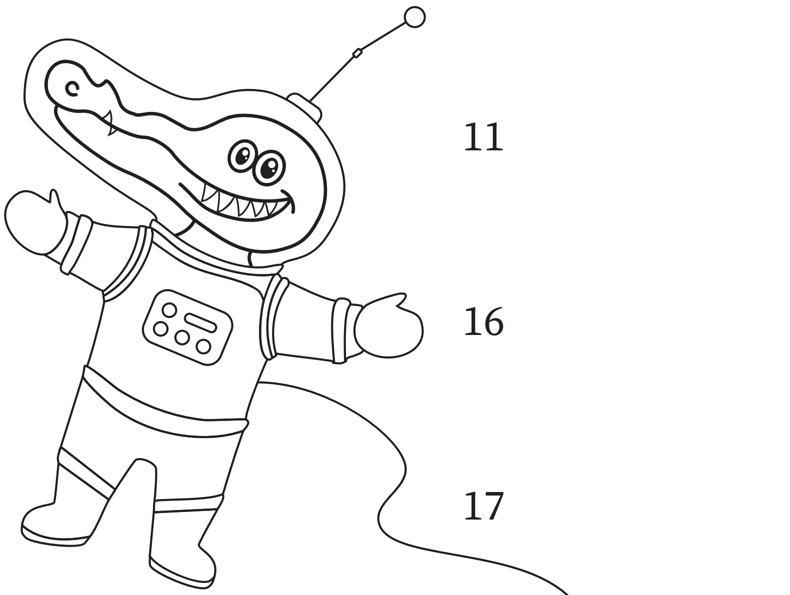

JEREMY
Issue 1, 2025
PHYSOC

Astro Contents



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JEREMY

Issue 1, 2025 *The Physics Society Magazine*

Editorial

Who is this mysterious Jeremy? The editors have long been asking this question, for the magazine has been clouded in conspiracy ever since its enigmatic beginnings in 1986. One theory is that the magazine was named after Jeremy Bentham, a 19th century philosopher and social reformer whose mummified body remains on display in the University College London. A second theory is that the magazine's namesake is Jeremy Rutherford, second cousin to Ernest Rutherford and long serving ticket collector on the London Underground. Yet another theory harkens back to the day when Harry Messel (the Head of the School of Physics in the 80's), after attempting a tracking experiment which involved "flying round in a helicopter shooting anaesthetic bullets into polar bears and then landing on the ice to mark them,"[1] decided to instead track crocodiles; was Jeremy the name of one of Messel's crocodiles? After much distress the editors came across an old, flaky letter from 1986 in an abandoned corner of the physics storeroom, which made the following claim: The magazine was originally named after Jeremy Trefam, a little-known 20th century physicist who, while working on a connection between prime numbers and energy spectra,[2] wrote in a letter to a friend that he had discovered a marvellous pattern hiding within quantum mechanics that allowed for its unification with gravity, but which was too long to fully describe in the letter's margins. Shortly after sending the letter, he died of a sudden stroke, carrying the secret of quantum gravity with him. Is this the true origin of Jeremy's name? The editors are hopeful, but we may never know for sure.

Quote of the Issue

"The Earth is flat"

- Prof. Tim Bedding

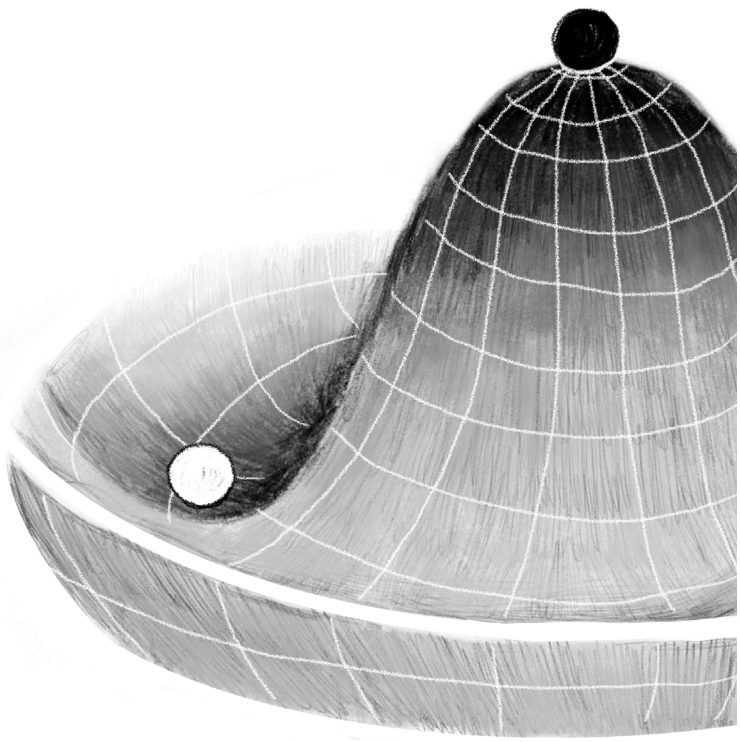
Cheeky context: Tim lecturing PHYS2923 and assuming the gravitation field to be uniform. i.e. the Earth is flat (obviously!)

