Wormhole Engineering in Orion's Arm:
An Overview

Adam Getchell
University of California, Davis
First Version: 9/09/2005
Second Version: 1/14/2006

Abstract

Wormhole travel through a Morris-Thorne-Kuhfittig metric is described. Kuhfittig's description of a traversable wormhole is revisited, and the Morris-Thorne engineering requirements for traversable wormholes are discussed at length, giving useful parameters for physical size, mass, interior geometry, travel times, constraints upon velocity, tidal forces, and stability regimes. Wormhole construction, stabilization, and the consequences of destabilization are discussed, with their attendant effects upon wormhole placement. Wormhole networks and the issues of chronology protection are covered. Non-traversable wormholes, used in communication and computation are discussed. These will be seen to form a separate phylum of wormhole, and the methods for their construction and stabilization are examined. Finally, more exotic wormhole phyla are briefly mentioned.

In this context, although the background has been written for the fictional shared universe of Orion's arm, the theory and results described are detailed and supported by scientific literature on wormholes as recent as August 2005. Naturally, speculative matters such as wormholes can be said to have critics (to put it mildly), but as of the date of this paper no theorems explicitly denying the possibility of traversable wormholes have been published in the literature. As in many instances, the "what-if" scenario described herein provides powerful incentive to exercise the theoretical bounds of wormhole engineering.

"A wormhole is any compact region of spacetime with a topologically simple boundary but topologically non-trivial interior."

– Matt Visser, 26A.T.

Wormholes are artifacts of spacetime engineering which provide rapid traversal across distances that would normally require decades, centuries, or millennia to cross. The Wormhole Nexus, or simply Nexus, is the foundation of modern galactic commerce.

Wormholes are topologically related to Black Holes, and arise naturally in physical theories that explore the precepts of general relativity. Although a rich and diverse topic, this article will concentrate upon the practical spacetime engineering of wormhole construction, leaving theoretical flights of fancy to other articles.

"It turns out that there are very simple, exact solutions of the Einstein field equations, which describe wormholes that have none of the above problems. If, somehow, an advanced civilization could construct such wormholes, they could be used as a galactic or intergalactic transportation system and they might also be usable for backward time travel."

– Michael Morris and Kip Thorne, 18A.T.

Travel

Modern traversable wormholes can be divided into a number of regimes for descriptive purposes: discussion of the engineering rationale for these regions follows.

Passage through a wormhole begins with docking at the transport station orbiting one of the mouths of the wormhole. The mouth is the region where the wormhole metric becomes asymptotically flat. This station is traditionally called Exit Station, as the travelers are exiting this region of spacetime. Passage through a wormhole from mouth to throat is passage through a series of increasingly smaller spheres; the minimum radius sphere is at the throat.

These stations are located at a distance where the gravity from the wormhole is comfortable for station travelers. With modern wormhole construction, the gravitational monopole mass is small enough that the distance from the station to the throat of the wormhole is constrained purely by asymptotic flatness, which is uniformly 327 A.U. (0.0052 ly) for all traversable (Morris-Thorne-Kuhfittig) wormholes.

From the mouth of the wormhole to 3 A.U. (.00005 ly) distant from the throat is the Transition, the region where the wormhole metric has been engineered to minimize the final mass of the wormhole mouth. Spacetime curvature effects and tidal stresses are relatively mild, and most vessels have already accelerated to maximum velocity, executed turnaround, and are decelerating for final approach.

From 3 A.U. to the throat of the wormhole is the Vortex. Spacetime closes in around the ship exponentially with decreasing distance, and velocities attained in the Transition can be fatal in the Vortex. The diverging null-like geodesics from the Caustic can be seen in the forward view, and the ship continues to decelerate towards rest.

Finally, the Throat, the region of maximal spacetime constriction and linkage to the destination spacetime, is reached. The Caustic, the thin ANEC-violating shell around the throat and the *sine qua non* of spacetime engineering, disrupts computation and communications as the spacetime manifold becomes hyperbolic. Light paths with small incidence angles to the Caustic form null geodesics which wind one or more times around it[1], creating an infinite set of relativistic images. Any observers would notice two disruptions, as the vessel passes from the Caustic to the Throat and back out. Tidal and shear stresses are maximal, and this is the most hazardous phase of the journey. Contact with the boundaries of the Throat lead to exposure to immense gravitational tides; ships making actual contact with the Throat are shredded by gravitational stress and strain, and even small energy releases turn into violent sprays of energetic radiation which can disrupt or destroy computational or hibernation substrates.

