Interstellar Shortcuts

LUE National Geographic Article

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March 23, 2017
ISCI 3A12 (LUE)

'Wormholes. In the revealing jargon of theoretical physics, the universe was their apple and someone had tunneled through, riddling the interior with passageways that criss-crossed the core.' - Carl Sagan, Contact (1985)

INTERSTELLAR SHORTCUTS

In 1915, Einstein released his theory of relativity stating that the presence of energy warps the fabric of both time and the three dimensions of space - known together as space-time (Rahaman et al., 2007; Al-Khalili, 2011). The release of this revolutionary theory began a quest in the scientific community to solve the field equations which function as a mathematical description of general relativity. Eventually, in 1916, Karl Schwarzchild, a German astronomer, found the exact solution of the equations while laying on his deathbed (Collas and Klein, 2011; Al-Khalili, 2011). In retrospect, it has been identified that the Schwarzchild solution describes a black hole, at which in the centre, there exists a singularity - a theoretical point of infinite density (Al-Khalili, 2011; Thorne, 1994).

INTRODUCTION

Shortly after the Schwarzschild solution was published, Ludwig Flamm realized that the solution could possibly describe what we now call a ‘wormhole’. In 1935, this idea became formalized when Einstein and Rosen proposed theoretical structures, that they named “Einstein-Rosen bridges”, as a possible geometric model to avoid the singularities of infinite mass; in these structures, the singularities become a bridge connecting two parallel universes, as seen in Figure 1 (Collas and Klein, 2011; Al-Khalili, 2011). Since these initial developments, the ideas surrounding singularities and bridges have gotten more accurate and modern. In 1955, John Wheeler extended the idea of connecting parallel universes by demonstrating that these interstellar short-cuts could link curved space-time and result in an intra-universe bridge. Two years later, Wheeler went on to coin the term ‘wormhole’ to describe the bridges that had been discussed in academia for quite some time (Thorne, 1994).

At first, the name “wormhole” may seem like a strange choice for describing astronomical phenomena; however, it arose from an analogy Wheeler made that a worm could chew a hole from one end of an apple, through the center, and come out to the other side, creating a shortcut through the intervening space. Other names you may encounter for different variations of the same phenomenon are: Einstein-Rosen bridge, Schwarzschild wormhole, Lorentzian wormhole, and Morris-Thorne wormhole. All of these names arise from various theories based on different properties and circumstances. For the purpose of this article, we will be generalizing the classifications into traversable and non-traversable (Thorne, 1994).

“The energy sources and requirements for wormholes have been of hot discussion since the mid-20th century.”

Spatially, a wormhole is a compact and simply bounded region of space-time with a complex interior (Visser, 1996). Since they were first proposed, wormholes have been described in various regions of space and in many different coordinate systems. Einstein’s field equations predict that wormhole lifetimes would be extremely short, if existing at all (Thorne, 1994). This is mostly due to the unstable nature of the wormhole arising from the acceleration of infalling radiation due to the gravity of the wormhole. This is because singularities are of infinite density, and so they have really strong gravitational fields. In addition, wormholes have no natural way to be created, unlike black holes; thus, their existence is subject to much skepticism from the scientific community. As many argue, even if they could exist, the likelihood of the two singularities finding each other in space-time so as to create a wormhole is hard to rationalize (Thorne, 1994).

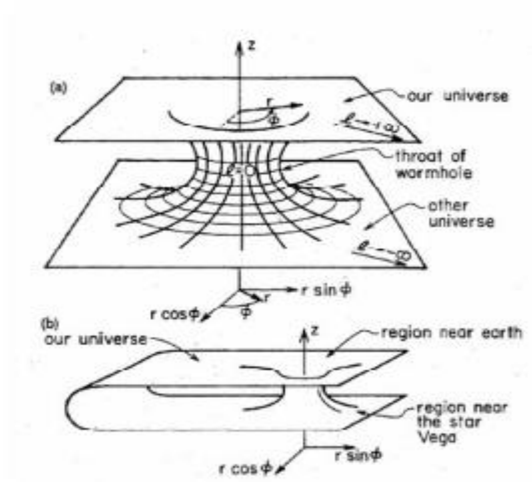


FIGURE 1. WORMHOLE SCHEMATIC. A technical schematic of a theoretical wormhole as described by Wheeler shown as its main throat (above) and as a shortcut between regions in space-time (below) (Getchell, 2003).

THE FEASIBILITY OF WORMHOLES

The nuances of wormhole existence defy physical laws and are subject to much investigation. The energy sources and requirements for wormholes have been of hot discussion since the mid-20th century. In 1955, Wheeler described “geons” which are self-gravitating bundles of electromagnetic fields, helping define **doubly-connected** space. This alluded to Einstein and Rosen’s initial theory which speculated that charged particles with electric fields contributed to the creation of wormholes. In the 1960s, Wheeler and his colleague, Robert Fuller, demonstrated that the Einstein-Rosen Bridge would not be able to remain open if one happened to generate, and would pinch off before even a photon could go through (Cramer, 2000; Getchell, 2003).

In general, wormholes can be placed into two categories: non-traversable and traversable. Non-traversable wormholes are cosmological shortcuts that link two points in space-time. However, there is no possibility of passage from one point to another through this shortcut. Contrarily, theorized wormholes that do consider such passage are known as traversable wormholes - these wormholes will be discussed later in this article.

NON-TRAVERSABLE WORMHOLES

Einstein-Rosen bridges, Schwarzschild wormholes, and Lorentzian wormholes are all examples of non-traversable wormholes (Collas and Klein, 2011). This is because the topology of the connections in space-time stem from solutions to Einstein's field equations, and they can be understood through what is known as the "maximally extended version of the Schwarzschild metric". This maximal extension refers to the idea that space-time should be able to continue indefinitely into both the future and past for any object existing at any given moment. In order to describe how the particle or object would move through this space-time into the future, there must exist a black hole exterior or mouth where a particle can fall in when it is within the **event horizon** of this black hole. In order to satisfy the requirements of being able to continue into past events, there must also exist another exterior or mouth that surrounds a white hole, where particles can leave, but not enter. A white hole is the opposite of a black hole, and so if you consider an observer watching a particle enter a black hole as past events, then you must consider a particle exiting a black hole as viewing future events. We call this future event system a white hole (Collas and Klein, 2011). This is system is shown in Figure 2.
The geometry of wormholes can be thought of as four regions. These regions are often explained using Kruskal-Szekeres coordinates (Figure 3), named after Martin Kruskal and George Szekeres. This coordinate system, which spans the entire space defined by the maximally extended Schwarzschild solution, is used to describe the Schwarzschild geometry for a black hole (Collas and Klein, 2011).

