Wormholes and Warpdrives:

Peculiarities in General Relativity

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Syllabus:

- Two key questions:
  - Q1: Is faster-than-light (FTL) "respectable physics"?
  - Q2: Is the speed-of-light barrier beginning to look just a little bit "porous"?

- Two key answers:
  - A1: It depends.
  - A2: Don't hold your breath.

Syllabus:

Culled from the pages of:

- *Physical Review Letters*
- *Nature*
- *Science*
- *Physics Letters*
- *Physical Review*
- *Nuclear Physics*
- *Classical and Quantum Gravity*

and other journals.

Syllabus:

- Wormholes.
- Warpdrives.
- Brane-world cosmology.
- Tachyons.
- Time machines — logic loops.
- Hawking's chronology protection conjecture.
- Exotic matter (negative energy).
- Superluminal photons?

Syllabus:

Finally I'll wrap things up by:

- showing how these ideas relate to some of the other talks in the workshop,

- discussing where things could break down,

- discussing where the maneuvering room is for new physics.

Wormholes/warpdrives:

Over the last decade or so it has become increasingly clear that the interface between quantum physics and Einstein's gravity (general relativity) seems to lead to (or at least permit) a large number of very strange theoretical constructs.

The fringes of general relativity almost seem to be infested with wormholes and warpdrives.

While it is clear that we will not be able to build such objects in the foreseeable future— the technological difficulties are immense—they provide very useful gedanken-experiments for sharpening our ideas of where physics might be heading.

Background:

The normal philosophy in General Relativity is: Take the Einstein Field Equations, add some form of matter, make simplifying assumptions, then solve to deduce what the geometry of spacetime is. (This is difficult.)

(Ten non-linear second-order partial differential equations with four redundancies [arbitrary choice of coordinates] and four constraints [stress-energy conservation]).

There is a tremendously large body of research that takes exactly this approach, either analytically or numerically.

This is not the best strategy for understanding wormholes and warpdrives.

Strategy:

[1] Decide on your definition of a wormhole/ warpdrive.

What does the spacetime geometry look like?

[2] Given the geometry, use the Einstein equations to calculate the distribution of matter required to set up this geometry.

[3] Ask: Is this distribution of matter physically reasonable?

Does it violate any basic rules of physics?

Q: Is the construction of wormholes/ warp-drives merely a problem of technology, or is it in violation of fundamental physical principles?

What is a wormhole?

Morris–Thorne traversable wormholes:

- Q: What would you have to do to build a wormhole that you could safely stuff a human through?

- A: Nothing too drastic: you just need to some "exotic matter" / "negative energy". (More on this later.)

- Quantum effects are potentially important.

- Warning: We know how to get small amounts of "negative energy"; We don't know for sure if it is possible to get large quantities of "negative energy".

Traversable wormhole geometry:

An example:

Take the geometry

$$ds^2 = -dt^2 + \left[1 + \frac{GM}{2r}\right]^4 \left(dx^2 + dy^2 + dz^2\right).$$

(This is Schwarzschild geometry in isotropic coordinates; with $g_{tt} \to -1$ to get rid of the event horizon.)

This solves the Einstein equations with a source

$$T_{\mu\nu} = -\nabla_\mu \phi \, \nabla_\nu \phi.$$

(Which corresponds to a massless scalar field with the wrong sign for the stress–energy tensor.)

Homer G. Ellis:
Drainholes and reversed polarity gravity.

A brief history of wormhole physics:

- 1935: Einstein—Rosen;
  Physical Review 48 (1935) 73–77.

  "These solutions involve the mathematical representation of physical space by a space of two identical sheets, a particle being represented by a 'bridge' connecting these sheets."

- This is the Einstein–Rosen bridge.

- Do not attempt to cross an Einstein–Rosen bridge — You will die.

- 1955: Wheeler; Physical Review 97 (1955) 511–536.

Wheeler discusses a special type of "*geon*" that possesses two "*tunnel mouths*".

— First diagram of a wormhole.

> "One's interest in following geon theory down into the quantum domain will depend on one's considered view of the relationship between very small geons and elementary particles."

- 1957: Misner–Wheeler; Annals of Physics (NY) 2 (1957) 525–603.

  “There is a net flux of lines of force through what topologists would call a handle of the multiply–connected space and what physicists might perhaps be excused for more vividly terming a ‘wormhole’.”

— First use of the word “wormhole”.

  “On the atomic scale the metric appears flat, as does the ocean to an aviator far above. The closer the approach, the greater the degree of irregularity. Finally, at distances of the order of ℓ_P, the fluctuations in the typical metric component, $g_{\mu\nu}$, become of the same order as the $g_{\mu\nu}$ themselves.”