Would you like to publish your work? Whether it is a short and fun blurb, or a full-on scientific paper, *Jeremy* is a place to kick off your scientific ingenuity! Send your submissions to:

Jeremy.physoc@gmail.com

Meet the School of Physics

Meet our beloved leader, Prof. Tara Murphy! Animal-lover, literature fanatic, and astrophysicist extraordinaire, Tara often finds herself wondering: if I went back in time to ancient Australia or Medieval Europe with modern inventions like radios and antibiotics, how would it alter the course of history?



1. Donald D. Millar, 'The Messel Era', 1987
2. Number theory is filled with quirks, like Fermat's Last Theorem; its fascinating history is too long to fit in this footnote, but have a google.

Monoceros

By Masashige Akioka

I went along Midsummer's night,
Along coasts as white as carcass,
Shooting bare gummed worries into,the Sea—
Like pennies
Tossed into fountains.

Alone, as an eloper's witness, the Moon watched over me
And her tedious eye unfailing, never ailing,
Redoubled convictions that an hour had gone paling,
And in fit of madness, I began soliloquy:

'Upon the shoulders of giants,' Newton
Foreshadowing his stature on eternity
(or his fixture in ours),
Compares nothing to nothing to Nyx's speckled gown
—Tonight, she wears that same impossible dress,
Ancient, named even in Ptolemy's Almagest
And what will I do.
And nothing changes.

"Forty-eight names to name the sky
And where will I… what is there to do?
Since nothing changes."

And long I asked myself:
"This inevitable sky; this irrefutable sea?"
—When along Moon's ichor pathway
A horse came down from heaven,
Shook its mane and spoke to me!

"Dreams and stars," spoke the horse,
"are born to die
But never yet has death won over life:
For long as there is living, stars in skies,
And laughs, then woe to permanence and strife.
"Fourteen billions, the age of Time itself
And mere millions, the age of babe suns
Plucked like encyclopaedias from shelves
Called nebulae, through which the cosmos runs.

"Of types of nebulas, you must know three:
Absorption, emission and reflection,
Whose uniting nature it seems to be
Is altering starlight before you see.
"Blue stars emit their hot celestial light,
Reflection nebulae gather themselves,
And dusty clouds rebound in sapphires bright.
—So, it is said (Ridpath, I, 2012)[1].

(Star Registration, 2025) Monoceros Constellation

"Red gasses cold suffused of ancient star
Give light though dim (emission nebula),
Irradiated by those hot orbs blue;
(Ridpath, I, 2012) declares it true.

(White, T, 2024) Fox Fur and Cone Nebula

"And finally, there is that cosmic lack
Where starlight gets absorbed into the dark
And we are left with nothing more than black,
Says (Ridpath, 2012) if it could bark."

The beast was cast of celestial dust,
Moors of gold. I felt myself sewing shadows through
As if to gouge a hollow,
As if to imprint myself upon it, with a word:
"But beast," I said, "where is there change?
Is the universe a box of wilting leaves and nothing strange?
"I have seen the great eclipse and

1. Said "Ridpath I twenty twelve."

nothing,
I have suffered the mediocrity of my life,
I have waged a war, and I have rebellion,
And it was all for nought,
Since nothing changes."

Curious. Now the creature turned and an ivory protrusion
Like dawn that breaks the night
Split its eyes.

"Two thousand, four hundred light years away,
A young "Cone Nebula" stands bold alive,
In NGC2264[2] it stays (SEDS, 2025)[3].