Since neither effective communication nor computation can occur in the Caustic around the Throat, the vessel shuts down and is essentially ballistic. The size, g-tolerance, and acceleration of the vessel determine the length of time required to traverse the Netherworld – the traditional name of this transition.

Exit from the Netherworld begins acceleration and turnaround back out towards Entrance Station.

As any object within the mouth of a wormhole experiences both tidal and shear stresses proportional to their linear or angular velocity, travel time is usually constrained by the g-tolerance of the traveler. For a typical sophont capable of sustaining 1 earth gravity of transverse tidal stress per 2 meters, the transit time from Exit Station to Throat takes ~52 days, for a total trip time of 103 days. In practice, most sophonts undergo hibernation during transit; this lessens the transit time by increasing allowable acceleration, and adds an additional safety margin for maneuvering.

Modern Wormhole Ferries are capable of crossing from Exit Station to Entrance Station in 32 days. They typically provide lavish virtual-reality environments; the most expensive ferries have facilities for Known Net access during most of the journey. Of course, all communications and virtual realities shut down during passage through the Netherworld.

Engineering

The basic wormhole engineering criteria were delineated long ago by Morris and Thorne[2]:

1. Spherically symmetric, static metric
2. Solutions of the Einstein field equations
3. Throat connecting two asymptotically flat regions of spacetime
4. No event horizons
5. Bearable tidal gravitational forces as experienced by travelers
6. Reasonable transit times with respect to all observers
7. “Physically reasonable” stress energy tensor
8. Stable against perturbations
9. “Physically reasonable” construction materials

Deviations from these criteria will be discussed as they arise. Spherically symmetric, static wormholes will be discussed first, as the vast majority of traversable nodes in the Wormhole Nexus are comprised of this type.

Consider the classic general metric in Schwarzschild coordinates which describes black holes, wormholes, and the interior of stars:

$$ds^2 = -e^{2\gamma(r)}dt^2 + e^{2\alpha(r)}dr^2 + r^2 d\Omega^2$$

γ delineates the redshift function; α delineates the modified shape function, both are functions of the radial coordinate.

The shape function is given by[3]:

$$b(r) = r(1 - e^{-2\alpha(r)})$$

The radial coordinate describes the geometry of the metric; from the perspective of the traveler, the proper radial distance is given by:

$$l(r) = \int_{r_0}^{r} e^{\alpha(r')} dr'$$

The practical engineering constraints to viable, traversable wormholes are as follows:

Spherical and Stable: It turns out that the original wormhole as proposed by Morris and Thorne is unstable[4] in interesting ways. In particular, the wormhole solution is stable to linear perturbation, but has non-linear instabilities that cause either explosion to an inflationary universe, or collapse to a black hole. For collapse, a certain fraction of the wormhole mass-energy is radiated away; the rest becomes the mass of the black hole. For explosion, radiated energy self-reinforces leading to inflation.

Apart from non-linear stabilities, all wormholes have the ability to form Closed Timelike Curves, either via special relativistic motion or general relativistic time lapse. Observation has shown that the Hawking Chronology Protection Conjecture[5] is correct. Specifically, the establishment of an exterior CTC creates a Cauchy horizon around the wormhole throat which generates quantum perturbations that lead to its destruction. From certain perspectives this is equivalent to the generation of Visser radiation between the mouths.

Solutions of the Einstein Field Equations: The modified Morris-Thorne-Kuhfittig metric, the basic blueprint for spacetime engineering, satisfies these criteria, as well as the more exacting criteria given by modern M-theory and Chronodynamics. It is essentially a piecewise function engineered to have desirable properties.

In the region $\boldsymbol{r_0}$ (throat radius) to $\boldsymbol{r_1}$ (the Caustic):

$$\alpha_1(r) = \ln \frac{K}{(r - r_0)^x} \quad , 0 < x < 1$$

$$\gamma_1(r) = -\ln \frac{L}{(r-r_2)^y}$$, $0 < y < 1$ and $0 < r_2 < r_0$ to avoid an event horizon at the throat.

To preserve the correct values for the derivatives of α and γ and satisfy the Ford-Roman Quantum Inequalities[6]:

$$y = \frac{r_1 - r_2}{r_1 - r_0} x$$

In theory x > .5, but in practice x ~ y ~ .5.

