe. Observations show that the universe is expanding and does not exhibit global rotation. Additionally, the presence of closed timelike curves in the Gödel model leads to violations of causality, meaning that cause-and-effect relationships are no longer well-defined.

2.4 Possible Solution: Novikov correction

Among the fundamental complications that arise because of time travel to the past is the emergence of causal paradoxes. A prime example is the "Grandfather Paradox", which describes how a traveler could go back in time and prevent their own existence. To solve this problem, physicist Igor Novikov proposed the eponymous Novikov self-consistency principle in the 1980s. The principle essentially suggests that the universe has an autocorrect feature, thereby fundamentally preventing any contradictory events from occurring. In other words, if time travel were possible in the first place, events would adjust themselves so that the timeline remains consistent. For example, if someone traveled back in time and tried to stop an event from happening, something else would occur to prevent it, keeping the history unchanged. This principle provides possible solutions to keep CTCs stable. However, it is still uncertain whether such self-consistent loops could exist in reality since quantum effects and instability might destroy them.

3. Methods

3.1 Basic Closed Timelike Curve Model

To provide a conceptual visualization of a closed timelike curve (CTC), a simple parametric model was constructed in three-dimensional spacetime. The spatial coordinates were defined as:

$$x = R \cos(t) \quad (5)$$

$$y = R \sin(t) \quad (6)$$

and the temporal coordinate was represented as:

$$z = h \sin(t) \quad (7)$$

where R denotes the radius of the spatial loop, h represents the amplitude of oscillation along the time axis, and (t) is the curve parameter. The parameter t was varied continuously from 0 to $4/\pi$, generating a closed trajectory in three-dimensional spacetime (Bräuer, 2018). The spatial coordinates form a circular path in the $x - y$ plane, while the temporal coordinate oscillates periodically. As a result, the trajectory repeatedly returns to its initial position in both space and time, providing a conceptual representation of a closed timelike curve.

3.2 Curved Spacetime Representation

To extend the visualization beyond a simple closed trajectory, a curved spacetime surface was introduced using a paraboloid geometry. This representation provides a conceptual analogy to the gravitational curvature surrounding massive objects such as black holes. Although the paraboloid is not an exact solution of Einstein's field equations, it serves as a useful visualization tool for illustrating how spacetime curvature can influence particle trajectories and potentially permit closed timelike curves. The paraboloid surface was defined by:

$$z = r^2 \quad (8)$$

where r denotes the radial coordinate measured from the center of the spacetime well. The particle trajectory was parameterized by:

$$x = r \cos(\theta) \quad (9)$$

$$y = r \sin(\theta) \quad (10)$$

$$t = \sin(2\theta) \quad (11)$$

3.3 Multiple Particle Interactions on a Curved Spacetime Surface

To investigate how multiple objects may behave within a closed timelike curve environment, three independent particle trajectories were simulated on the paraboloid spacetime surface. Each particle followed a distinct parametric path characterized by different phase shifts and temporal oscillations. This approach provides a conceptual visualization of how particles may interact while traversing a curved spacetime geometry containing closed timelike curves. The radial coordinate of each particle was allowed to vary according to:

$$r = r_0 + A \sin(2\theta + \phi) \quad (12)$$

where r_0 represents the average orbital radius, A denotes the oscillation amplitude, and ϕ corresponds to a phase shift that distinguishes individual particle trajectories. The temporal evolution of each particle was represented by:

$$t = \sin(2\theta + \phi) \quad (13)$$

Three particles were generated using different phase offsets to produce unique trajectories. Particle A followed a stable closed timelike curve, Particle B was phase-shifted relative to Particle A, and Particle C included stochastic perturbations representing quantum decoherence effects. The resulting trajectories demonstrate how multiple objects may coexist within a curved spacetime environment while exhibiting distinct temporal behaviors (Bräuer, 2018).

3.4 Novikov Self-Consistency Correction

To examine how causal paradoxes may be resolved within a closed timelike curve, a temporal perturbation was intentionally introduced into the trajectory. This perturbation represents a hypothetical paradox in which a time traveler attempts to alter an event that is already part of their own history. To maintain logical consistency, a correction mechanism inspired by the Novikov self-consistency principle was applied. The paradoxical trajectory was modeled as:

$$tp = t + \Delta t \quad (14)$$

where Δt represents an abrupt temporal displacement that breaks the continuity of the original closed timelike curve. A proportional correction term was then introduced to gradually restore the trajectory toward its original self-consistent form.

$$C = -k(tp - t) \quad (15)$$

where k is a correction coefficient controlling the strength of the self-consistency adjustment. As the correction is repeatedly applied, the perturbed trajectory converges toward a stable closed loop. This model provides a conceptual illustration of the Novikov principle, which states that any event occurring within a closed timelike curve must be self-consistent. Rather than allowing contradictions to occur, the system dynamically adjusts the trajectory so that causal consistency is preserved.