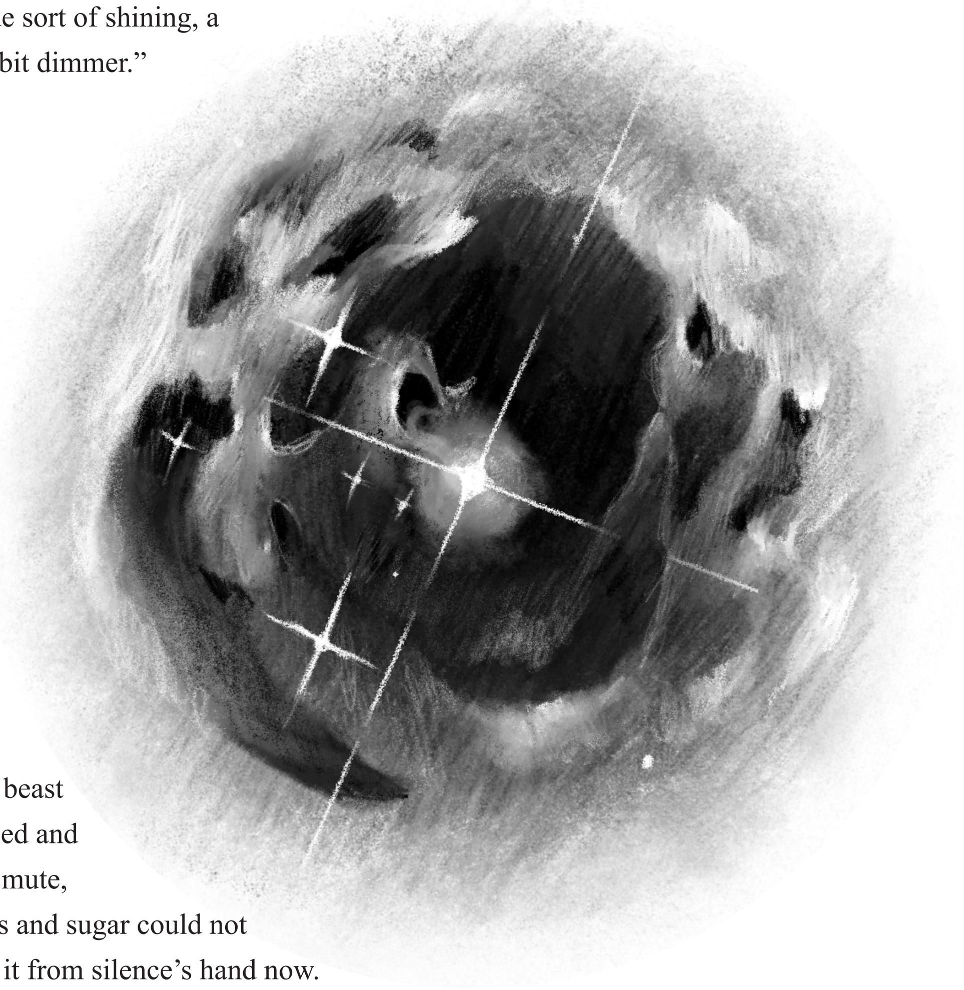
"It's only quite young, five or a couple…
Million years is the age of its blue,
Relative youth in the cosmic timescale
(Parker and Schoettler, 2022)[4].

"From dense and giant molecular clouds
(Determined by watching runaway stars[5])
A million years has formed those large shrouds
Whose mountainous body hides brightly hue,
Of stars that were made in that cosmic churn
(Parker and Schoettler, 2022).

"Absorption Nebula is not alone,
But points to the ruddy face of its friend,
Who also deserves an ode of its own
Of which I joyously sing till the end.

"Oh, Fox Fur Nebula, small segment free
Of that large complex, cluster Christmas Tree,[6]
Your single proton coat[7] emitting light
(Stimulated by those stars hot and blue,
Their radiation ultraviolet bright)
Gives your pelage that reddish-ferrous hue!

"Your aquamarine highlights, your shimmer,
Follows the ruffle and billow of gas
And its sparce composition gives, alas,
A blue sort of shining, a
little bit dimmer."



The
great beast
stopped and
went mute,
Pearls and sugar could not
draw it from silence's hand now.

"Which constellation, and which atom of the sky?"
And the horse went backward, with a sigh
To its origin in heaven.

Long I stood upon my sandy station,
Till I saw the beast arrive
At his shifting celestial destination
To his home within the sky.

2. Said "N G C two two six four."
3. Said "S E D S two thousand, twenty five."
4. Said "twenty twenty two."
5. That is, stars traveling faster than 30 km/s.
6. The Fox Fur Nebula is a small section of the Christmas tree cluster.
7. That is, hydrogen gas.

Gravity: An Entropic Force.

Exploring the realm unveiled by the Second Law of Thermodynamics

By Murray Jones

The realm of physics is a changeable one.

Our cutting-edge theories are developed then rebutted, modified and changed day in day out.

Different takes on almost any idea, from quantum gravity to dark energy, briefly surface to the popular eye only to once again be buried in obscurity almost as quickly as they arrived.
With one exception.

*"**Thermodynamics** is the only physical theory that has never been overthrown."*

-Max Planck[1]

"If your pet theory of the universe is in disagreement with Maxwell's equations then so much the worse for Maxwell's equations. If it is found to be contradicted by observation -- well experimentalists do bungle things sometimes. But if your theory is found to be against the ***Second Law of Thermodynamics***, I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

-Arthur Eddington[2]

"General relativity and quantum mechanics are so fundamentally different that bringing them together in a single theory is a daunting challenge."

-Leonard Susskind[3]

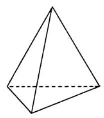
So, when faced with a daunting challenge, why not build a theory based off of the one, single law, that we believe is totally insurmountable: ***The Second Law of Thermodynamics***.