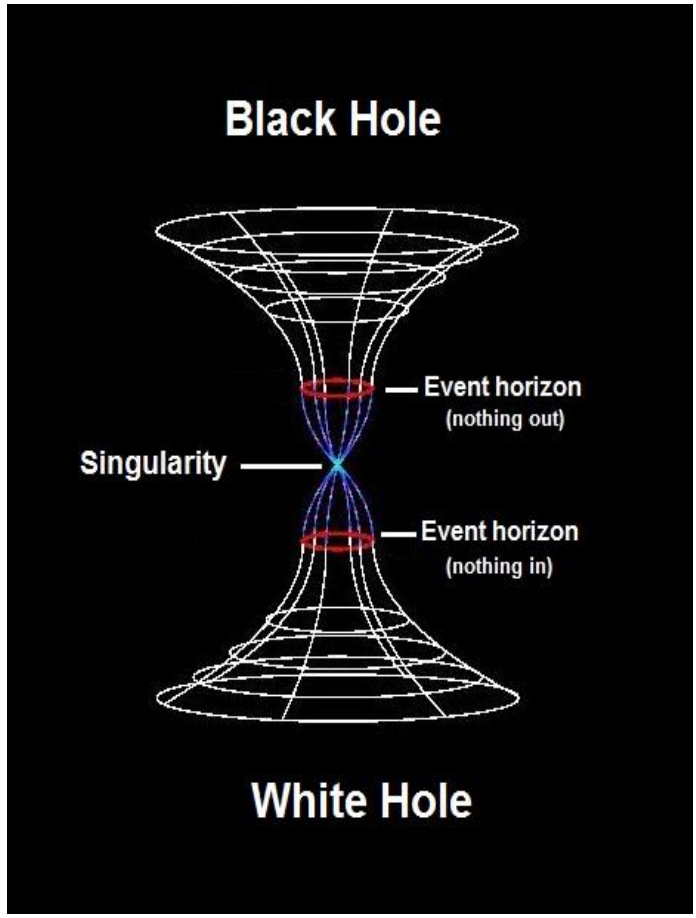
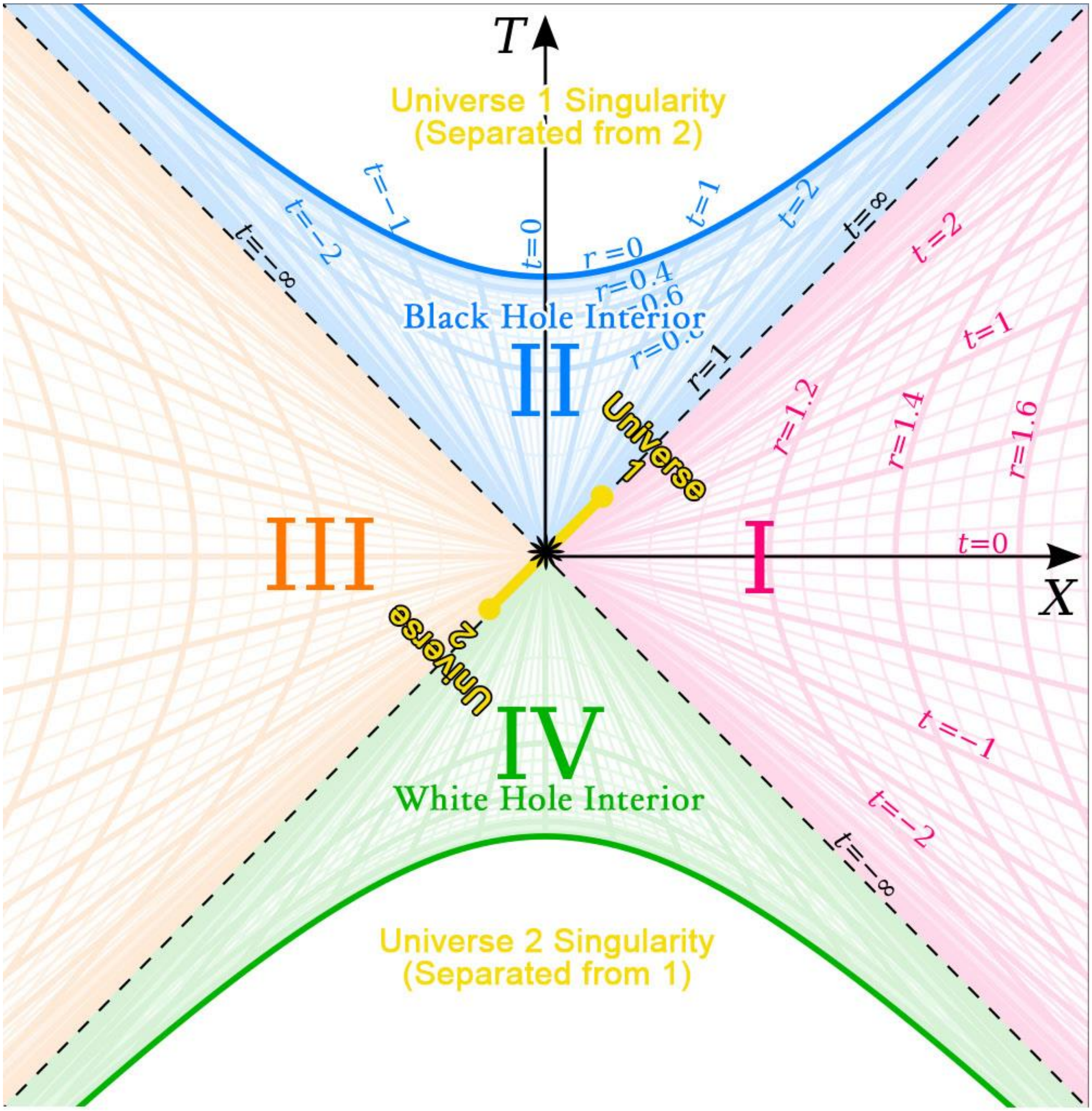


FIGURE 2: A SCHEMATIC OF A BLACK AND WHITE HOLE RELATIONSHIP. A visual of the relationship between black and white holes; note that in the black hole, once a particle has reached the event horizon, it has no choice but to fall in. In the white hole, a particle passing the event horizon will have no choice but to fall out. This makes clear the antonymy of black and white holes (Xiao, 2013; Collas and Klein, 2011).