In the region $\boldsymbol{r_1}$ to $\boldsymbol{r_3}$ (the Vortex)

$$\alpha_2(r) = \frac{x(r_3 - r_0)}{r - r_0}$$

$$\gamma_2(r) = -\frac{y(r_3 - r_0)}{r - r_0}$$

The value of $\boldsymbol{r_3}$ is chosen to be 0.00005 ly to fix the constants K and L in the Caustic metric; the Vortex metric cuts off the eventual negative values that the Caustic would produce.

In the region $\boldsymbol{r_3}$ to ***a*** (the Transition), the shape function is given by[7]:

$$b(r) = r_0^2 / r$$

$$\gamma \approx 1$$

Where ***r*** is the radial coordinate and ***a*** is the radius of the wormhole mouth. Note that this also gives the mass of the wormhole as:

$$M \approx \frac{c^2 r_0^2}{2Ga}$$

Where **c** and **G** are the speed of light and gravitational constant respectively. In the modified MTK metric, the value of ***a*** is always 4.9192×10^{13} meters (since the throat size can be neglected), giving a typical wormhole of 100 meters radius a mass of 1.36×10^{17} kilograms (compare with the mass of Ceres at 8.7×10^{20} kilograms).

The Transition metric is an idealization which gives a lower limit to a modified MTK wormhole. In practice it is not ever achievable; however, the incentives for doing so are powerful. The canonical MTK metric normally has the Vortex metric extend through the Transition; such a wormhole has a mass given by:

$$M \approx \frac{c^2 a}{2G}$$

A typical 100 meter radius wormhole would then mass 3.31×10^{40} kilograms, or 1.67×10^{10} solar masses, a substantial fraction of the Milky Way. Such wormholes are not practical, so the degree to which the wormhole architect can produce a spacetime with the desired Transition layer determines the amount of mass-energy necessary for construction. Earlier wormholes required much more mass for the same throat size; modern spacetime engineering has reduced considerably the mass constraints of wormhole construction to orders of magnitude within the idealized value given above.

Asymptotic Flatness: Wormholes connect two regions of space not normally adjacent to each other. These regions of space must reduce to Minkowski-flat spacetime, or equivalently, be described by a Calabi-Yau manifold. Violation of asymptotic flatness results in wormhole destabilization, as described above.

Mathematically, this corresponds to a "flare-out" condition, wherein the wormhole metric expands from the throat to an asymptotically flat region. This is the Transition, as described above.

Theoretically, the manifolds connected by the wormhole do not have to be equivalent, although all known examples are equivalence classes.

No Event Horizons: This translates to the requirement that the redshift function be non-zero everywhere. This is the classic difference between a wormhole and a black hole, since a non-zero redshift function can only be accomplished if the spacetime possess a region violating the Averaged Null Energy Condition (ANEC).

This was referred to in ancient times as "exotic matter", but there are in fact at least three known sources of negative stress-energy tensor fields:

1. Quantum Fluctuations: Quantum fluctuations occur in classical quantum field theory in scalar fields describing photons and neutrinos. Such fields are governed by the Quantum Inequalities first formulated by Ford and Roman, and can be classically observed in the Casimir effect (although practical wormhole construction is impossible using Casimir fields). Such fields form the extraction kernel of a Weylforge.

2. Inflaton: The inflationary scalar field which caused expansion of the current Universe. One of the unanswered mysteries remains the status of the "Landscape", the enormous phase space of M-theory compactification parameters. A local minimum of the Landscape is responsible for our current Universe.

3. Phantom Energy: The accelerated expansion of the Universe may be attributed to the approximately ~70% of mass-energy known as dark energy, or quintessence in some Cosmological models. Candidates for dark energy include ghost scalar fields[8] and axions[9], and phantom energy traversable wormholes have been shown to exist[10] which are capable of accreting dark energy and expanding sufficiently fast to

overtake the accelerated expansion of the Universe. Such models will not be considered, but the construction of Hayward wormholes from Black holes will be briefly mentioned.

Bearable Tidal Forces: A would-be traveler through a wormhole is subject to tidal forces. For pure radial motion (e.g. towards the throat, no angular motion) the wormhole will exert tidal accelerations that can be broken down into radial and transverse components.