Processes naturally evolve to maximise the entropy of the universe.

Today, my friends, we are going to build a complete theory of gravity, based *solely* on entropy.

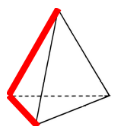
Let's start with the simplest possible example, then work our way up from there.

This, right here, is a **tetrahedron**:



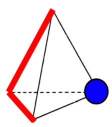
Now, I'm going to impose two very specific rules on our tetrahedron:

1. *First,* we can shine **rays** along any of the edges. An edge either has a ray on it, or it doesn't. Like so:

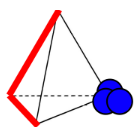


It doesn't matter what it's a ray of; it could be light, could be electrons, whatever. So long as it carries a *causal effect*, it'll do.

2. *Second,* if a vertex of the tetrahedron doesn't have any rays going to it, we put at least one **particle** there:



We don't want the particles getting in the way of the rays, but apart from that we can stick in as many as we like:

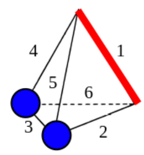


Okay. Now, in our tetrahedron we have six possible ray paths, each along an edge, which we'll label 1 to 6. Each path can either have a ray on it, or be empty. So, we have six possible degrees of freedom.

That means there are a total of $2^6 = 64$ possible states for our **rays**.

Now, for the sake of simplicity, let's consider states that strictly have *exactly two* **particles**. They could be on the same vertex, or on different ones, but there must be exactly two of them in there.

And now the game begins! We throw in an allowed starting configuration (doesn't matter which) ...



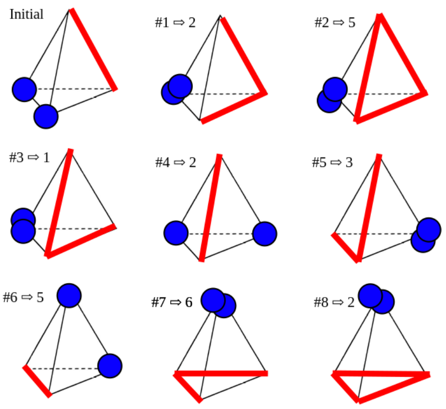
... and grab ourselves a die!
Rolling the die, we note down the number, and . . .

A. if that ray path already has a ray in it, we make it empty, unless doing so would cause there to be more than two vertices that could contain particles.

B. If that ray path is empty, we put a ray in it, unless doing so would leave no possible spots for the particles on an empty vertex.

Now, by repeating this process - throwing our dice over and over simulating the *Thermodynamic Limit* - we generate a whole host of possible arrangements of our rays:

1. Ref. *A Survey of Physical Theory* by Max Planck (1915)
2. Ref. *The Nature of the Physical World* by Arthur Eddington (1928)
3. Ref. *The Black Hole War* by Leonard Susskind (2008).



… and so forth. There'll be 22 possible arrangements of our rays[4]. You get the gist.

Now, in this model there's no explicit *force* between the particles on the vertices of our tetrahedron, so one might hazard a guess that they'll just jump around randomly and be together as often as they're apart.

That guess would be wrong.

There are 16 possible states where they're on the same vertex, but only 6 possible states where our particles are on different vertices.

Since each state in our tetrahedron model is equally likely in the long run, our **particles** will be together more often than they're apart.

Now, this may seem intuitively backward, but since the microstates we're considering are those of our ***rays***, it does actually work out.

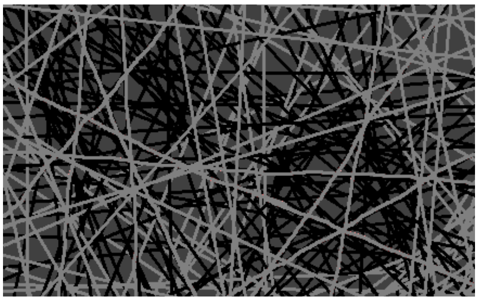
Now, *"what"*, you may very well ask, *"was the point of all that!?"*.

That, my friend, was a *toy*.

A toy model intended to show you the rules of our game in the simplest possible scenario.

Time to ramp things up a notch.

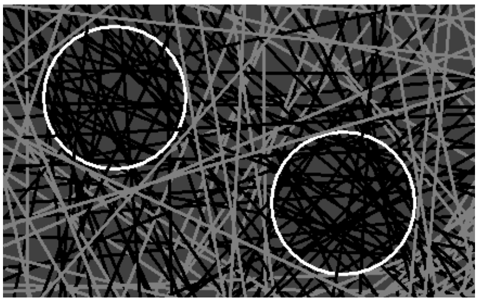
Consider this two dimensional space, criss-crossed by a large number of infinitely long ray paths. Some have rays on them *(grey lines)*, and some don't but theoretically could *(black lines)*. Each ray path is an elementary degree of freedom of our system.



