TIME MACHINES
Space, time, and relativity in science and science fiction

John F. Lindner
PRELIMINARY EXPERIMENT

- If any of us ever invent a workable time machine, let’s agree to return to this moment…

- MIT’s 2005 Time Traveler’s Convention similarly unsuccessful at attracting time travelers
OUTLINE

- Flat spacetime of special relativity
- Curved spacetime of general relativity
- Philosophical Interlude
- Wormholes and timeholes
- Paradoxes?
FLAT SPACETIME OF SPECIAL RELATIVITY
Can an instantaneous cube exist?

Don’t follow you, said Filby.

Can a cube that does not last for any time at all have real existence?

Filby became pensive. Clearly, the Time Traveler proceeded, any real body must have extension in four directions: it must have Length, Breadth, Thickness, and — Duration… There are really four dimensions, three which we call the three planes of Space, and a fourth, Time.

H. G. Wells, *The Time Machine*, 1895
ALBERT EINSTEIN

Theories of Special & General Relativity (1905-1915)
revolutionized our understanding of space & time
HERMANN MINKOWSKI

Einstein’s math teacher found (1908) the idea of spacetime in Einstein’s relativity.
SPECIAL RELATIVITY 1905

- Space & time on equal footing
- But time not identical to space
- Else we could simply walk back to yesterday!
- Geometry of spacetime is non-Euclidean
SPATIAL ROTATION:
EUCLIDEAN GEOMETRY
2D solid
Spatial coordinates \( \{y, x\} \)
Spatial rotation
Parameterized by slope (or angle)
Circular geometry

\[ x^2 + y^2 = \text{constant} \]
1) 1D side corner projections no longer coincident

\[ \delta y \neq 0 \]
2) 1D top projection contracts
3) 1D height projection dilates
SPACETIME ROTATION: MINKOWSKIAN GEOMETRY
Henceforth, space by itself and time by itself are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality

Hermann Minkowski, 1909
1D rod separates \textit{simultaneously} flashing lights ...
... extends in spacetime as a 2D sheet
... extends in spacetime as a 2D sheet
A spacetime rectangle bounded by successive flashings of top & bottom lights
Spacetime coordinates \( \{ct, x\} \)
Rod at rest in the $x$-direction
Rod at rest in the $x$-direction
Spacetime rotation
Rod moves in the positive $x$-direction.
Parameterized by velocity

\[ v = \frac{dx}{dt} \]
\[ x^2 - (ct)^2 = \text{constant} \]
1) Relativity of Simultaneity

\[ \delta t \neq 0 \]

bottom clock flashes early
2) Time Dilation

Flashings slower
3) Length Contraction
RELATIVITY OF SIMULTANEITY

- Clock desynchronization: $\delta t = (L/c)(v/c)$
- If I walk towards you, my present includes your future
- If I walk away from you, my present includes your past
- In spacetime, past and future are as real as the present
- So, perhaps, we can visit them…
The distinction between past, present, and future is only an illusion, even if a stubborn one

Albert Einstein
Motion slows time by a factor $\gamma = \frac{1}{\sqrt{1 - (v/c)^2}} \geq 1$

Can visit the future via speed

Time travel to the future is an engineering problem, but practically very difficult
Time dilation is negligible for terrestrial speeds

\[ \frac{1}{\sqrt{1 - (v/c)^2}} = \gamma \]
Atomic clocks flown around the world in commercial jets travelled ~59 ns into the future (wrt. to twin lab clocks)
GEOMETRIC CONSTRAINTS

- Space-space
  - Largest possible spatial rotation is 360°
  - That’s the largest relative rotation

- Space-time
  - Largest possible spacetime rotation is $c$ 
    ($c$ = the speed of light ~ 1 billion k.p.h.)
  - That’s the largest relative speed
Oh, this began Filby is all —

Why not? said the Time Traveller

It’s against reason said Filby

What reason? said the Time Traveller

H. G. Wells, *The Time Machine*, 1895
CURVED SPACETIME OF GENERAL RELATIVITY
EQUIVALENCE PRINCIPLE

- Einstein’s happiest thought
  - When you fall, you don’t feel your own weight!
  - You can eliminate gravity by freely falling!