- 1957: Wheeler;
  Annals of Physics (NY) 2 (1957) 604–614.

  “Space ‘resonates’ between one foam-like structure and another.”

  “*Spacetime foam*”

Renaissance:

- 1988: Morris–Thorne;
  American Journal of Physics
  56 (1988) 935–412.
  - traversable wormholes.
  - time travel.

- 1989: Novikov
  - time machines.

- 1989: Visser
  - portals.
  - stability.

- 1990: Frolov–Novikov
  - time machines.
  - perpetual motion.

- 1990's: Morris — Thorne — Yurtsever — Hawking — Novikov — Frolov — Kim — Klinkhammer — Lyutikov — Ford — Roman — Visser — and many others...
  - chronology protection.
  - quantum effects.

- 1990's:
  Wormholes enter the popular culture
  — ST:tng, ST:ds9, ST:voyager —
  — Sliders, Stargate —

The need for Exotic Energy:

It is a **theorem** that spacetimes containing traversable wormholes always violate the averaged null energy condition: Friedmann–Schleich–Witt.

In fact there will always be null energy condition violations at or near the throat.

(This is a fancy way of saying that you need to have some effectively "negative mass" at or near the throat to keep the wormhole throat open.)

Static spherical symmetry: Morris–Thorne.
Dynamic asymmetric: Hochberg–Visser.

There are quite a few **claims** that energy condition violations can be avoided.

Wormholes without ANEC violation?

Most of these claims are simply wrong.

Some of these claims are just semantic games.

[Divide the total stress-energy into “weird stuff” plus “normal stuff”, push all the energy condition violations into the “weird stuff” so that the “normal stuff” does not violate the energy conditions.]

Traversable wormholes violate the averaged (and unaveraged) null energy condition.

How big a violation?

Typically, near the throat, you need:

$$(mass\ @\ throat) = -\frac{(radius)\ c^2}{G}.$$

For $(radius) = 1$ metre,
$(mass\ @\ throat) = -1$ Jupiter mass!

Total mass might still be close to zero
(in principle, either positive or negative).

Whether or not large "mass separation" is
possible (even in principle) is far from clear.

The Alcubierre Warpdrive:

The warpdrive:
Hyper-fast travel in general relativity,
by Miguel Alcubierre,
Classical and Quantum Gravity,
11 (1995) L73–L77.

In general relativity, nothing can *locally* exceed the speed of light.

But if the space-time geometry is suitably arranged, you can think of the light-cones as "tipping over" with respect to some flat background geometry, so that *globally* objects can "effectively" travel faster-than-light [with respect to the background geometry].

Warpdrive Geometry:

Pick the metric (i.e. distance function):

$$ds^2 = -dt^2 + (dx - v_s\, f(r)\, dt)^2 + dy^2 + dz^2.$$

$$ds^2 = -dt^2(1 - v_s^2\, f(r)^2) - 2v_s\, f(r)\, dx\, dt$$
$$+dx^2 + dy^2 + dz^2.$$

The metric of 3D space is flat, all the complications are hiding in the space-time cross terms.

v_s is the speed of the warp-bubble.

$f(r)$ describes the shape of the warp-bubble, with

$$r(x, y, z, t) = \sqrt{(x - v_s\, t)^2 + y^2 + z^2}$$

and

$$f(0) = 1; \qquad\qquad f(\infty) = 0.$$

Warpdrive stress–energy:

Use the Einstein equations to calculate the stress-energy.

Bad news: the energy density is negative!

That is: Exotic matter.

$$\rho = -\frac{1}{8\pi G} \frac{v_s^2 (y^2 + z^2)}{4\left[(x - v_s\, t)^2 + y^2 + z^2\right]} \left(\frac{df}{dr}\right)^2 .$$

Other parts of the stress-energy are worse.

The deep question is: Is this negative energy density enough to tell you cannot, not ever, build a warpdrive?

The answer is not obvious...

(Surprise?)

Problems with Warpdrive:

- Superluminal censorship.
  - Exotic energy/negative mass (large quantities; at least planetary masses).

- Bootstrap problem.
  - The front end of the warp-bubble is not causally connected to the back end.
  - Effects of any decision you make spread out at lightspeed or less.
  - The "characteristic surfaces" of GR are the lightcones.

Brane world:

"Brane cosmology" is all the rage in the string theory/ quantum field theory/ phenomenology communities; generating theory papers at the rate of about 300 per year.

What's going on?

Why is it interesting?

- Physics.
- Sociology.
- Shortcuts through the fifth dimension.

What are the prospects for an empirical test?

Overview:

"Brane cosmologies" are based on the idea that our familiar (3+1)–dimensional universe is a "membrane" (D-brane) in a more fundamental (9+1)–dimensional or (10+1)–dimensional reality.