The whole network forms a discrete Planck-scale configuration from which the planar space emerges.

This is called a *'Mikado Universe'*, but that's really just a big fancy name for basically the same thing that we've already seen on our tetrahedron:

- Each ray path is like one of the edges of our tetrahedron, with empty ray paths making no contribution to the entropy of the system.
- We can add in two objects as shown below. This time they're simply circles of a fixed radius.



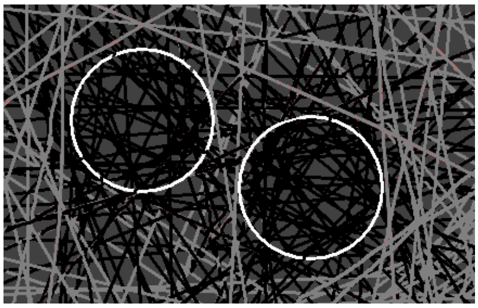
The key point here is that the rules of our system haven't changed; the objects aren't allowed to block rays, so any ray path that passes through an object must be empty.

Time to toss the dice.

After setting an allowed initial condition (like the one shown above), we label our ray paths 1, 2, 3, ..., N, then flip an N sided die, note down what we roll, and ...

A. If the ray path has a ray on it, we make it empty.
B. If the ray path is empty, we put a ray on it, unless doing so would leave no region large enough for our circle of a fixed radius to move to without crossing other rays.

Repeating this over and over and over, something very interesting begins to occur:



*Our **objects** move closer together.*

Simply by playing our dice game -- following the rules of our system -- we observe a tendency for any two objects to move closer together over time, even though all they're doing is chilling in the gaps between the rays, with *no explicit force between them*.

If you followed what was going on in our tetrahedron model, this shouldn't seem all that weird. It's the second law of thermodynamics at work:

- When the two objects are **far apart**, each object *requires* a certain number of ray paths to be empty, therefore reducing the total entropy of our system by some value.
- When the objects are **closer together**, each still requires that all ray paths passing through it be empty, however, this time there'll be some overlap, since many of the ray paths will pass through both objects. These don't need to be counted twice, so the total entropy reduces less when the objects are closer together.

So, since more possible configurations means greater entropy, and our rock-solid Second Law of Thermodynamics is doing its level best to maximise the entropy of the universe, ***entropy itself*** is causing our two objects to be attracted

4. Note that the particles don't contribute to the entropy of our system, because we're essentially modeling them as voids through which a ray of causality cannot pass. More on that later.

to each other.

Phew, okay. Now, this might seem extremely bizarre, but entropic forces are actually a really well established concept in Chemistry. They're the driver behind osmosis, and are directly responsible for the elasticity of long chain polymers.

All we've done is extend this concept by considering a system of ray paths that allows us to model Gravity as an Entropic Force.

Still not convinced? Well, let's put some maths to the problem.

Let's start by calculating the gain in the entropy S as the distance R between the objects reduces.

We've already established that the entropy gain is occurring due to ray paths crossing both objects, so what we really want to consider is the scaling of this value

$$S \sim \frac{r_1 \cdot r_2}{R}$$

where the r values are the radii of each object.

Now, the entropic force F will be proportional to the gradient of this value. So

$$F \sim \frac{dS}{dR} = \frac{-r_1 \cdot r_2}{R^2}$$

where the negative sign indicates that the force is attractive.

Right. Now it's time to take a deep breath, because this next bit is properly weird.

One of the key assumptions for our model was that rays can't go through objects. By our own definitions, rays were anything that carried a causal influence. So, in this model, no causal influence may leave our objects.

Sound familiar?

Yup, we've just gone and modeled every particle of matter as a black hole.

But don't panic! Most of the (hypothesised) weirdness of black holes comes from space-time curvature -- which was more or less a side effect of Einstein's explanation of gravity. Here we have a model for gravity that *doesn't need space-time curvature*, so we don't really have to worry about any of that.

In fact, there's only one property of black holes that we're going to need to consider here, and that is that their radius is proportional to their mass.

So, we can write:

$$F \sim \frac{-m_1 \cdot m_2}{R^2}$$

And this right here is *Newton's Law of Gravitation* -- or at least the guts of it -- derived from purely thermodynamic principles.

BUT WE'RE NOT DONE YET!
Ho ho no we are not!

Newton's Law of Gravitation is an antique little trinket that's been moping around since 1687. We can do better!

This same principle of entropic force can, in fact, be used to fully derive Einstein's Field Equations.

The heart of General Relativity can be conjured up from our insurmountable Second Law of Thermodynamics, without having to rely on notions of space-time curvature.