- Einstein’s elevator (or rocket)
  - Constant acceleration equivalent to uniform gravity
  - So, gravity is not a true force…
Free objects move along geodesics, the straightest possible lines, in spacetime

But Earth converges these lines toward its center

Hence, Earth must curve spacetime
Matter tells spacetime how to curve, spacetime tells matter how to move

John Archibald Wheeler
MEASURING SPACETIME

- Measure space by filling a displacement with rulers
- Measure time by filling a duration with clock ticks
- Compare spacetime far and near to a star by free floating a ticking clock and a meter stick from far to near
1) Calibrate faraway clocks & rulers
2) Relax! (Free fall from far to near)
3) Compare with star clocks & rulers
1) Calibrate faraway clocks & rulers
2) **Relax!** (Free fall from far to near)
3) Compare with star clocks & rulers
1) Calibrate faraway clocks & rulers
2) **Relax!** (Free fall from far to near)
3) Compare with star clocks & rulers
Compare far away clocks & meter sticks to star clocks & radial meter sticks
Compared to far away observer, star radial lengths contracted ⇒ shorter rulers ⇒ longer displacements ⇒ space warp
Compared to far away observer, star time dilated ⇒ longer ticks ⇒ shorter durations ⇒ slow time
SPACETIME CURVATURE

- **Space Warp**
  - Too much radius
  - Too little circumference \[ C < 2\pi r \]

- **Slow Time**
  - Nearer clocks run slower
  - Farther clocks run faster
Space warp like removing wedge from circle to form cone, which is tangent to the space along the circumference.
So orbiting gyroscopes no longer return to themselves.
MEASURING SPACE WARP

Ultra-precise gyroscopes in polar orbit during 2004-2005 measured one less inch in orbital circumference

Francis Everitt
Stanford/NASA Gravity Probe B
1962 - 2010
MEASURING SLOW TIME

Atomic clock launched in Scout rocket 10,000 km high travelled ~100 ns into the future

Martin Levine & Robert Vessot
SAO/NASA Gravity Probe A, 1976
SR speed & GR height imply opposing time changes

\[ \Delta t > 0 \quad \Delta t < 0 \]
RECORD TIME TRAVELER

Onboard Mir space station
~183 km @ 7.8 km/s for 748 days
travelled ~20 ms into future

Sergei Vasilyevich Avdeyev
APPLICATION:
GLOBAL POSITION SYSTEM

The Concept
The General
The Switch
The Success

GPS nominal constellation
PHILOSOPHICAL INTERLUDE
time is the fire in which we burn

Dr. Tolian Soran, *Star Trek: Generations*
Do physicists have a bad habit of reifying their successful abstractions?

Is spacetime merely an abstract bookkeeping structure invented to organize events?

Are space and time modes by which we think, rather than conditions under which we live?

IS SPACETIME REAL?
TIME UNEXISTS

- All possible configurations of matter exist
- Now you are in Universe A looking at this slide...
All possible configurations of matter exist

Now you are in **Universe A** looking at this slide...

And now you are in **Universe B** looking at this slide (& with memories of looking at the last slide)

All universes are static & change is illusory

Time is simply a way to sequence some of the universes in the multiverse
BOLTZMANN BRAINS

- But aren’t you more probably a lone “Boltzmann brain”, a stochastic fluctuation in a chaotic universe?
- Or is the organization you observe vastly more than what is required to explain your consciousness?
QUANTUM MANY WORLDS

- 1957 Everett interpretation of quantum mechanics (without the random collapse postulate)
- Reality splits at every event into superpositions of many different realities
- Observers experience splitting as randomness
- Science fiction often exploits such parallel histories to avoid time travel paradoxes
WORMHOLES & TIMEHOLES
BACKWARDS IN TIME?

- Flat spacetime of Special Relativity does not allow CTCs (closed time-like curves)
- Curved spacetime of General Relativity does allow CTS, at least classically
World line of particle at rest
World line of particle in uniform motion
Forward light rays at each event form future light “cone”
Light cones constrain your world line, as you always move slower than light.
A CTC is impossible in flat spacetime, where all light cones are parallel.
Extreme mass density can curve spacetime so light cones tip over, permitting CTCs.
CLOSED TIMELIKE CURVES

- Rotating Universe (Gödel)
- Rotating Cylinder (van Stockum, Tipler)
- Traversable Wormholes (Thorne, ...)
- Cosmic Strings (Gott, ...)


I’m afraid I cannot convey the peculiar sensations of time travelling [said the Time Traveller] They are excessively unpleasant

H. G. Wells, *The Time Machine*, 1895
Carl Sagan
Kip Thorne
Mike Morris
Me
A wormhole is a geometry of four-dimensional spacetime in which two regions or “mouths” of the universe are connected by a short narrow “throat” —a short cut through space and time.
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HOW TO CREATE?