These models are based on cross-fertilization between some of the more bizarre and outre speculative models of 20'th century physics.

Specifically:

- Mutant Kaluza–Klein theories.
  (Exotic Kaluza-Klein theories.)

- String theory/ D-brane theory/ M-theory/...
  (pick your favorite "nom du jour".)

- Feeble forces.
  (The "fifth force".)

Kaluza–Klein: I

The Kaluza–Klein theories date back to the early days of GR (1920's).

They started out as an attempt to classically unify electromagnetism with gravity, by introducing a "fifth dimension".

In the original versions this extra space dimension was supposed to be curled up into a little circle.

Electric charge was supposed to be momentum in the fifth direction, with quantization of electric charge guaranteed by periodic boundary conditions in the extra dimension.

Being rather generous with the experimental bounds:

$$R_{extra\ dimension} < \frac{\hbar\ c}{1\ \text{TeV}} \approx 10^{-18} \text{ metres.}$$

Kaluza–Klein: II

During the 1970's Kaluza–Klein theories got more complex — more dimensions, more classical fields (gluons, electro-weak bosons).

Fermions were added, as were various additional symmetries.

Almost always people kept the extra dimensions "compact" and small.

The suspicion generally was

$R_{extra\ dimension} <$ Planck length $\approx 10^{-35}$ metres.

This was the era of extended supergravity theories and the like.

By and large, these theories were not demonstrably wrong; but they were not demonstrably right either.

String theory: I

In 1984 Kaluza–Klein theories got a new lease on life with the advent of the anomaly-free string theories.

String theory had been languishing in the wilderness since the early 1970's, when it was first conceived as a model for the strong nuclear interactions, but quickly shown to have several undesirable features. (Mark 1 string theory.)

In the late 1970's an early 1980's steps were taken to recycle string theory as a candidate model for a theory of quantum gravity.

The discovery in 1984 that the resulting theory was free of quantum field theory "anomalies" surprised everyone.

(The point being that once you are sure that certain classical symmetries are *not* broken by quantum effects it is much easier to prove renormalizability or even finiteness.)

String theory: II

For various technical reasons string theory is most easily set up in (9+1) dimensions, though (10+1) dimensions is increasingly popular.

(There are also arcane ways of setting up string theory in (3+1) dimensions, but let's not open that particular can of worms right now.)

If you are going to work in (9+1) dimensions you had better quickly find a way of getting rid of the six extra embarrassing dimensions — Kaluza–Klein theories were drafted to do the job.

The resulting "Mark 2 string theory" is not demonstrably wrong; and is a reasonable candidate for a quantum theory of gravity; but is not demonstrably right either.

Brane theory: I

In the mid 1990's string theorists began to realize that string theory was not just a theory of strings but that it also contained a large number of membrane-like solitonic degrees of freedom that would be excited in generic collision processes.

Thus was born p-brane theory:

- -1 brane: instanton.
- 0 brane: particle.
- 1 brane: string.
- 2 brane: membrane.
- p-brane: p-dimensional object sweeping out a (p+1)-dimensional world volume.

Brane theory: II

In standard Kaluza-Klein theory the particles are free to move in the extra dimensions, which is why you have to keep them small.

In Kaluza–Klein theories based on brane theory, (Mark 3 string theory) string theory effects trap the matter on (near) the brane, and you can let the extra dimensions get large without mucking up particle physics.

Consider a 3-brane/D-brane (Dirichlet-brane); this means that the open strings in the theory are constrained to end on the D-brane.

If a string has energy E and string tension α, then the maximum distance it can penetrate into the extra dimensions is

$$L = \frac{E}{2\alpha}.$$

Brane theory: III

So the new model of empirical reality is this: We are living on a 3-brane in higher-dimensional spacetime.

All normal "particles" (electrons, quarks, photons) are associated with open strings whose end-points lie on the 3-brane, and are thus trapped on the 3-brane by stringy effects.

On the other hand, "gravitons" are associated with closed strings with no endpoints — they can in principle move off the 3-brane; and so you have a hybrid theory where (low-energy) particle physics is automatically (3+1) dimensional but gravity probes the higher-dimensional structure of "reality".

Can we "dodge into the fifth dimension"?

Feeble forces: I

Feeble forces (the "fifth force") are the theoretical framework used to describe hypothetical deviations from the inverse square-law of gravity.

Observationally, the inverse square law works well on solar system scales, and on stellar cluster scales.

Something goes wrong at galactic scales, but this is typically attributed to dark matter (not to a breakdown of the inverse square law).

The inverse square law also works well at laboratory scales (about 1 metre; Cavendish experiments).