These tides are most extreme in the vicinity of the throat:

$|\gamma'| \leq \frac{2gr_0}{(1-b')l}$ Where g is bearable acceleration and l is the length

$\gamma^2 \beta^2 \leq \frac{2gr_0^2}{(1-b')l}$ Where γ here represents the Lorentz factor

The first equation is a limitation on the wormhole shape function, which is amply satisfied by the modified MTK metric. The second equation limits the transit velocity of the throat. A handier, but inexact formula for a more general metric yields throat traversal velocity:

$$v \leq r_0 \sqrt{\frac{4g}{l}}$$

For the typical 100 meter wormhole, 1 earth gravity of tidal force per 2 meters is generated by a transit velocity of 442 meters per second.

Vessels that execute non-radial motion are also subjected to shear stresses in the most general case, although circular orbits do not produce shear stresses. These formulae are complicated functions of the Riemann tensor:[11]

For a traveler moving with 4-velocity V^μ, a separation vector ξ^μ between two points yields a difference in acceleration between the two points of:

$$(\Delta a)^\mu = -R^\mu_{\alpha\nu\beta} V^\alpha (\Delta\xi)^\mu V^\beta$$

Where the Riemann tensor is defined by:

$$R^\alpha_{\beta\gamma\delta} \equiv \partial_\gamma \Gamma^\alpha_{\beta\delta} - \partial_\delta \Gamma^\alpha_{\beta\gamma} + \Gamma^\alpha_{\sigma\gamma}\Gamma^\sigma_{\beta\delta} - \Gamma^\alpha_{\sigma\delta}\Gamma^\sigma_{\beta\gamma}$$

And the affine connection or Christoffel symbols (which are not tensors) are defined by:

$$\Gamma^\alpha_{\beta\gamma} \equiv \frac{1}{2} g^{\alpha\sigma} (\partial_\gamma g_{\sigma\beta} + \partial_\beta g_{\sigma\gamma} - \partial_\sigma g_{\beta\gamma})$$

Where $g^{\mu\nu}$ is the matrix inverse of the metric $g_{\mu\nu}$. Since by definition $V^{\mu}(\Delta\xi)_{\mu}=0$ (that is, velocity is perpendicular to separation vector) then this leads to $(\Delta a)^{\mu}V_{\mu}=0$, allowing decomposition of non-radial tidal accelerations as:

$$(\Delta a)^{I} = Q^{I}_{J}(\Delta\xi)^{J}$$

Then, picking an orthonormal frame (denoted by hats):

$$V^{\hat{\mu}} \equiv (V^{\hat{t}}, V^{\hat{r}}, V^{\hat{\theta}}, V^{\hat{\varphi}}) = (\gamma, \gamma\beta\cos\psi, 0, \gamma\beta\sin\psi)$$

Since $Q^{I}_{J} = Q_{IJ}$ here, we have a simple 3 x 3 matrix given by:

$$\begin{aligned}
Q_{11} &= -R_{\hat{t}\hat{r}\hat{t}\hat{r}}\cos^2\psi - R_{\hat{t}\hat{\varphi}\hat{t}\hat{\varphi}}\sin^2\psi \\
Q_{22} &= -\gamma^2(R_{\hat{t}\hat{r}\hat{t}\hat{r}}\sin^2\psi - R_{\hat{t}\hat{\varphi}\hat{t}\hat{\varphi}}\cos^2\psi + \beta^2 R_{\hat{r}\hat{\varphi}\hat{r}\hat{\varphi}}) \\
Q_{33} &= -\gamma^2(R_{\hat{t}\hat{\varphi}\hat{t}\hat{\varphi}} + \beta^2 R_{\hat{r}\hat{\varphi}\hat{r}\hat{\varphi}}\cos^2\psi + \beta^2 R_{\hat{\theta}\hat{\varphi}\hat{\theta}\hat{\varphi}}\sin^2\psi) \\
Q_{12} &= -\gamma(R_{\hat{t}\hat{r}\hat{t}\hat{r}} - R_{\hat{t}\hat{\varphi}\hat{t}\hat{\varphi}})\cos\psi\sin\psi \\
Q_{13} &= Q_{23} = 0
\end{aligned}$$

Since $Q_{12} \neq 0$ tidal shear exists. Here, γ and β are relativistic factors.