I'm not going to try and work through the gory maths of that here, partly because Jeremy has page limits, and partly since Liu Tau already has a very elegant derivation of it in his 2020 paper *Holographic Theory, Emergent Gravity, and Entropic Force.*

Instead, we'll strike at an even grander prize.

Dark Energy.

Our universe is expanding increasingly rapidly, and nobody seems quite able to agree on why.

In lieu of an explanation, physicists have taken to terming the effect 'dark energy'.

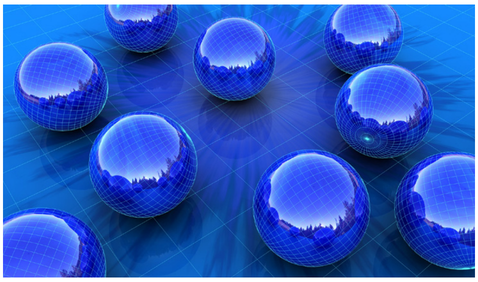
Whatever dark energy is, it's very weak. Its energy density is so low, with a value of approximately $\rho = 10^{-123}$ natural units, that it does basically nothing on all but the most enormous cosmic scales.

This minuscule value of $\rho = 10^{-123}$ has been a real headache for a lot of physicists for a long time. Straightforward calculations based on Quantum Field Theory predict that the value should be pretty close to one.

That's a disagreement between theory and measurement of *123 orders of magnitude*. A discrepancy that many have termed "the biggest embarrassment in the history of theoretical physics".[5]

But, by taking cosmic acceleration to be the result of an entropic force ... *we can solve this -- and it's actually really easy.*

Consider, if you will, a computer screen. The screen itself is only two dimensional, and yet it can display complex 3D graphics with no trouble at all.



To describe something three dimensional, we need only *two* dimensions.

This, in a nutshell, is the *Holographic Principle*, and very soon it's going to allow us to make a very important assumption.

The biggest thing that we definitely know exists is the observable universe. For all practical purposes, it's a ball with

5. Ref. J Koelman and many, many others.

a radius of approximately 2.7×10^{61} natural units.[6]
By the Holographic Principle, encoding the information contained within this ball -- the observable universe -- should require one fewer dimensions: A spherical surface of radius $R = 2.7 \times 10^{61}$ natural units. We call this surface the *cosmic horizon*.

So, our assumption from the Holographic Principle is that all of the information in the observable universe can be encoded in $N = \pi R^2$ ‘bits’, located on the cosmic horizon. Yes we’ve leveraged our natural units quite heavily here -- but that’s the nice thing about natural units -- we can do that!

So, now that we’ve got our $N = \pi R^2$ ‘bits’ -- degrees of freedom -- located on the cosmic horizon, we can do something truly clever.

Per the equipartition theorem, the entire energy $E = mc^2$ (simply $E = m$ in natural units) of the observable universe can be evenly distributed over these degrees of freedom located at the cosmic horizon, with each degree of freedom contributing an energy of $\frac{1}{2}kT$, where k is Boltzmann’s constant.

This means we can associate a finite temperature T with the cosmic horizon. Here $m = 1.4 \times 10^{61}$ is the mass of the observable universe, so

$$
\begin{aligned}
N \cdot \tfrac{1}{2}kT &= E \\
kT &= 2\frac{m}{\pi R^2} \\
&= 3 \times 10^{-64}
\end{aligned}
$$

Now, by applying the holographic assumption to the definition of Entropic Force:

$$
\begin{aligned}
F &= kT\nabla N \\
&= kT\nabla\left(\pi R^2\right) \\
&= 2\pi kTR
\end{aligned}
$$

Now, since dark energy density and cosmic acceleration are equivalent by definition when using natural units, we can compute a value for the dark energy density predicted by our entropic model as follows:

$$
\rho = \frac{1}{R}\frac{d^2}{dt^2}R
$$

Finally, using newton’s second law, $F = ma$, we get:

$$
\begin{aligned}
\rho &= \frac{1}{R}\frac{F}{m} \\
&= \frac{2\pi kT}{m} \\
&= 1.3 \times 10^{-123}
\end{aligned}
$$