Feeble forces: II

Surprise 1: Until about 1993 $G_{\text{laboratory}}$ as measured by Cavendish experiments could have differed from $G_{\text{solar system}}$ by up to 30 percent; present data constrain them to be equal to within one percent or so.

Surprise 2: Below about 5 cm, there's almost no constraints on the inverse square law.

This is one of the experimental windows that the brane theorists hope to exploit; the other is cosmology...

Brane model building: I

There are three main branches of brane-based model building:

- Antoniadis, Arkani-Hamed, Dimopoulos, Dvali (1998; 500 citations):
  In this scenario (AADD) the extra dimensions are large (millimetre) but still "compact" in the mathematical sense.

- Randall–Sundrum (1999; 300 citations):
  In (one version of) this scenario (RS1) the extra dimensions are large (millimetre) but still "compact" in the mathematical sense. We live on one 3-brane, and there is an additional anti-brane which carries "mirror matter".

Brane model building: II

- Randall–Sundrum (1999; 300 citations):
  In (one version of) this scenario (RS2) the extra dimensions are infinite and "non compact" in the mathematical sense. There is only one 3-brane and we are on it.

For technical reasons these models are all (4+1)-dimensional.

They start out in (10+1) dimensions, but six dimensions are eaten up in the usual Kaluza–Klein fashion with compact dimensions; it is only the last step in going from (4+1) to (3+1) dimensions that uses these "exotic techniques".

There are now also a number of papers attempting to have many infinite dimensions, not just one...

Brane model building: III

All three of these models predict deviations from the inverse square law at short distances, typically at centimetre scales.

The experimentalists are very happy to finally have some sort of prediction from string theory... (very happy!)

The other place where these brane models might lead to experimental/ observational testing/ verification are in cosmology...

Brane cosmology: I

I will discuss a particularly simple and compelling implementation of brane cosmology.

Details: Physics Letters **B482**, 183-194 (2000)

To keep life as simple as possible, I will have only one 3-brane, and only one bulk (4+1)-dimensional region.

The 3-brane will be the boundary of the (4+1)-dimensional region, so that we are quite literally "living on the edge" of spacetime.

Take the bulk geometry to be

$$\mathrm{d}s^2_{4+1} = -F(r)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{F(r)} + r^2\,\mathrm{d}\Omega_3^2.$$

$$\mathrm{d}\Omega_3^2 \equiv \mathrm{d}\chi^2 + \sin^2\chi\,(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2).$$

Brane cosmology: II

Now truncate this cosmology at finite "radius" $r = a(\tau)$.

The surface of this truncated geometry is automatically a (3+1)-dimensional $k = +1$ FLRW geometry with induced metric

$$\begin{aligned} \mathrm{d}s^2_{3+1} &= -\left[F(a(t)) - \frac{1}{F(a(t))}\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)^2\right] \mathrm{d}t^2 \\ &\quad + a(t)^2\, \mathrm{d}\Omega_3^2. \end{aligned}$$

Go to a new coordinate τ measuring proper time along the edge, then

$$\mathrm{d}s^2_{3+1} = -\mathrm{d}\tau^2 + a(\tau)^2\, \mathrm{d}\Omega_3^2.$$

Brane cosmology: II

Now apply the (4+1)-dimensional Einstein equations. To do this you need a (4+1)-dimensional version of the "thin shell" formalism, modified for this one-sided brane. A brief agony of formal GR yields

$$8\pi\, G_{4+1}\, \rho_{3+1} = 3\, \frac{\sqrt{F(a) + \dot{a}^2}}{a}.$$

Rearranging

$$\left(\frac{\dot{a}}{a}\right)^2 = -\frac{F(a)}{a^2} + \left(\frac{8\pi\, G_{4+1}\, \rho_{3+1}}{3}\right)^2.$$

In contrast the *standard* Friedmann equation for a $k = +1$ closed FLRW universe is

$$\left(\frac{\dot{a}}{a}\right)^2 = -\frac{1}{a^2} + \frac{\Lambda}{3} + \frac{8\pi\, G_{3+1}\, \rho_{3+1}}{3}.$$

How do we get these equations to (more or less) agree?