Reasonable Transit Times

As can be seen from the above, reasonable transit times are attainable in a Morris-Thorne-Kuhfittig wormhole. At 1g of acceleration from Exit Station, turnaround at midpoint, and arrival at the throat at zero velocity, followed by an identical flight profile to Entrance Station, the travel time is 103 days. At a more brisk 10g acceleration, travel time is cut to 32 days proper time.

Since the redshift function $\gamma \sim 1$ for most of the journey, the proper time seen by the voyager does not diverge significantly from the observer time seen on Exit or Entrance Station.

Physically Reasonable Stress-Energy Tensor

The modified MTK wormhole metric minimizes the amount of exotic and normal material used, and is an example of a physically viable wormhole[12]. The tricky part is the spacetime engineering.

Stable Against Perturbations: As discussed above, wormholes are dynamically unstable.

1. Non-linear instability: For small (~ 1% rest mass of the wormhole) energies, certain non-linear perturbations result in formation of a black hole with mass given by:

   $M \sim 0.30\ a$

Since the mass of a wormhole mouth is typically defined by the shape function out to radius ***a***, this means that wormhole destabilization is catastrophic, resulting in the release of about 70% of the wormhole mass as radiated energy.

Inflation of a wormhole is typically limited to Hubble parameter:

H ~ 1.1/a

Where $H = \frac{1}{r}\frac{dr}{dt}$; thus smaller wormholes expand faster.

In general, the "static" wormhole solution is a chaotic instanton with a collapse attractor and inflation attractor in nearby phase space.

2. Linear instability: Wormholes are typically subjected to linear instabilities during the deployment phase, right after the wormhole has been inflated from the quantum regime, but before it is inflated to traversable size. These instabilities come from Lorentz contraction during transport of the mouths to their final destinations, and are typically limited to perturbations of less than 50%. This problem can be analyzed using linear perturbation methods[13]:

   $\gamma(\Delta z) \leq 1.5$

   Where $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

   This constrains transport velocities to < .74c.

3. Chronodynamic instability: Possession of a wormhole apparently produces time machines rather easily[14]. Because the formation of a Closed Timelike Curve immediately generates a Cauchy horizon, a wormhole will be destabilized any time a CTC exists. The procedure for creating a CTC is:

   - Create a wormhole
   - Induce a time shift between the mouths
   - Bring the mouths close enough together so that the distance through the simply-connected region is less than the time shift.

   The simplest way to induce a time shift is to move one mouth at relativistic velocity. This is the usual course of events in deployment of a wormhole gate between systems. However, once brought to the target system, the wormhole is inflated and remains in far orbit around the star, so a normal wormhole will not create a time machine.

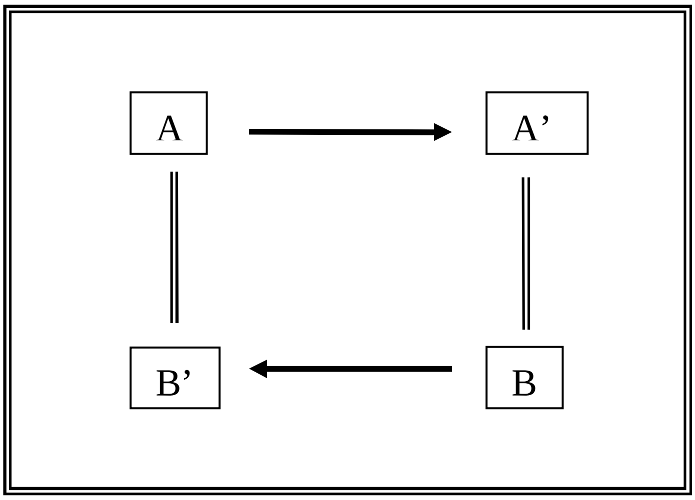
General relativistic means for inducing time shift exist (e.g. orbit around massive objects), but they are of no engineering concern.

A "Roman" configuration (named for an Information Age physicist that first considered this) results when a set of wormholes by themselves are not time machines, but form a network that does produce a time machine.

For the simplest two-wormhole configuration, there are essentially 3 requirements:

- Net distance traversed through the wormhole as measured in asymptotically flat space exceeds distance traversed in flat space to the mouths (trivially satisfied)
- The wormhole time shift is antiparallel
- The distance between mouths is shorter than the overall time shift

Consider the wormhole network to be a directed graph, with the direction corresponding to time shift. Label mouths of the wormhole by A, A', etc, and let == be travel time in normal (flat) space and → be time shift through the wormhole. If A→A' + B→B' > A'==B + B'==A then the following diagram represents a time machine:



To avoid Roman time machines in general, one of two criteria are sufficient:

- The wormhole network consists only of directed, acyclic graphs
- Wormhole linelayers carry wormhole mouths from core systems to exterior systems only; no "backtracking" networks allowed.