4. Results

Simplified mathematical visualizations of spacetime trajectories are generated in MATLAB, considering the parametric expressions defining the closed timelike curve introduced in the previous section. Firstly, CTC visualization is performed in a 3-D environment. Figure 1 illustrates a three-dimensional parametric curve plotted in space and time. The horizontal axes, x and y , represent spatial coordinates, while the vertical axis represents the time coordinate t . The motion in the spatial plane follows a circular path, since both x and y vary sinusoidally with a fixed radius. At the same time, the time coordinate changes periodically, moving smoothly upward and downward. As the parameter increases, the curve traces a repeating path in space while oscillating along the time axis. After one full cycle, the curve returns to its original position in both space and time, forming a closed loop in three dimensions.

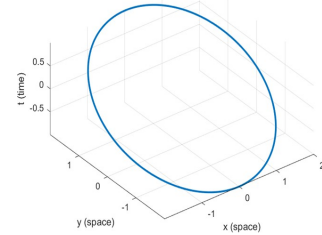


Figure 1. 3D Closed Timelike Curve (CTC) Visualization.

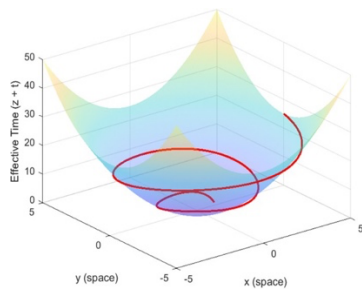


Figure 2. Closed Timelike Curve on a Paraboloid Spacetime Surface.

Next, a closed timelike curve is visualized on a paraboloid-shaped spacetime surface, as shown in Figure 2. The surface has a bowl-like shape that rises outward from the center, representing a curved spacetime geometry. The horizontal axes, x and y , correspond to spatial coordinates, while the vertical axis represents an effective time coordinate. A red spiral curve is drawn on top of the surface, representing the trajectory of a particle. As the particle moves, its path spirals around the paraboloid while also moving upward and downward along the time axis. Rather than progressing monotonically forward in time, the trajectory bends and loops, eventually returning to earlier time values. This creates a closed path on the curved surface, where the particle revisits its starting region after completing one full loop.

Figure 3 illustrates how spacetime is curved under the influence of gravity as described by the theory of general relativity. It presents a three-dimensional visualization of a curved spacetime surface modeled as a paraboloid. The surface is defined by $Z = x^2 + y^2$, which produces a symmetric bowl-shaped geometry centered at the origin.

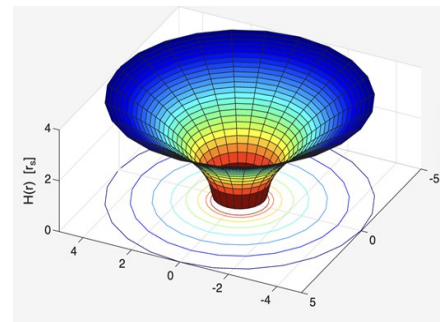


Figure 3. Paraboloid under the influence of gravity.

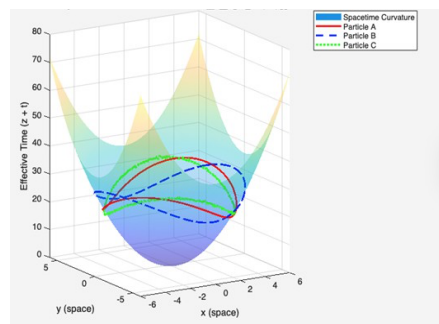


Figure 4. Multiple Particle Closed Timelike Curves on a Curved Spacetime Surface.

A parametric spiral trajectory is plotted on top of this surface, where the spatial coordinates follow $x = r \cos(\theta)$ and $y = r \sin(\theta)$. As the radial coordinate r increases, the trajectory moves outward while descending and ascending along the curved surface. The vertical axis represents an effective time coordinate, defined as the sum of the spatial curvature term and a sinusoidal time component. This causes the trajectory to oscillate vertically as it progresses, producing a looping spiral pattern on the paraboloid.

Figure 4 illustrates three particle trajectories propagating on a paraboloid spacetime surface. The red trajectory represents a stable closed timelike curve, while the blue trajectory is phase-shifted relative to the first particle. The green trajectory contains random perturbations that model quantum decoherence. Although the model is purely conceptual, it demonstrates how different particles may experience distinct paths through a curved spacetime geometry while remaining confined to a common gravitational structure.

Figure 5 illustrates a particle traveling along a closed timelike curve under three conditions: the original trajectory, a paradoxical trajectory, and a self-consistent corrected trajectory. In Figure 5, the original CTC (black curve) forms a smooth closed loop in spacetime,

where the particle returns to its initial spacetime point without any discontinuity. This represents a stable time-loop before any disturbance is introduced. The paradox trajectory (red dashed curve) shows a sudden jump in the time direction halfway through the loop. While the spatial path remains continuous, the time coordinate no longer closes smoothly. This break represents a time-travel paradox, where the particle's future path becomes inconsistent with its own past. The self-consistent trajectory (blue curve) shows the effect of applying the Novikov self-consistency principle. After the paradox occurs, the time coordinate is gradually corrected, smoothing out the discontinuity and restoring a closed loop. As a result, the trajectory becomes continuous again without producing a logical contradiction. These results show that paradoxes disrupt the closure of a time loop, but self-consistent mechanisms can restore a stable closed timelike curve.