Brane cosmology: III

Split the (3+1)-dimensional energy into a constant ρ_0 determined by the brane tension, plus "ordinary" matter ρ, with $\rho \ll \rho_0$ to suppress the quadratic term in comparison to the linear. Then

$$G_{3+1} = G_{4+1} \left(\frac{16\pi \, G_{4+1} \, \rho_0}{3} \right);$$

that is

$$G_{4+1} = \sqrt{\frac{3 \, G_{3+1}}{16\pi \, \rho_0}}.$$

Therefore

$$\left(\frac{\dot{a}}{a}\right)^2 = -\frac{F(a)}{a^2} + \left(\frac{8\pi \, G_{3+1}}{3}\right) \left[\frac{1}{2}\rho_0 + \rho + \frac{1}{2}\frac{\rho^2}{\rho_0}\right].$$

Observational cosmology forces us to take ρ_0 large [electro-weak scale or higher to avoid major problems with nucleosynthesis], and then forces us to deduce the presence of an almost perfectly countervailing cosmological constant in the bulk.

Brane cosmology: IV

For the (4+1)-dimensional Reissner–Nordstrom–de Sitter geometry

$$F(r) = 1 - \frac{2M_{4+1}}{r^2} + \frac{Q_{4+1}^2}{r^4} - \frac{\Lambda_{4+1}\, r^2}{6}.$$

M_{4+1} is a (4+1)-dimensional "mass" parameter, corresponding to the mass of the central object in (4+1)-space — it does not have a ready (3+1)-dimensional interpretation and is best carried along as an extra free parameter that from the 4-dimensional point of view can be adjusted to taste.

Q_{4+1} corresponds to an "electric charge" in the (4+1)-dimensional sense.

Our universe, the boundary D-brane, must then be viewed as carrying an equal but opposite charge to allow field lines to terminate.

Brane cosmology: V

From the (3+1)-dimensional view Q_{4+1} may be taken to be a second free parameter.

The (4+1)-dimensional cosmological constant combines with the term coming from the D-brane tension to give an effective (3+1) dimensional cosmological constant

$$\Lambda = \frac{\Lambda_{4+1}}{2} + 4\pi G_{3+1}\, \rho_0.$$

The generalized Friedmann equation is now

$$\begin{aligned}\left(\frac{\dot{a}}{a}\right)^2 \;=\; & -\frac{1}{a^2} + \frac{2M_{4+1}}{a^4} - \frac{Q_{4+1}^2}{a^6} + \frac{\Lambda}{3} \\ & + \left(\frac{8\pi\, G_{3+1}}{3}\right)\left[\rho + \frac{1}{2}\frac{\rho^2}{\rho_0}\right].\end{aligned}$$

By tuning these parameters appropriately one can recover standard cosmology to arbitrary accuracy.

Brane cosmology: VI

Rewrite the generalized Friedmann equation as

$$\left(\frac{\dot{a}}{a}\right)^2 = -\frac{1}{a^2} + \frac{\Lambda}{3} + \left(\frac{8\pi\, G_{3+1}}{3}\right)\,\rho \\ + \frac{2M_{4+1}}{a^4} - \frac{Q_{4+1}^2}{a^6} + \left(\frac{8\pi\, G_{3+1}}{6}\right)\left[\frac{\rho^2}{\rho_0}\right].$$

M_{4+1} can be used to mimic an arbitrary quantity of what would usually be called "radiation" (relativistic fluid, $\rho = 3p$).

Q_{4+1} mimics "stiff" matter ($\rho = p$), though with an overall minus sign.

An observational astrophysicist or cosmologist could now simply forget about the underlying string theory and D-brane physics, take this expression as the D-brane inspired generalization of the Friedmann equations, and treat M_{4+1}, Q_{4+1}, Λ, and ρ_0 as parameters to be observationally determined.

Prospects for brane physics:

Of course we actually want to do more than just reproduce standard cosmology. We can already see several interesting possibilities:

- Look for short-distance deviations from the inverse square law.
- Use the extra free parameters M_4, Q_4, ρ_0, for better observational cosmological fits.
- Re-do the analysis for $k = 0$ and $k = -1$; (relatively easy but not as "nice").
- Re-do the analysis for more complicated (4+1)-dimensional geometries; (downright ugly and increasingly baroque).

Conclusions regarding branes:

The model cosmology I've just described is the best compromise I have come up with between something complicated enough to be interesting, and yet close enough to standard cosmology to not be completely unconstrained by current observational data.

If you actually want to confront string theory with observation or experiment, this sort of cosmology is the best hope string theory has.

Remember:

$$\left(\frac{\dot{a}}{a}\right)^2 = -\frac{k}{a^2} + \frac{\Lambda}{3} + \left(\frac{8\pi\, G_{3+1}}{3}\right)\, \rho + \frac{2M_{4+1}}{a^4} - \frac{Q_{4+1}^2}{a^6} + \left(\frac{8\pi\, G_{3+1}}{6}\right)\left[\frac{\rho^2}{\rho_0}\right].$$

Tachyons:

Tachyons have been around as a theoretical idea since the 1970's.

Repeated searches (cosmic rays, accelerators) have found either no tachyons, or at best ambiguous results that keep receding as data get better.