In Figure 3, quadrants I and III are copies of each other. Quadrant II is the interior of the black hole event horizon, leading into the respective singularity. Quadrant IV is the interior of the white hole event horizon leading into its singularity. This coordinate system depicts the connection of two universes, one consisting of quadrants I and II, the other consisting of quadrants III and IV (Collas and Klein, 2011). In the region defined below the green hyperbola on this coordinate system, the two universes are disconnected and exist as their singularities. When an observer is within quadrant



✷ Point at which maximum throat width is reached, T=0

FIGURE 3. THE KRUSKAL-SZEKERES COORDINATES. This coordinate system is used to describe the topology of a non-traversable wormhole. Coordinate T refers to time, while coordinate X refers to space. There are two singularities at r=0, one for positive T and one for negative T. The negative T describes the time-reversed black hole, also known as a white hole, where particles can escape, but not enter. The pink and orange hyperbolas represent the fabrics defined by the Schwarzschild r coordinate, while the orthogonal lines through them represent the fabric of the Schwarzschild t coordinate. The bolded blue and green hyperbolas represent the singularities of the black and white hole respectively, while the dotted 45° lines that separate the four regions represent the event horizons of the singularities (Martin-Moruno and Gonzalez-Dias, 2009).

IV, they see two singularities joining to form a bridge. This bridge grows and expands until the maximum width is reached at the point T=0. Here the observer is at the center of the wormhole throat, but as time increases past T=0 the bridge immediately begins to narrow again. Once our observer has reached the next singularity, the bridge again pinches off and the two universes are separated once again. In practice, due to the short lifespan of a wormhole, no particle - not even a photon - can pass between universes (Collas and Klein, 2011).

TRAVERSABLE WORMHOLES

In 1988, physicists Mike Morris and Kip Thorne studied the possibility of traversable wormholes by solving Einstein's field equations in a topologically non-trivial manner (Getchell, 2003).

Before delving into the unique energy requirements of these cosmic shortcuts, it is imperative to understand the basic energy conditions of energy and momentum in space-time (Marquet, 2012; Roman, 2004):

1. **Null energy condition (NEC)**
   All time-varying null (equivalent to zero) vector fields have an averaged version of themselves.
2. **Weak energy condition (WEC)**
   All time-like vector fields have positive matter density, as observed by an outsider.

Morris and Thorne discovered that matter threading through the throat of the wormhole should violate the WEC, as the radial pressure exceeds density, causing a negative matter density. In addition to the WEC violation, wormholes also violate the NEC. This is perhaps a more significant fact, as it gives rise to the idea that wormholes cannot be built with currently known physical and cosmological matter. However, this has not stopped physicists from researching possibilities of matter that can be feasible for wormhole creation. One of the more popular candidates that fulfill the energy requirements is known as "exotic matter", a term coined by Thorne. In fact, the occurrence of exotic matter is crucial to the survival of a wormhole (Getchell, 2003).

WHY DO WE ALWAYS GET NEGATIVE MASS DENSITY?

Solutions to Einstein's field equations are the basis on which wormhole theory is developed. By Birkhoff's theorem, it is known that there can only be one vacuum solution to these field equations. The usage of this theorem in solving these equations results in an inequality of the following:

$$\rho(r_0) - \tau(r_0) \leq 0$$

where ρ is the energy density, and τ is the difference between radial tension and radial pressure.

Thus, for a wormhole throat with radius r_0, it should be noted that there will always be a negative mass-energy density, since the $\tau(r_0)$ factor will always be greater than $\rho(r_0)$, given that the wormhole throat violates the WEC (Getchell, 2003).

Exotic matter, put simply, is a type of matter that can exist while violating physical energy conditions and laws. Exotic matter threaded through wormholes will allow for "physically reasonable" **stress-energy tensors,** and stability, which can permit traversable wormholes to survive (Getchell, 2003). Perhaps one of the biggest difficulties exotic matter presents in wormhole construction is relating it to solutions of Einstein's field equations in the form of a general solution. Far from the throat of the wormhole, it is noticed that solutions become similar to that of Schwarzschild's vacuum solution. As seen in Figure 4, within the throat, there is a non-trivial sphere of exotic matter (Chianese, 2017).

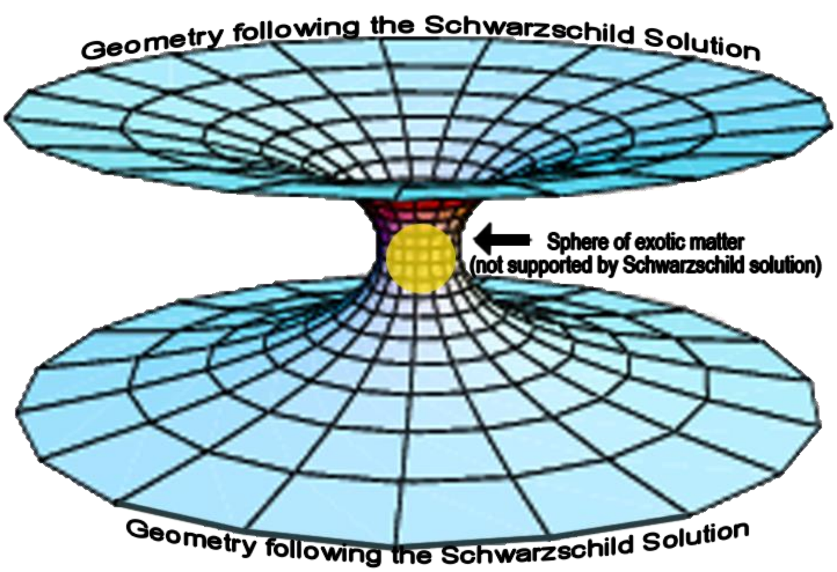
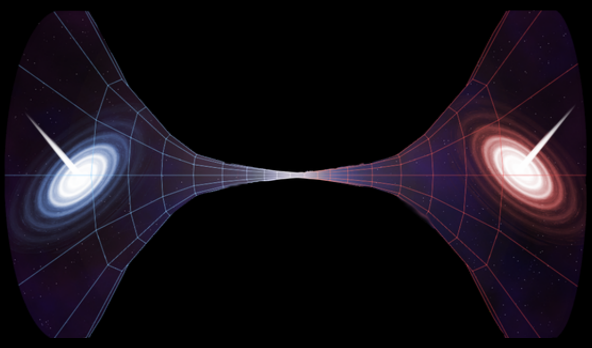