Add a handle to spacetime and change its topology?
Inflate a wormhole fluctuation from the quantum foam

\[ \sim 10^{-35}\text{m for } \sim 10^{-43}\text{s} \]
HOW TO STABILIZE?

- Positive mass (energy) gravitates
  - Focuses light
  - Tends to collapse wormhole

- Negative mass (energy) anti-gravitates
  - Defocuses light
  - Can prop open wormholes
EXOTIC MATTER

- So tightly bound that the magnitude of its negative binding energy exceeds its positive mass energy
- Has less energy than a pure vacuum!
- Yet exists in certain quantum physics phenomena
  - Casimir effect
  - Evaporating black holes
  - Accelerated mirror
  - Squeezed states of light
CASIMIR EFFECT

- Force between uncharged conductors due to quantum vacuum fluctuations
- Conductors are so close that only small fluctuations fit in between & the bigger modes are excluded
- Energy density between the conductors is less than outside in the unconstrained vacuum ⇒ less than zero!
Fast starship carries 1 wormhole mouth to Tau Ceti

- $v = 0.99995c \rightarrow \gamma = 100$
- 11.9 light years away
- 12 years for Earth
- 44 days for starship

Since space and time connected via wormhole throat, link to Tau Ceti opens in just 44 days!
Establish permanent time difference between mouths

- Viewed through wormhole, time difference small
- Viewed across “outer” space, time difference large

Techniques

- SR: Add charge to one mouth and spin it around particle accelerator
- GR: Move BH near one mouth until desired time lag accumulates
Wormhole mouth B moves out and back wrt. mouth A
SR time dilation desynchronizes mouths externally but not internally.
This light signal returns 3 days later
This light signal returns 3 days earlier
Backwards-in-time travel possible after 4 days
TIMEHOLE VS. WELLS’ TIME MACHINE

- Wells’ time traveler seems to move through time only
- Does Wells’ time machine travel in space?
  - If not, must it not collide with itself?
  - Earth itself moves at 30 km/s wrt. Sun etc.
- Wormhole time traveler moves through space and ends in the past
Hawking’s chronology protection conjecture:

- CTCs are not physically realizable
- Quantum effects will close any timehole before it can be traversed
- Vacuum fluctuations may pass through timehole infinitely often causing its immediate collapse

CP keeps history safe for historians!
PARADOXES?
OBJECTIONS

- Time Tourists?
- Causality Violation?
- Information Creation?
- Energy Violation?
- Entropy Violation?
WHERE ARE ALL THE TIME TRAVEL TOURISTS?

- You can't use a (timehole) time machine to go back in time to before the time machine was built.
- You can go anywhere in the future, and come back to where you started, but no further.
- We’ll never return to the age of the dinosaurs — unless ETI has already constructed a time machine!
CAUSALITY

- Changing the past
  - The (infamous) grandfather paradox
- Affecting the past
  - Feynman’s tale of frustrated suicide
  - Timehole billiards
Principle of Least Action prevents time travel paradoxes by selecting only self-consistent solutions.

In each case, there's only one ball!
Inventor finds instructions for building a time machine, which she constructs and ultimately uses to send the instructions back to her younger self!

- Who invented the time machine?
- Unusual state of affairs, perhaps, but where does any information come from?
- cf. Robert Heinlein’s “By His Bootstraps”
Energy

- Travel to yesterday to meet yourself
  - Invite your (slightly younger) self to travel back another day to meet yourself again...
  - Form two competing basketball teams
  - Now try duplicating gold bars!
- OK, so long as satisfy conservation laws?
- cf. David Gerrold’s *The Man Who Folded Himself*
An old woman gives a young man a pocket watch

He later goes back in time and gives the now young woman the watch

Who built the watch?

How can the watch be both new and old?

Perhaps the time travel reversed the watch’s entropy increase
AN IMPOSSIBLE OBJECT?

How can the watch be both new and old?

Jane Seymour and Christopher Reeve in *Somewhere in Time*
Robert Heinlein’s “—all you zombies—”

1945

Cleveland Ohio

A newborn girl Jane is found on the steps of an orphanage...
Jane
Jane

Joe

Time Cop

Temporal Service
I know who I am,
but who are
all you zombies?
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Recommended Reading

Black Holes & Time Warps: Einstein's Outrageous Legacy
Kip S. Thorne

Time Machines: Time Travel in Physics, Metaphysics, and Science Fiction
Paul J. Nahin
Second Edition