Theoretically, tachyons are a mess: they lead to grossly unstable field theories, or worse.

The instability leads to spontaneous symmetry breaking, which if there is any ground state at all, will lead to ordinary slower-than-light particles once the symmetry has broken.

Example: no-one took string theory seriously until people jumped through hoops to get rid of the tachyons.

A Serious Problem:
FTL generically implies time machines.

(EG: traversable wormholes, warpdrives, and generic tachyons.)

Q: What is a time machine?

A: Any closed timelike curve (CTC) —
not necessarily a geodesic.

Given a traversable wormhole, it *appears* to be very easy to build a time machine.

It is so easy that it *seems* that the creation of a time machine might be the generic fate of a traversable wormhole.

In fact, classical general relativity is pretty much infested with time machines...

(diseased time machines to be sure..)

How to build a time machine?

1. Get your hands on a traversable wormhole.

2. Induce a time shift between the two mouths.

   - SR time dilation — rectilinear motion.
   - SR time dilation — circular motion.
   - GR time dilation — gravitational redshift.

3. Bring the two mouths together.

Whatever you do:
— don't mention the twin paradox —
It only puts the lunatic fringe into an excited state.

Problem: Time machines imply paradoxes.

Two classes of paradox —

- consistency paradoxes.
- bootstrap paradoxes.

Examples —

- All you zombies.
- By his bootstraps.
- The technicolor time machine.

Responses:

There are *many* ways of dealing with the paradoxes.

1. The radical rewrite conjecture.
   "all hell breaks loose"

2. The Novikov consistency conjecture.
   "suffer not an inconsistency to exist"

3. The Hawking chronology protection conjecture.
   "suffer not a time machine to exist"

4. The boring physics conjecture.
   "forget all this nonsense"

The radical rewrite conjecture:

Rewrite all of physics from the ground up — let the universe have multiple timelines, with time travel effects switching the universe from one timeline to another.

Rewriting physics is a very painful task — not to be undertaken lightly. Especially since there is NO experimental evidence...

One begins to sound like a refugee from a bad sci–fi convention...

> "Whenever one attempts to change history, the resulting temporal anomaly emits a non–Hausdorff wavefront which sweeps out and splits the universe into two separate histories..."

For a real mess; add quantum physics...

The Novikov consistency conjecture:

Classical — There is only one universe.
The universe *must* be consistent no matter what...

"You can't change recorded history".

Complicated situations lead to a rather unsatisfying "consistency conspiracy".

Quantum — Try to derive consistency from some assumed microphysics for quantum gravity.

Inconsistent histories interfere destructively?

In the presence of time travel, certain low probability events become virtual certainties.

Quantum effects blur the line between multiple timelines and consistency constraints...

Hawking's chronology protection conjecture:

Quotes from Stephen Hawking: (PRD)

> "The laws of physics do not allow the appearance of closed timelike curves."

> "It seems that there is a Chronology Protection Agency which prevents the appearance of closed timelike curves and so makes the universe safe for historians."

> "There is also strong experimental evidence in favour of the conjecture — from the fact that we have not been invaded by hordes of tourists from the future."

The Physics of chronology protection:

Physically the conjecture is based on the observation that there are nasty singularities in the renormalized stress–energy tensor as one gets close to forming a time machine...

That is — once quantum effects are included, the energy required to build a time machine is infinite.

— The "chronology horizon" is thoroughly unpleasant place; our current theories are unreliable.

[Two-point functions are not of Hadamard form.]

— The "chronology horizon" always hides behind a "reliability horizon".

The boring physics conjecture:

Just forget about all of these nasty messes —

- Abolish traversable wormholes;
- Abolish complicated topology;
- Enforce strong cosmic censorship;
- and be done with it...

After all, what's the experimental evidence?

Time for a reality check!

Twilight for the energy conditions?

Most of these weird effects seem to need "exotic matter" / "negative energy".

The energy conditions of general relativity are basically assertions that energy is always positive; they permit one to deduce very powerful and general theorems.

However, the energy conditions are now realized to be a lot less secure than they once seemed:

— There are quantum effects that violate all of the energy conditions.

— There are relatively benign classical systems that violate all the energy conditions.

This opens up a Pandora's box of rather disquieting possibilities.

Is it twilight time for the energy conditions?

Overview:

Classical: In classical general relativity the energy conditions are used to prove lots of general theorems...

Quantum: Everyone who thought about it expected the energy conditions to eventually break down once one reaches the Planck slop...

Surprise 1: The energy conditions already fail miserably in **semi-classical quantum gravity**.

Failures occur at first order in $\hbar$, long before one reaches the Planck slop...