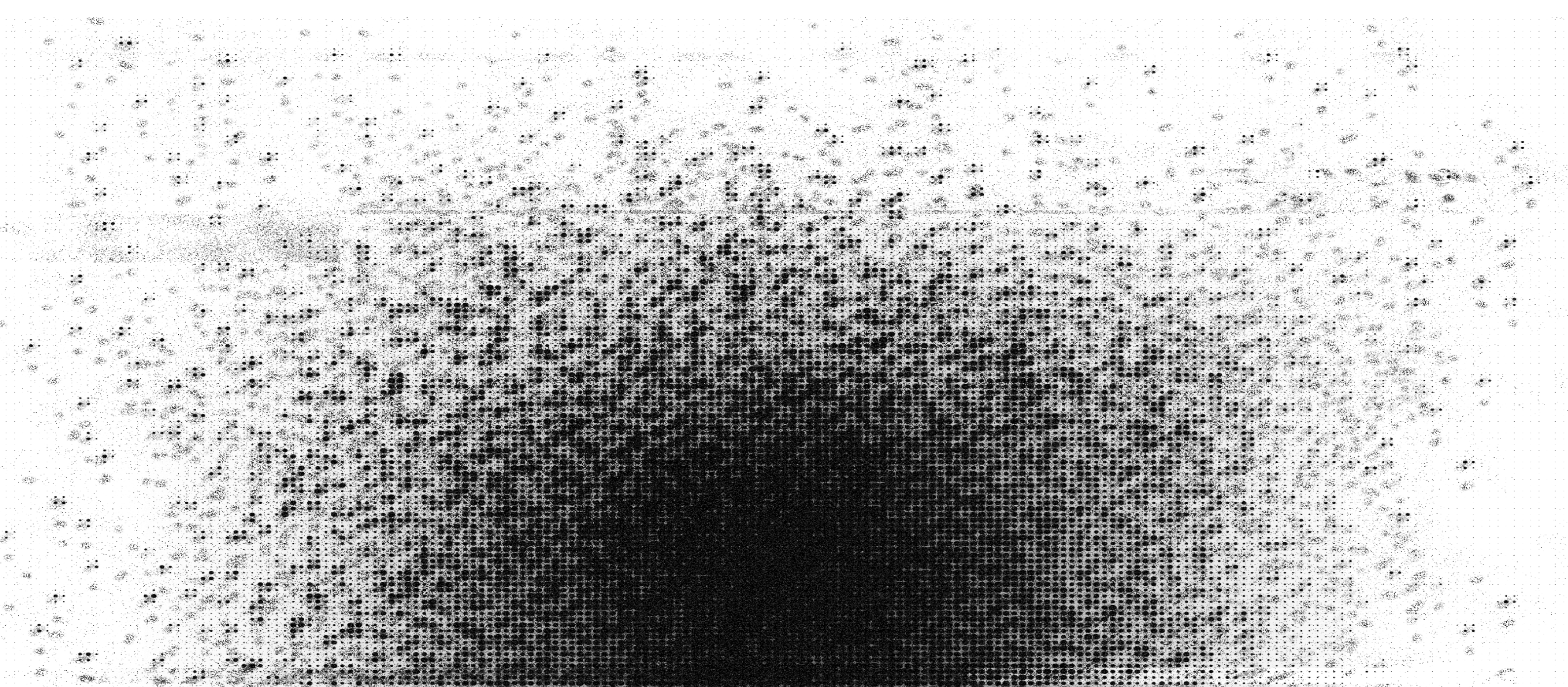
Lo and behold.

We’ve just built a model of Dark Energy that matches observations for which the widely accepted Quantum Field Theory fails spectacularly.

References

1. Verlinde. (2011). *On the Origin of Gravity and the Laws of Newton.* Journal of High Energy Physics, 2011(4), 29. (arXiv:1001.0785)
2. Liu, T. (2020). *Holographic Theory, Emergent Gravity, and Entropic Force.* University of Florida.
3. J Koelman. (2010, March 26). *Entropic Gravity For Pedestrians.* Science 2.0.
4. J Koelman. (2010, January 18). *How To Get Rid Of Dark Energy.* Science 2.0.

6. Natural units are a system of units achieved by setting Boltzmann’s constant, the speed of light, the gravitational constant, and the reduced Plank constant to all be simply one. With them, we no longer need to consider most of the constants in our equations, and have far fewer unit conversion issues to worry about than we would if we were using the metric system. Natural units can still scale linearly to metric.



The Race to Beat Einstein

By Peter Lavilles

An agitating breeze ruffles through Einstein's notebook. It is the autumn of 1915, and he has not been able to sleep for days. Amidst a roaring world, he can feel his fingertips closing around the cloth draping the universe, but time is ticking as the world's greatest mathematician joins the race to discover the dance of our universe's garment - Einstein furrows his brow, deep in thought...

The passage of time is closely interwoven with distances in space, for they are shadows of the same whole. Time and space are braided together into a single 4D manifold clothing the universe which curves, giving rise to gravity. This spacetime garment's behaviour can be captured within an Equation, and the streets of Göttingen are holding their breath in anticipation as Albert Einstein and David Hilbert race to find this Equation. Where could we begin to look?

It is helpful to first picture spacetime as a large rubber sheet. A point on this sheet represents an event, a certain place at a moment in time, which can be described by four numbers, $(t \quad x \quad y \quad z)$ called *coordinates*. To save ink, let's write these numbers as x^μ; Greek symbols like μ mean "run through all four coordinates".[1]

To describe spacetime, we need the notions of direction and change at a single point. Luckily, there already exist mathematical objects that do this!