FIGURE 4: WORMHOLE GEOMETRY. A basic concept image of how wormhole dynamics work according to the Schwarzschild solution and with exotic matter (Visser, 1996).

INTERSTELLAR SHORTCUTS

NON-TRAVERSABLE[1]

Connected black hole and white hole singularities.



NULL ENERGY CONDITION (NEC)[2]

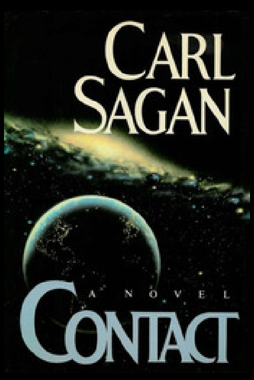
A vector with a positive (future) pointing timeline component will always have an averaged version.

WEAK ENERGY CONDITION (WEC)[2]

For every time-like vector, an observer will view positive matter density.

TRIVIA

CONTACT[4]



Carl Sagan's famous sci-fi novel, "Contact", involving traversable wormholes was worked on with physicist Kip Thorne, and in fact sparked Thorne's interest in researching the topic. Thorne would later go on to publish many of the first papers on traversable wormholes which are considered the fundamentals of current wormhole theory.

NOMECLATURE[4]

The name "wormhole" came from the analogy that a worm burrowing through an apple is like matter passing through space.

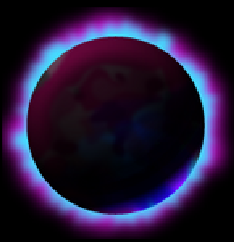
TIME TRAVEL[3]

In order to use wormholes for time travel, we need a stable traversable wormhole large enough for a human to fit through. Currently, we are not able to stabilize such a wormhole. However, maybe a future civilization will be able to?

TRAVERSABLE[5]

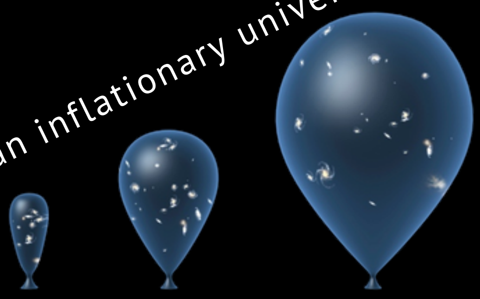
Held open by exotic matter. Their eventual fate is:

Black Hole



OR

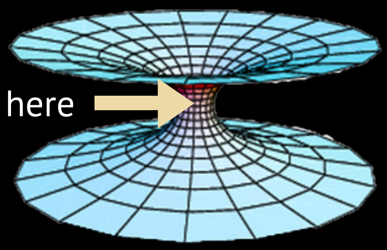
an inflationary universe



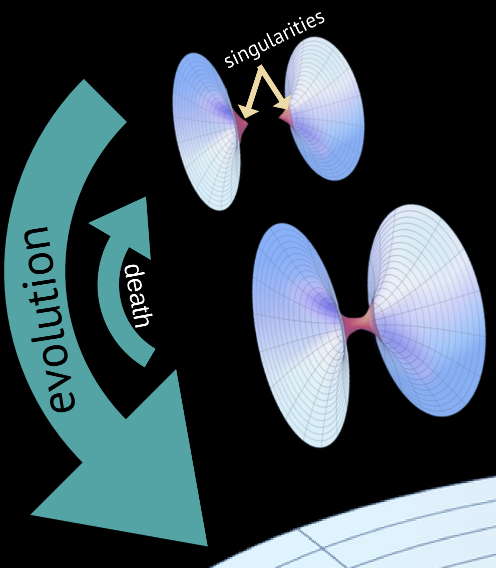
EXOTIC MATTER[2]

In wormhole theory, exotic matter is a unique type of physical matter that helps hold open wormholes.