As a concrete example, a linelayer with 1g of acceleration will achieve .7c in 10 months. Neglecting acceleration and turnaround (which is a small fraction of the total trip), the travel time as measured by the home system will be ~ 14 years; the linelayer will measure ~ 10 years. Upon arrival, if a second linelayer is sent back to the original system, it will generate a CTC when ~ 5 ly distant. Thus, Chronodynamics significantly restrict wormhole placement.

In sum, wormholes must be stabilized by transapient systems using pulses of phantom radiation. Larger wormholes are more stable, but the results of disaster are correspondingly greater. Chronology Protection mandates careful arrangement of wormhole networks.

Physically Reasonable Construction Materials: Wormholes exist at the quantum level, in the Wheeler spacetime foam[15]. With a source of ANEC-violating mass energy, extremely ample amounts of energy, and the correct configuration, a quantum Wheeler wormhole can be enlarged via exponential inflation of its outer trapping horizons (explosion) to desired size. Presumably, expansion is halted by energy supply and field configuration, although the exact details remain unknown.

A wormhole can be constructed from a Schwarzschild black hole, if sufficient quantities of phantom radiation exist. This process involves symmetric, precisely timed imploding pulses of pure radiation with negative energy density, and is essentially the reverse process of wormhole collapse to a black hole. Since the resulting wormhole throat is smaller than the Schwarzschild radius, the collapse process involves at least 70% of the mass of the wormhole radiating away, and the pulses must be nearly infinitely thin and precisely timed, this method of wormhole construction is not believed to be feasible without enormous quantities of inflaton or axion fields and exceptional computational ability. Nevertheless, this technique is widely studied for the insights it gives to the stability problem.

Requests for interviews with transapient wormhole architects went unanswered, and various Hider clans reputedly capable of spacetime engineering remain unavailable. Some researchers have also noted extremely large energy signatures in intergalactic regions where phantom energy densities would be expected to be large.

Network Topology

For large wormholes, destabilization releases energies sufficient to completely sterilize the system containing them, as well as any nearby systems. Therefore, the Wormhole Nexus has developed as a branch and spoke system with large, busy wormhole termini are typically located in otherwise unpopulated systems, and smaller wormholes providing access to important systems. A busy hub may possess a dozen large wormholes and hundreds of smaller wormholes, all carrying commerce to highly populated worlds.

As discussed earlier, the creation of a useful wormhole entails relativistic velocity, and the traveling mouth will have a time shift with respect to the stationary mouth. This can be represented by a directed edge denoting the time difference between the two nodes (wormhole mouths). The Wormhole Nexus as a whole then forms a directed graph; whenever the time difference between two nodes along a given path exceeds the travel time via an alternate route, a CTC will form. The Cauchy horizon formed typically destabilizes the least massive wormhole along the CTC, although for wormholes that are close in mass and/or insufficiently stabilized, a number of wormholes can collapse and explode.

Generally, to avoid catastrophe, the Wormhole Nexus has been constructed as a directed, acyclic graph. Fortunately, avoiding CTCs is trivial using this representation, as algorithms to solve for negative weight cycles in directed acyclic graphs date to the Information Age (Bellman-Ford). This network topology was mandated during early expansion, when exploration and settlement radiated outwards from core worlds to outlying regions. In latter times, however, astrography and the ever increasing size of the Nexus made cross-linkage desirable. Methods have since been developed to minimize time shift between wormhole mouths, such as constructing wormholes midway between two desired systems, and sending both mouths of the wormhole with identical relativistic velocities to their final destinations. Greater mastery of metric engineering stabilization technology enables Chronodynamic synchronization devices, which are essentially special-purpose relativistic massdrivers.

In the latter times of Terragens Expansion, minimal time shift gateways have been employed as replacements for older wormholes, enabling the creation of gateways to reduce congestion to certain systems.

Communicable Wormholes

A simpler class of wormhole to construct is a Communicable Wormhole. In this case, tidal forces and proper transit time is not a consideration, since only null geodesics (light beams) traverse the throat.