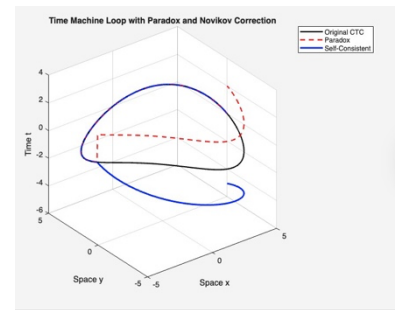


Figure 5. Time machine loop with Paradox and Novikov correction.

5. Discussions

Some solutions of general relativity suggest that time does not always behave as a straight, one-directional line, but can instead form closed loops. In such cases, an object could theoretically return to an earlier time, making time travel to the past appear possible. However, this same feature immediately raises serious problems for causality, since events could influence not only the future but also the past. As illustrated in Figure 1, this tension between mathematical possibility and physical consistency forms the central issue of this study.

This idea becomes more concrete when considering spacetime models in which such closed behavior arises naturally. In a rotating universe, for example, rotation can twist spacetime in a way that allows closed timelike curves to exist. As shown in Figure 2, these closed paths emerge as a direct result of rotation, reinforcing the theoretical possibility introduced earlier. At the same time, the presence of CTCs highlights why these models are problematic: they introduce instability and violations of causality, making it difficult to imagine how a physically realistic time machine could be constructed.

Similar questions arise in more physically motivated scenarios involving strong gravitational fields. Extreme spacetime curvature, such as that associated with black holes, has been proposed as a possible mechanism for time travel, including ideas involving black holes and white holes. Figure 3 helps visualize this curvature, but it also emphasizes the major physical challenges involved. Conditions near singularities represent regions where current physical theories break down, and white holes remain purely theoretical without observational support. These limitations suggest that, although such solutions are allowed mathematically, they do not provide stable or practical mechanisms for time travel.

This instability is further amplified when multiple objects are considered. In realistic systems, more than one particle would be present, and small differences in initial conditions can lead to significantly different trajectories. As shown in Figure 4, multiple particles can follow different CTC-like paths within the same curved spacetime. This sensitivity to perturbations suggests that maintaining stable and consistent time loops becomes increasingly difficult in multi-particle scenarios.

Given these challenges, some theories propose that consistency may be preserved not by eliminating time travel, but by restricting it. The Novikov self-consistency principle suggests that only self-consistent histories are allowed, preventing paradoxes from occurring. As illustrated in Figure 5, paradoxical paths are replaced by self-consistent trajectories that avoid contradictions. While this approach offers a way to address logical inconsistencies, it also reinforces the idea that strict constraints are required, further emphasizing that instability, rather than paradox itself, is the main obstacle to time travel.

5.1 Comparison of Gödel and Black Hole Models

Although both the Gödel universe and black hole models permit the existence of closed timelike curves, they arise

from different physical mechanisms. In the Gödel model, CTCs emerge because of the global rotation of the entire universe, which twists spacetime on a cosmological scale. In contrast, black hole models rely on extremely strong localized spacetime curvature and frame-dragging effects near rotating massive objects. Despite these differences, both models face a common challenge: the formation of causal loops that may lead to instability and violations of causality. As a result, both approaches suggest that while time travel may be mathematically possible, maintaining stable and physically realistic closed timelike curves remains highly problematic.

5.2 Limitations of the MATLAB Models

Several limitations should be acknowledged regarding the MATLAB visualizations presented in this study. The models are based on simplified parametric equations designed to illustrate conceptual features of closed timelike curves rather than exact solutions of Einstein's field equations. The simulations do not calculate gravitational forces, dynamic spacetime feedback, quantum gravity effects, or interactions between matter and spacetime. In addition, the paraboloid geometries are used only as visual analogies for spacetime curvature and should not be interpreted as physically accurate representations of black hole metrics. Therefore, the results provide qualitative insight into possible behaviors of closed timelike curves but do not constitute physical predictions.

5.3 Connection to Instability and Causality

The figures presented throughout this study collectively support the central question of whether closed timelike curves can remain stable while preserving causality. Figures 1 through 3 demonstrate how spacetime geometries may mathematically permit trajectories that return to earlier times. Figure 4 shows that even small variations between particles can generate different temporal behaviors, indicating sensitivity to perturbations. Figure 5 further illustrates how paradoxes can disrupt a closed timelike curve and how self-consistency constraints may be required to restore stability. Together, these results suggest that instability and causality violations remain the primary obstacles to realizing physically meaningful time travel, even when mathematical models allow closed timelike curves to exist.

6. Conclusion

This study reviewed and modeled various theories concerning time machines, focusing on the ideas of instability and paradoxes. The available theories, like those describing black holes, the Gödel model, and the Novikov principle, are studied and analyzed to understand how time travel could work in theory. The visual models illustrate that traveling to the future is possible based on relativity, but there are certain instability concerns for time travel to the past. The study concludes that significant theoretical barriers to retrograde time travel persist within our current understanding of physical laws, suggesting a wide avenue for further exploration of the topic.

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