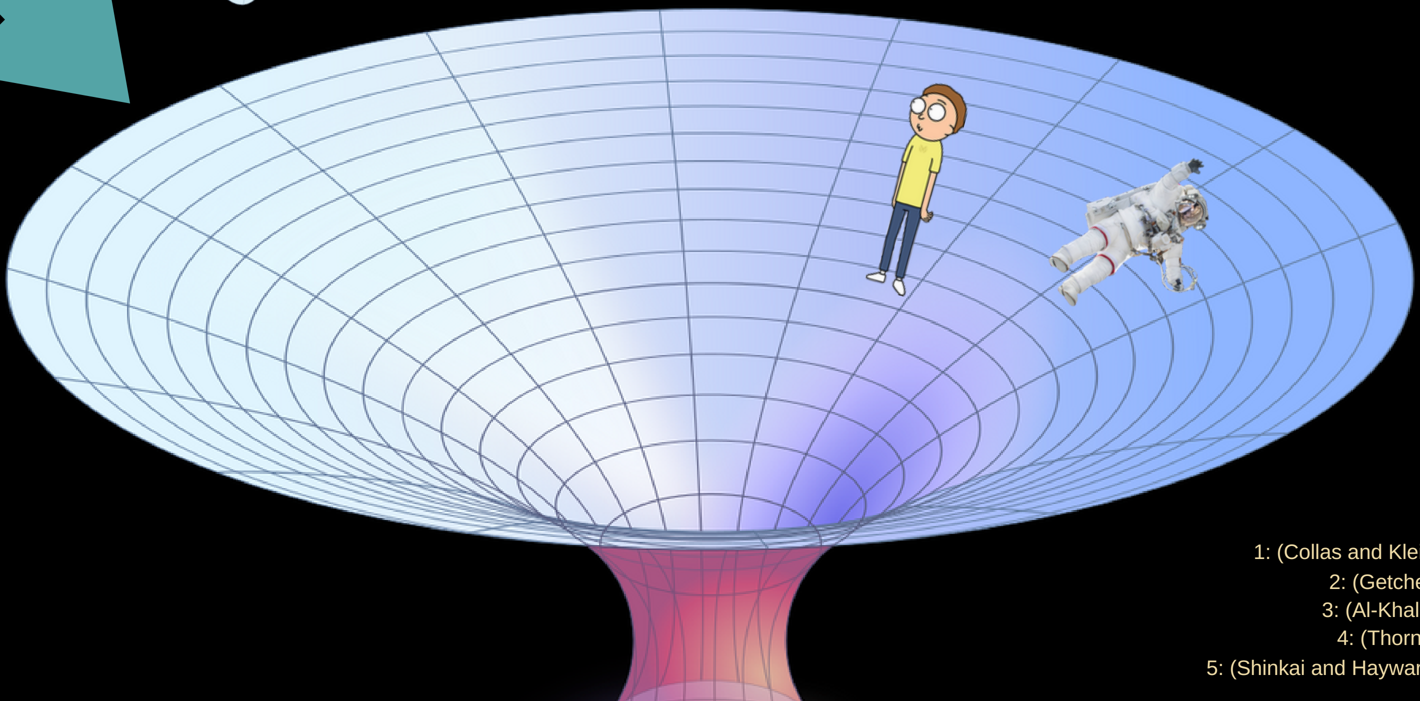
exotic matter here



Unfortunately, exotic matter violates the NEC and WEC and thus is not seen in real life and thus cannot be used to help create wormholes in reality.



In fiction, wormholes are often portrayed as shortcuts humans can take to distant universes. In actuality, traversable are so unstable, that nothing can travel through them before they collapse. 4



1: (Collas and Klein, 2011)
2: (Getchell, 2003)
3: (Al-Khalili, 2011)
4: (Thorne, 1994)
5: (Shinkai and Hayward, 2002)

Research has gone into studying the embedding of Schwarzschild geometry into the throat of the wormhole with exotic matter, while actively modelling different types of exotic models and different numerical considerations (Visser, Kar, and Dadhich, 2003).

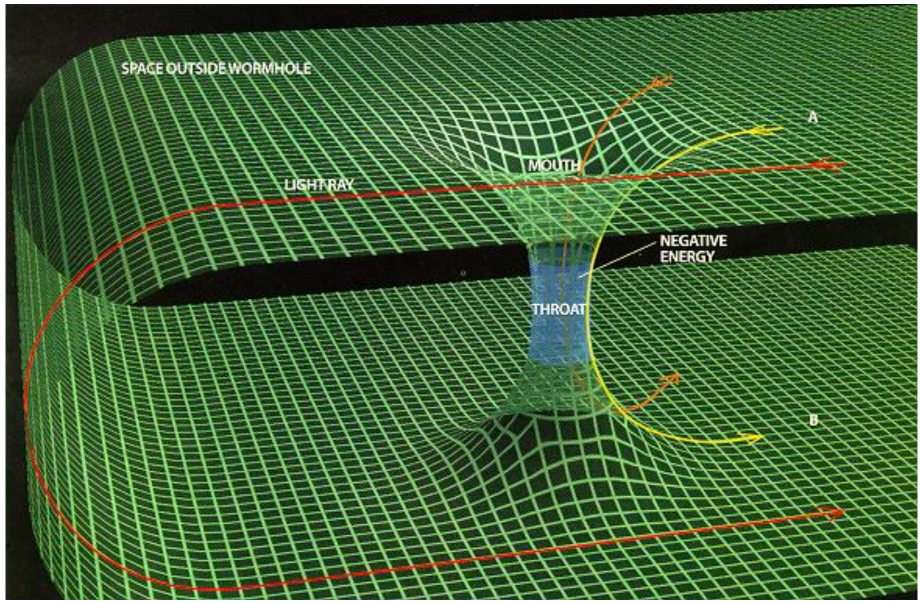


FIGURE 5: WORMHOLE TOPOLOGY. Wormhole topology is shown, outlining the location of each mouth, the throat, and where the negative energy resides. Shown by the orange and yellow lines are the pathways that light can take, and the difference in path length when traversing the wormhole versus when following the fabric of space-time (Thuresson, 2005).

Exotic matter is the most necessary in the throat of the wormhole, where the radius nears zero at the connection between the two mouths. The mouths of a wormhole refer to the two different regions of curved space-time in their respective universes, and the throat refers to the connection between these two mouths, as seen in Figure 5 (Rahaman et al., 2007).

Scientists currently believe that the universe is undergoing accelerated expansion - meaning that the objects in the universe are moving away from each other at an increasing rate. Thus, objects farther away from the observer are moving away at a faster rate. With this knowledge, scientists have come to believe that this phenomenon might be due to exotic matter – in this context, we can think of this matter as negative energy (Rahaman et al., 2007). The idea of negative energy is not one that comes easily to us, as humans only encounter positive energy in our everyday lives (Thorne, 1994).

As its name suggests, negative energy would have the opposite properties of positive energy; thus, if a light beam were to travel through it, the negative energy would gravitationally push outwards on the light beam, causing the rays to pry apart and defocus them as seen in Figure 6 (Thorne, 1994).

In addition to exotic matter and negative energy, another important consideration to make when constructing wormholes is the notion of **quantum inequalities**. Physicists have discussed a type of constraint within a quantum context that restrict the magnitude and time duration of negative energy and exotic matter. Due to these restrictions, there are also limits to the physical structure of traversable wormholes (Kuhfittig, 2011). Quantum field theory suggests that existence of exotic matter and negative energy come from short bursts of positive and negative energy changes called quantum fluctuations (Roman, 2004). While experimentation in a quantum context is not always possible, energy and structure characteristics of wormholes are often predicted using theoretical explorations. A result, or expected value from such an experiment in quantum mechanics is known as the quantum mechanical expectation. Despite not being able to physically build or analyze the wormhole, this expectation can be used to help infer different characteristics of wormholes in their construction, such as the thickness of the wormhole's throat, and length scale of the fluctuations involved in the wormhole (Preskill, 1998).