However, this is compensated for by the difficulty entailed in attempting stabilization of wormholes with small masses. Because non-linear destabilization can occur from as little as 1% of the wormhole rest-mass, exotic gravitational artifacts are enough to convert microscopic wormholes into microscopic black holes. This has a number of other spacetime engineering uses, but for the purposes of wormhole construction, microscopic, so-called comm-gauge wormholes require transapient stabilization.

Discarding traversability relaxes the constraints on the shape function and redshift functions for wormholes, although the Ford-Roman quantum inequalities still apply.

If large amounts of phantom energy are available, a Hayward wormhole can be constructed by carefully bombarding a Schwarzschild black hole (which differs topologically from an astrophysical black hole by having both mouths)[16]. Hayward wormholes are attractive for communication purposes, because asymptotic flatness requirements are reduced to:

$$a \approx 10^4 r_0$$

This allows decreased distances between communication routers centered on the Communicable (comm-gauge) Wormhole. Such a wormhole would have a mass given by:

$$M \approx \frac{c^2 \sqrt{a r_0}}{2G}$$

A typical 100 meter Hayward wormhole would mass 6.73×10^{30} kilograms, or ~3.38 Solar Masses, of which 1 Solar Mass of materials could come from a Black Hole. The rest of the material would be mass equivalence in dark energy.

Although this is much heavier than a modified-Morris-Thorne-Kuhfittig metric wormhole of equivalent size, a comm-gauge wormhole with a 1-nanometer radius would only mass a reasonable 6.73×10^{19} kilograms, or ~7% of Ceres.

The equation for maximum possible information transfer between two points using photons is:

$$\frac{\dot{I}}{A} \leq \frac{4(\sigma_{SB})^{1/4}}{3k_B \ln 2}(\frac{P}{A})^{3/4}$$

Where $\dot{I}$ is information transfer rate in bits per second, A is the area, σ_{SB} is the Stefan-Boltzmann constant, P is power, and k_B is the Boltzmann constant[17]. This formula is valid in the range 10^3 K to 10^9K, where temperatures above 10^9K have an additional factor $(q/2)^{1/4}$, q being the number of elementary particles in the Universe.

This gives a 1 nanometer wormhole a bandwidth of 4.048×10^{21} bits per second using 1 megawatt of power.

The outstanding engineering challenge in Hayward wormhole construction is the procurement of phantom energy and a Schwarzschild black hole. Astrophysical black holes have only one mouth and, due to theorems forbidding topology change, cannot be converted to Schwarzschild black holes. It is possible, however, that they can be extracted from the quantum foam using a process similar to the construction of wormholes. Phantom energy, likewise, could be obtained if dark energy could somehow be extracted from the Universe.

Few examples of comm-gauge wormholes have been studied, but detector and particle counts suggest that they are, indeed, a variety of microscopic Hayward wormhole.

Exotic Wormholes

Toroidal wormholes, which possess axial but not spherical symmetry, are theoretically attractive due to their topological characteristics: they can be exactly mapped to flat space, allowing perfect tangent bundles at all points and no coordinate singularities (unlike a sphere, which has two, one at each pole). However, these theoretical advantages are outweighed by the engineering difficulty in creating a toroidal solution with less mass and negative stress energy than the (spherical) modified MTK metric. Toroidal stability seems to be another problem, as evinced by the lack of examples in astronomical phenomena such as stars and black holes.

Static, aspheric wormhole solutions are also known; these would consist of pairs of dihedral (flat planar) wormhole throats distributed in a polyhedral framework. Aspheric wormholes possess a number of advantages over the modified MTK wormhole. Each face would provide a separate gateway, allowing one construct to serve as a gateway between many systems simultaneously. Traversing a pair of faces would incur no tidal forces. Finally, asymptotic flatness requirements are much less stringent than the spherical case; depending upon the total mass of the wormhole, it can be approximated by the gravitational monopole such that a few tens of A.U.s would suffice.

However, the engineering requirements for aspheric wormholes are nearly intractable. Static aspheric wormholes absolutely require large amounts of negative stress energy, which cannot be minimized in the manner that the modified MTK metric does for spherical wormholes. If not for the observation that transapients use comm.-gauge wormholes extensively and therefore possess the means to obtain large amounts of dark energy, this would relegate the study of static aspheric wormholes to pure theory. Even so, a one-meter facet would require about 10^{-3}

solar masses of negative energy density, and required mass scales quadratically with linear gateway size, making them potentially less efficient than spherical wormholes.