The quantum failures are widespread, albeit small...

Surprise 2: The energy conditions also fail miserably in quite reasonable **classical systems**.

Energy conditions:

Standard (pointwise) energy conditions:

TEC — trace energy condition
(now abandoned).

NEC — null energy condition.

WEC — weak energy condition.

SEC — strong energy condition.
(*aka* unphysical energy condition.)

DEC — dominant energy condition.

Standard averaged energy conditions:

ANEC — averaged null energy condition.

AWEC — averaged weak energy condition.

ASEC — averaged strong energy condition.

Standard propaganda:

Physically reasonable Lagrangians give classical theories satisfying the energy conditions...

The standard propaganda is wrong.

Definition:

In a Lorentzian spacetime:

The null energy condition [NEC] is said to hold at a point x, if for all null vectors k

$$T_{\mu\nu}\, k^\mu k^\nu \geq 0.$$

NEC Is the weakest pointwise energy condition in common use.

Notes:

DEC $\Rightarrow$ WEC $\Rightarrow$ NEC.

SEC $\Rightarrow$ NEC.

SEC does *not* imply WEC —
— the terminology is misleading.

Uses of the Energy Conditions:

- Penrose singularity theorem (WEC).
- Hawking–Penrose singularity theorem (SEC). [Relevant to the cosmological singularity.]
- Tipler's version of the Hawking–Penrose singularity theorem (WEC+ASEC).
- Schoen–Yau positive mass theorem (DEC).
- Witten's variant positive mass theorem (DEC).

Hypotheses are all stronger than the NEC.

Uses of the ANEC:

ANEC is the weakest averaged energy condition in common use.

The ANEC is used as input hypotheses in proving:

- Focussing theorems for null geodesics. [Borde]

- Generalized Penrose singularity theorem. [Roman]

- Topological censorship theorem. [Friedman–Schleich–Witt]

- Generalized positive mass theorem. [Penrose–Sorkin–Woolgar]

Quantum violations of the energy conditions:

- 2-particle Fock states. (NEC+)
- Casimir vacuum. (NEC+)
  [DeWitt, Einstein Centenary Survey]
- Hawking radiation. (NEC+)
- Squeezed vacuum. (WEC+DEC)
  [Morris–Thorne]
- Conformal anomaly (NEC+)
  [Visser, PLB 349 (1995) 443–447;
  gr-qc/9409043].
- Gravitational vacuum polarization (NEC+)
  [Visser, gr-qc/9604007-8-9; 9703001].
- Cosmological particle production. (SEC)

Classical violations of the energy conditions:

"Observational"

- Cosmological inflation. (SEC)
  [Minimally coupled massive scalar]

- Cosmological inflation. (NEC+)
  [Conformally coupled massive scalar]

- Galaxy formation: $0 < z < 10$. (SEC)
  [Visser, Science 276 (4 April 1997) 88]

- Accelerating universe. (SEC)

Classical violations of the energy conditions:

"Theoretical"

- Tolman wormholes (SEC)
  [Hochberg, Molina–París, Visser]

- Massless conformally coupled scalar (ANEC+)
  QFT: new improved energy-momentum
  [Barceló–Visser, gr-qc/9908029, PLB]
  [Barceló–Visser, gr-qc/0001099, Cosmo99]

- Non-minimally coupled scalar (ANEC+)
  massive/massless
  [Wald–Flanagan, gr-qc/9602052, PRD]
  [Barceló–Visser, gr-qc/0003025, CQG]

- Negative tension branes (ANEC+)
  [Barceló–Visser, hep-th/0004022, NPB]

Tolman wormhole:

Q: What are the *minimal* conditions for a “bounce”?

D: (Tolman wormhole $\equiv$ “bounce”.)

A: Perform a model-independent analysis of the geometry near a bounce, along the lines of the Morris–Thorne analysis for traversable wormholes.

Details:
gr-qc/9810023, PLB455 (1999) 90-95
[Molina-París, Visser]
gr-qc/9810029, PRD59 (1999) 044011
[Hochberg, Molina-París, Visser]

Flare-out at the bounce $\Rightarrow$ SEC violated at or near the bounce.

Notes:

SEC violations are a *necessary* but not *sufficient* condition for a "bounce".

You do not *need* to violate NEC, WEC, or DEC to get a "bounce".

If you believe inflation you have already abandoned the SEC anyway.

Inflation will not *guarantee* a bounce, but it opens the door.

New improved stress tensor plus gravity:

Take a massless conformally coupled scalar field and add Einstein gravity.
(Static, spherically symmetric.)

Absurdly easy problem; surprising result.

— NEC and ANEC are often violated.

— There is a three-parameter class of exact solutions (total mass, scalar charge, scalar field at infinity).