WHAT IS QUANTUM FIELD THEORY?

Quantum field theory (QFT) is the theoretical framework for quantum modeling of subatomic and quasiparticles with excited states as the base physical field. QFT helps describe different aspects of the energy constraints of wormholes, especially in relation to the nuances of quantum states within wormholes related to exotic matter. It should be noted that QFT violates all classical energy conditions (Finster, 2012)

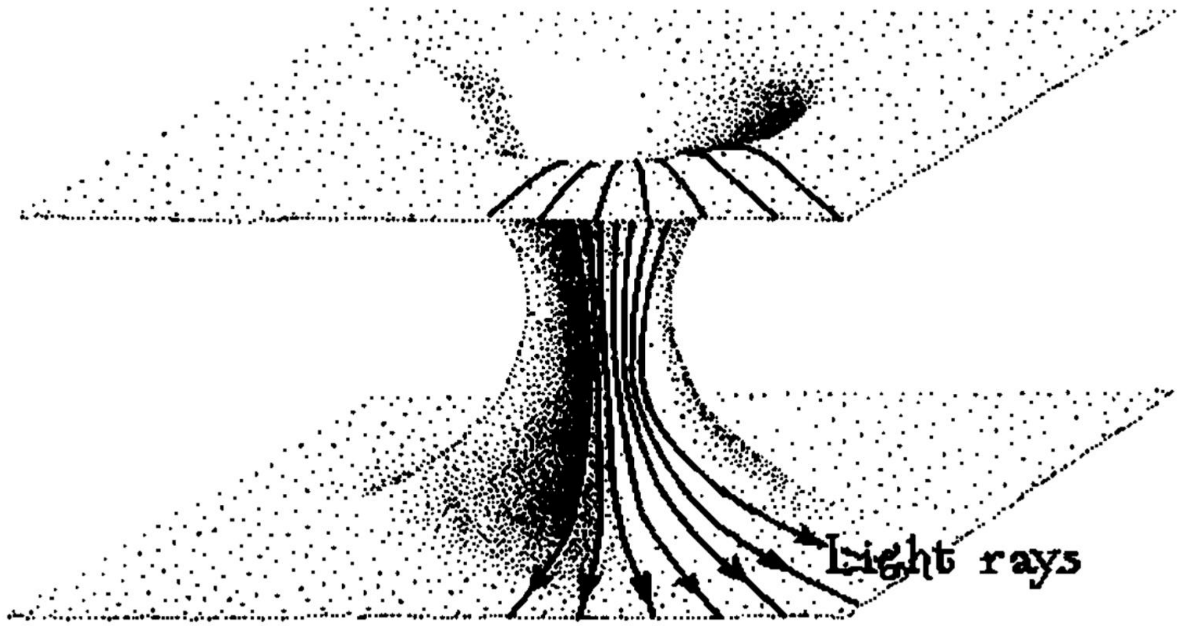


FIGURE 6: LIGHT RAYS ACROSS A WORMHOLE. Due to the negative energy holding the throat of a traversable wormhole open, light rays passing through will be pryed apart as they pass. This is due to the nature of the negative energy, as it must pull matter apart to keep it from collapsing (Thorne, 1994).

The structure of the famous Morris-Thorne traversable wormhole cannot contain event horizons (unlike non-traversable wormholes) around the singularities (Shinkai and Hayward, 2002; Martin-Moruno and Gonzalez-Dias, 2009). We can instead introduce for them the concept of trapping horizons. These horizons are understood to exist at the throat of the wormhole and are known as the "**bifurcation** trapping horizon". The presence of a trapping horizon in wormhole space-time allows the wormhole to be studied through its similar nature to black holes (Martin-Moruno and Gonzalez-Dias, 2009).

EVENT HORIZONS	vs. TRAPPING HORIZONS
a boundary in space-time that when past it, events cannot affect an outside observer, but when within it, the gravitational pull of a singularity is so great that light can't even escape. This boundary is for light in the future (Collas and Klein, 2011).	a boundary in space-time between light rays that are directed outwards and moving outwards, and those directed outwards but moving inward (due to gravitational pull of a singularity). The trapping horizon can be thought of as the boundary in space-time for light at that instant (Martin-Moruno and Gonzalez-Dias, 2009).

TRAVERSABLE WORMHOLE EVOLUTION

Much information about traversable wormholes can be gained from studying mathematical simulations of energy pulses onto the throats that are held open. These pulses can either be positive or negative and can be understood as objects traversing the wormhole. The initially "stable" structure of the wormhole is known to change due to these pulses (Shinkai and Hayward, 2002).

Figure 7 shows how the dynamical system will evolve in space-time with the different pulses. The trapping horizon will move depending on the sign of the energy pulse (Shinkai and Hayward, 2002). This is due to the fact that the wormhole throat suffers a **bifurcation** and will remain static if untouched, evolve to explode and form an inflationary universe, or collapse to a black hole (Shinkai and Torii, n.d). As seen in Figure 7, the throat lies at the center of the diagram where this splitting occurs, and the mouths lie to the left and to the right of it. When you pulse the throat of the wormhole positively, the location of the trapping horizon becomes positive (x plus in Figure 7), like those that occur in expanding universes. Thus, positive energy passing through the throat results in the throat rapidly increasing, causing the wormhole to explode into an inflationary universe. In this case, the evolution of the two wormholes leads to their combination into one universe (Shinkai and Torii, n.d).

When you pulse the throat of the wormhole negatively, the trapping horizon becomes negative (x minus in Figure 7). This negative trapping horizon defines future trapped surfaces, like the types that occur inside of black holes. The evolution of the structure's total radius heads towards zero over time, and this combined with the evolution of the trapping horizon suggests that the wormhole has collapsed into a singular black hole (Shinkai and Hayward, 2002).