The second issue is that the sharp corners of the dihedral metric pose serious challenges. The edges of the wormhole require tensions that cannot be supported by anything less than negative energy cosmic strings, which do not naturally arise in M-theory. They are also statically and dynamically unstable to a greater degree than spherical wormholes, since stability depends upon their angular measure. Furthermore the corners are completely unstable and, in fact, cannot be constructed using simple topological artifacts such as strings and monopoles; more exotic structures are required. Some of these problems can be solved with the use of “loop-based” wormholes, which replace polygonal faces with loops of (negative energy) cosmic strings, but then the strings themselves must possess an additional “stiffness” property not normally associated with Nambu-Goto/Polyakov strings. These issues make the construction of a physically reasonable stress-energy tensor with physically reasonable construction materials chancy at best.

The third issue is chronodynamic stability, which is complicated by the close proximity of separate wormhole gateways and the inherent cycles propagated in any network possessing more than one aspheric wormhole framework.

The most serious engineering problem is that static aspheric wormhole construction requires mathematical operations (“Minkowski cut-and-paste”) that do not have a physical realization. However, M-theory constructs in bulk space have the possibility of realizing some of these operations, if bulk-extended artifacts exist. Researchers are presently studying several candidate gravitational tensor events that may indicate signatures of this process.

The most exotic wormhole spacetime known is the potential creation of a bulk-space dynamical string wormhole. Such a stringhole may be able to propagate in the bulk, thus opening mouths on the brane in different times and locations. Unfortunately, the necessary extensions to M-theory to describe such effects lie within the realm of transapient mathematics.

References

[1] J. Tejeiro and E. Larranaga, "Gravitational Lensing by Wormholes", arXiv:gr-qc/0505054 v1 12 May 2005

[2] M. Morris and K. Thorne. “Wormholes in spacetime and their use for interstellar travel: A tool for teaching general relativity.” Am. J. Phys., 56:395-412, 1988

[3] Peter Kuhfittig. “Wormholes supported by small amounts of exotic matter: some corrections.” arXiv:gr-qc/0508060 v1, 15 Aug 2005

[4] H. Shinkai and S. Hayward. “Fate of the first traversable wormhole: black-hole collapse or inflationary expansion.” arXiv: gr-qc/0205041 v2, 11 May 2002

[5] S. Hawking. “Chronology protection conjecture.” Phys. Rev. D, Vol. 46, Number 2, pp. 603-11, 1992

[6] L. Ford, T. Roman. “Restrictions on Negative Energy Density in flat spacetime.” arXiv:gr-qc/9607003 v2, 24 Jan 1997

[7] J. Lemos, F. Lobo and S. Oliveira. “Morris-Thorne wormholes with a cosmological constant.” arXiv:gr-qc/0302049 v1, 12 Feb 2003

[8] S. Sushkov and S. Kim. “Cosmological evolution of a ghost scalar field.” arXiv:gr-qc/0404037 v1 8 Apr 2004

[9] P. Gonzalez-Diaz. “Axion Phantom Energy.” arXiv:hep-th/0401082 v1 13 Jan 2004

[10] F. Lobo. “Phantom energy traversable wormholes.” arXiv:gr-qc/0502099 v2 6 Apr 2005

[11] M. Visser, Lorentzian wormholes — from Einstein to Hawking, AIP Press, New York, 1995

[12] K. Nandi, Y. Zhang, and N. Migranov. “A quantum constraint for the physical viability of classical traversable Lorentzian wormholes.” arXiv:gr-qc/0409053 v2 29 May 2005.

[13] C. Armendariz-Picon. “On a class of stable, traversable Lorentzian wormholes in classical general relativity.” arXiv:gr-qc/0201027 v2 15 Jan 2002

[14] M. Visser. “From wormhole to time machine: Comments on Hawking’s Chronology Protection Conjecture.” arXiv:hep-th/9202090 v2 8 Oct 1992

[15] J. Wheeler. “Geons.” Phys. Rev., 97:511-536, 1955

[16] S. Hayward and H. Koyama. “How to make a traversable wormhole from a Schwarzschild black hole.” arXiv:gr-qc/0406080 v1 20 Jun 2004

[17] Warren D. Smith. “Fundamental physical limits on computation.” http://www.cise.ufl.edu/~mpf/fundphys.pdf May 5 1995