Special cases:
(1) Schwarzschild/ anti-Schwarzschild.
(2) Naked singularities.
(3) Naked singularities hiding behind wormhole throats. (Not really "traversable".)
(4) Traversable wormholes with two asymptotically flat regions.

Details: gr-qc/9908029, Barceló–Visser, PLB.

Non-minimally coupled scalars plus gravity:

Take a generic non-minimally coupled scalar field and add Einstein gravity.
(Static, spherically symmetric.)

Absurdly easy problem; surprising result.
— NEC and ANEC are often violated.
— There is a four-parameter class of exact solutions (total mass, scalar charge, scalar field at infinity, and curvature coupling).

Special cases:
(1) Schwarzschild/ anti-Schwarzschild.
(2) Naked singularities.
(3) Naked singularities hiding behind wormhole throats. (Not really "traversable".)
(4) Traversable wormholes with two asymptotically flat regions.
For $\xi \leq 0$ no traversable wormholes.
For $\xi > 0$ get traversable wormholes.

Details: gr-qc/0003025, Barceló–Visser, CQG.

Negative tension branes plus gravity:

Take a negative tension brane and add Einstein gravity.
(Static, spherically symmetric, (3+1)-D.)

(Negative tension branes are now extremely common in brane cosmology, and variants of the Randall–Sundrum scenario. More than 50 papers as of July 2000.)

Absurdly easy problem, surprising result.

— NEC and ANEC are always violated.

— There is a four-parameter class of exact solutions (total mass, brane tension, bulk cosmological constant, electric charge).

Special cases:

Traversable wormholes with two asymptotically de Sitter regions.

Details: hep-th/0004022, Barceló–Visser, NPB.

Specific Implications of EC Violations:

Don't focus on the specific technical details. The main points are:

- Classical violations of the NEC arise in these very reasonable classical systems.

- Conformally coupled scalars are from a QFT perspective the preferred choice — corresponding to the new improved stress-energy tensor.

- Negative tension branes are ubiquitous.

- It's the fact that you get classical NEC violations in such simple physical systems that's worrying — the fact that these NEC violations are big enough to support traversable wormholes is a bonus.

General Implications of EC Violations:

- We do not currently have an acceptable positive mass theorem.

- We do not currently have an acceptable singularity theorem.

- We do not currently have an acceptable topological censorship theorem.

- Traversable wormholes almost begin to look physically reasonable.

- Tolman wormholes almost begin to look physically reasonable.

- This opens up a whole mess of weird possibilities...

Conclusions regarding EC Violations:

We need:

- Improved understanding of just what conditions can sensibly be put on the stress-energy tensor.
  (Quantum inequalities?)

- Improved energy conditions —
  you do not want a free-for-all.
  (Arbitrary stress-energy tensor $\Rightarrow$ arbitrarily weird physics.)

- Improved (positive-mass/ singularity/ censorship) theorems of all types.

Superluminal photons?

Excerpt from “What’s New” [in physics]
by Bob Park
University of Maryland
http://www.aps.org/WN/
Friday, 21 July 2000 Washington, DC

GROAN! LIGHT IS REPORTED TO TRAVEL FASTER THAN LIGHT.

The real news in physics was that the tau neutrino, the last of the fermions predicted by the Standard Model, had been discovered at Fermilab. But front page headlines across the country were proclaiming, “The Speed of Light Has Been Broken”. It’s now going to be impossible to characterize any claim as physically impossible without people scoffing: “that’s what they said about the speed of light”.

Superluminal photons?

“What’s New”

At WN, we’re already getting triumphant phone calls and e-mails from Einstein deniers. Charles Bennett at IBM Watson points out that this is little more than a confused rehash of an old story, where the peak of the wave packet leaving the “superluminal” medium is causally related to just the leading edge of the wave packet entering the medium...

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If you dig deeply enough into the Nature paper:

Wang et al; Nature **406** (2000) 277–279.

“It has also been suggested that the true speed with which information is carried by a light pulse should be defined as the “frontal velocity” of a step-function-shaped signal which has been shown to not exceed c.”

Superluminal photons?

It's more than a "suggestion":

Signal speed = characterisitic velocity

$= c$

= infinite-frequency phase velocity

= infinite-frequency group velocity

— In this situation the "characteristic velocity $= c$" argument is quite enough all on its own.

— There are more complicated systems (Scharnhorst effect in the Casimir vacuum) where "characteristic velocity $\neq c$", but that's another can of worms.

Executive summary:

- FTL is certainly an "active" field.
- Use extreme caution: the S/N ratio is low.
- There is good physics being done here.
- There is also a lot of junk.
- Seek multiple opinions.

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