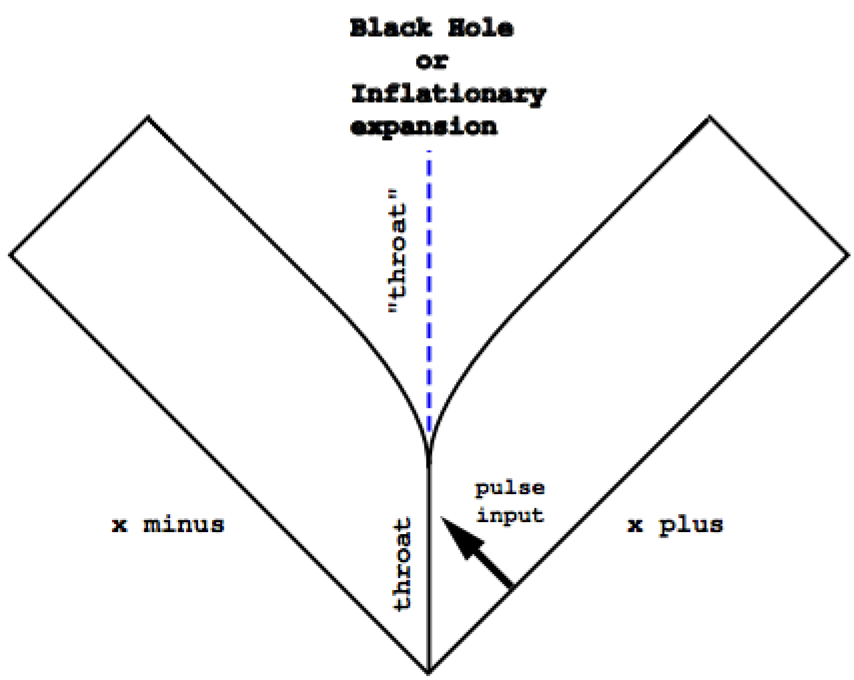


FIGURE 7: PARTIAL PENROSE DIAGRAM. A partial penrose diagram showing the evolution of space-time as negative or positive energy pulses interact with the throat of a traversable wormhole. A Penrose diagram helps to show the relations between different points in space-time where the vertical dimension represents time, and the horizontal dimension represents space where negative space or x minus refers to past trapped regions or events that happened in past defined regions (Shinkai and Hayward, 2002).

The myriad of mathematical models and theoretical setups compiled throughout history has allowed physicists to gain an immense understanding of the physical theory of wormholes. Unfortunately, it is difficult to even conceive building a wormhole within the constraints of our space-time. While wormhole theory is an interesting and hot topic among physicists, its practicality is quite limited due to the lack of necessary energy conditions. For one thing, wormholes are basically physical anomalies in the classical sense, and in the quantum sense, there are many nuances that need to be catered to before we can even think about beginning to construct one.

TEMPORAL WORMHOLES

So far, we have mostly been discussing the possibility of wormholes as shortcuts through space. While this itself is a difficult topic for physicists, it has not stopped others from delving into the temporal realm and treating wormholes as a shortcut through time as well. If wormholes could imaginably be treated as realistic time travel devices, then many of the most preposterous science fiction stories would immediately become less fiction and more science. Thus, the question that is on many people's minds is: Could time-machine wormholes ever exist in the way that we have seen them in fiction like in 'Interstellar' or "Doctor Who"?

The first step of building a wormhole time machine is finding a suitable wormhole. While classically, this may seem unlikely, if we take a different approach, we may find something more promising. First, consider the smoothest object that you can think of – say a slab of marble or a piece of glass. When you look more closely, you will always be able to find a level at which there are small gaps (Hawking, 2010). Similarly, there is a theory stemming from quantum mechanics which states that if you examine space-time on the scale of 10^{-33} (100 Planck lengths), then rather than a smooth expanse, you eventually see probabilistic foam. This is known as 'quantum foam', a term coined by Wheeler in 1955 (Thorne, 1994; Baird, 2007). This probabilistic foam defines small, fast changing regions for which space and time are no longer definite – instead, they fluctuate (Phys.org, 2015). On this scale, any conceivable distortions of space-time will be randomly appearing and disappearing (Al-Khalili, 2011).

One of the possibilities for creating a large wormhole suitable for time travel is if an advanced civilization with much better technology than us could manipulate quantum foam. Quantum foam is thought to contain 'quantum wormholes' – charged perturbative quantum matter that act as versions of the traversable wormholes connecting black holes and white holes (Engelhardt, Freivogel and Iqbal, 2015). Thus, in theory, if an advanced civilization were to distort the foam, it may be possible to open up and inflate a pre-existing 'quantum wormhole' to a scale at which it could be utilized for time travel (Baird, 2007). Unfortunately, this is where the hope of quantum wormholes for time travel becomes even more hypothetical than before. The creation of a wormhole from quantum foam almost always has the caveat of an advanced civilization for one very specific reason – we really don't have any idea how one might go about doing that. However, there are some possibilities proposed; one of these utilizes the history of our universe as a case study (Al-Khalili, 2011). When the universe first began, it underwent rapid inflation after the Big Bang. It is thought that the tiny quantum fluctuations expanded into huge irregularities during this inflationary period – these irregularities provided variations in density that produced the galaxies. If this theory is true, then perhaps inflation is what is necessary to harness a tiny wormhole and raise it to an astronomical scale. In order for the universe to inflate, there must have been some outward pressure that opposed the inward pull of gravity; theoretically, if we were able to apply a similar pressure onto a very small region, we could cause our own controlled inflation which may be able to create a human-scaled wormhole (Roman, 1992; Al-Khalili, 2011).

Although, the creation of a large wormhole is thus far unclear, when talking about time travel, it is still important to consider next steps for building a time machine if a macroscopic wormhole were possible. After the creation of a wormhole, the next step is to stabilize it. As discussed earlier, in order to stabilize a traversable wormhole, exotic matter would need to be threaded through (Getchell, 2003). Then, the wormhole must be transformed into a 'time machine' using Einstein's theory of special relativity. As shown in Figure 8, this theory states that if one object is accelerated to near light speed, then due to a time delay relative to a stationary observer, the accelerated object has passed through less time than the stationary object if they were to come together and compare time passed since last met (Anderson, 2012). This idea can be applied to wormholes to try to transform them into time machines. First, the time machine builder would need to electrically charge one of the wormhole mouths so that it can be moved with an electric field, and loaded onto some vehicle that can travel at speeds almost at that of light (Al-Khalili, 2011). Due to special relativity, as only one wormhole mouth is accelerating, the moving wormhole mouth's 'time' moves slower than the stationary mouth's time. The final step is to move the mouths to the same place where they are both stationary again, and thus in the same reference frame; then,

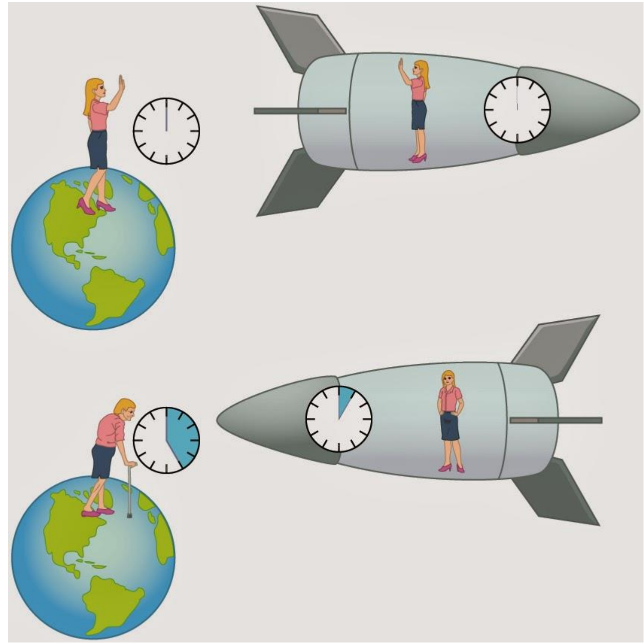


FIGURE 8: SPECIAL RELATIVITY. The above image shows how in special relativity, the forward motion of time for a stationary observer, say on Earth, would move much faster when compared to the forward motion of time for an observer moving on a spaceship at near-light speeds. If we imagine the person on Earth and the person on the space ship to be two wormhole mouths, this image can depict how a wormhole time machine could be created (Anderson, 2012; Johnson, 2014).

the two mouths have the same spatial location, but different ages (Anderson, 2012; Al-Khalili, 2011).

So far in our discussions of wormhole time machines, the main issue that has arisen is the challenge of finding or creating a suitable wormhole. Unfortunately, the issues with our time machine do not stop there. One important thing to consider is what will happen to our wormhole when the mouths are moved back to the same spatial location. In theory, moving the wormhole mouths back together would cause a feedback loop of electromagnetic radiation which would destroy our meticulously built wormhole. This would occur by virtue of the time shift that was just placed upon the mouths (Hawking, 2010; Al-Khalili, 2011). It is expected that light that had travelled through the wormhole can get back to the mouth it entered spatially at a time before it has even entered; that is, if light travelled through the younger mouth to the older mouth, then that light can exit the older mouth and return to the younger mouth 'before' the original light even goes through. In this way, there is twice as much radiation going through. However, this can keep doubling because then the already doubled radiation undergoes the same phenomenon until the magnitude of radiation grows very large. Thus, as soon as the two mouths are brought together, an infinite amount of light will have built up and the wormhole will be destroyed (Thorne, 1994).

> "In the distant future, it is possible that a wormhole time machine could be created by enlarging a quantum wormhole."

In the distant future, it is possible that a wormhole time machine could be created by enlarging a quantum wormhole, stabilizing it, and then accelerating one of the mouths to induce a time shift. Unfortunately, theoretical time machines created in this way have unresolved issues. For one, the creation of a human sized wormhole by enlarging a small one found in quantum foam is very theoretical, and it is not known how it could be done. As well, once the time machine is created, a feedback loop of radiation would likely destroy it.

So, in the end, the answer to our initial question of whether wormholes could act in the way we have seen them behave in fiction is dependent on your view; namely, do you trust future civilizations to solve these practical issues?

CONCLUSION

Since the early 1900s, wormholes and the idea of travelling through different points in space-time have been investigated by many physicists. Thanks to the initial work of physicists such as Einstein, Schwarzschild, Wheeler, and Thorne, wormhole theory has become greatly developed and is still being studied by astrophysicists today. Unfortunately, despite the immense amount of enthusiastic research that has gone into trying to understand how to construct wormholes within our space-time, there does not seem to be much possibility as of yet. The fact that wormholes require exotic matter that violate classic energy conditions, namely the WEC and NEC, that are not found in real life, hinders the development of wormhole creation. Before exploring the possibility of creating a wormhole in real life, it is imperative to find this exotic matter, or at least real and feasible substitutes that can be used instead. There have been several advancements in wormhole research that encourage feasibility with material that currently exists. These advancements include looking into the amount of exotic matter required, the possibility of wormhole creation via charged electric fields, and using existing **anisotropic** matter sources in the universe instead of exotic matter (Kuhfittig, 2011; Rahaman, Kalam, and Rahman, 2008). For now, it seems almost impossible to create a stable wormhole, let alone travel through it. Most current literature seems to suggest that without exotic matter, the throats of wormholes will not be able to be held open gravitationally for any amount of time for anything - even a photon - to go through. Unfortunately, the need for exotic matter is perhaps the biggest obstacle preventing real wormholes from being constructed or even conceived. Once this is combated, physicists can move on to the more advanced uses of wormholes, including time travel and perhaps multi-dimensional travel. For now, we likely need to come to terms with the idea that we will not get the opportunity to transport to different places via a wormhole. However, we can hope that the theory and practicality progresses enough such that it may happen in the distant future.

GLOSSARY

(in order of appearance)

BIFURCATION: the division of something into two branches or parts

DOUBLY-CONNECTED: A space where there exist two independent, non-mergeable paths between any two points in that space.

STRESS-ENERGY TENSOR: A geometric object relating density, energy flux, and momentum in space-time. In a mathematical sense, it is viewed as a series of vectors relating these quantities with associated scalars and operations. This tensor is fundamental to the gravitational field used in Einstein's field equations.

QUANTUM INEQUALITY: Quantum field theory imposes certain constraints on negative energy - the type of energy required to successfully construct a wormhole. These limitations and restrictions on such energy conditions due to quantum field theory are known as quantum inequalities (Roman, 2004).

ANISOTROPIC: Anisotropic refers to the idea that a material's physical property is different in one form or direction rather than another. For example, a piece of wood is easier to cut along the grain than against. Another way of describing such matter is "directionally dependent".

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