To examine a function in the direction of the y coordinate, the partial derivative $\frac{\partial}{\partial y}$ is used. Taking away the function and leaving just the partial derivative, we see that it is an object encoding direction at a point. There are four such objects, $\frac{\partial}{\partial x^\mu}$, one for each coordinate. Let's draw them as little red arrows (see Figure 1)[2].

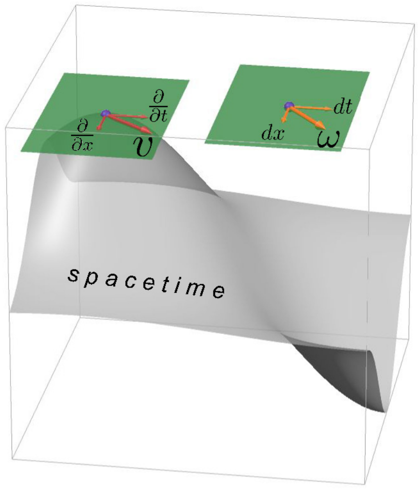


Figure 1. A 2D depiction of spacetime with tangent and cotangent spaces at a point containing the vector v, or v^μ, and covector ω, or ω_μ (drawn on Desmos).

To compare how a function changes overall as the t coordinate changes, the total derivative is taken, which is the function's infinitesimal ratio with dt. Treating dt as an object in its own right, we see that it encodes change at a point. There are four such objects, dx^μ, which will be drawn as little orange arrows.

The $\frac{\partial}{\partial x^\mu}$'s and dx^μ's are like Lego bricks; these basis elements are our fundamental building blocks, and at each point in spacetime they can be put together in different combinations.

Something can be built from just the little red arrows by first taking a certain amount of each $\frac{\partial}{\partial x^\mu}$; the amounts, or *components*, are written as v^μ. We then add up the little arrows weighted by these components to give an object called a vector $v = v^\mu \frac{\partial}{\partial x^\mu}$, which looks like a larger arrow[3]. Straight objects like vectors cannot be built on a bumpy rubber sheet, so they need a flat tray to live in, called a tangent space (the green plane in Figure 1).

Similarly, something can be built using just the little orange arrows by summing over the dx^μ's weighted by components ω_μ to give a dual object called a covector $\omega = \omega_\mu dx^\mu$, which again looks like a larger arrow. Covectors need their own flat home at the same point called a cotangent space.

Pairs of the little arrows can also be combined together, for example, one red and one orange. Each pair combination is weighted by a component M^μ_ν (upstairs indices for little red vector arrows and downstairs indices for little orange covector arrows), and summing up these weighted combinations gives an object called a tensor $M = M^\mu_\nu \frac{\partial}{\partial x^\mu} \otimes dx^\nu$, which can be visualised as a 4×4 matrix[4]. Tensors live in mansions atop the tangent and cotangent trays at each point in spacetime.

The star of the show is ready to make their appearance - enter the *metric tensor* $g_{\mu\nu}$, who plays the role of the unknown variable in the coveted spacetime equation[5]. Their power is to yank a vector ω^μ into the cotangent space, turning it into the covector ω_μ while transforming its new components[6]. This power is used to

1. μ is an index which runs from 0 to 3, labelling the coordinates as $(x^0 \quad x^1 \quad x^2 \quad x^3) = (t \quad x \quad y \quad z)$.
2. Figure 1 only shows a 2D cross-section of spacetime that has been embedded into three dimensions for visualisation purposes, since it is not easy to intrinsically visualise four dimensional manifolds.
3. I use the convention throughout that repeated indices implicitly sum over all four coordinates.
4. Tensors satisfy a transformation rule ensuring that they are coordinate independent.
5. From now on I will name vectors, covectors, and tensors after their abstracted components, leaving out the implied $\frac{\partial}{\partial x^\mu}$'s and dx^μ's.
6. The inverse metric tensor $g^{\mu\nu}$ does the opposite, turning covectors into vectors.

define the notions of length and angle, hence capturing the geometry, or overall shape, of spacetime.

Since length involves quantifying change along a direction, the squared length of a vector ω^{μ} is determined by first yanking it into the cotangent space using $g_{\mu\nu}$ and then adding up the products of components[7], or

$$g_{\mu\nu}w^{\mu}w^{\nu} = w_{\nu}w^{\nu} = \| w \|^2$$

A peculiarity of spacetime is that squared lengths of vectors don't have to be positive. We see light travelling at a speed c, but light sees itself travelling instantaneously (speed is relative!) since its motion (spacetime velocity vector) has zero squared length. Anything we see moving slower than c has positive squared length and is causally possible. If we saw something moving faster than c, its motion would have negative squared length and it would see itself moving back in time. Thus, by determining length, the humble $g_{\mu\nu}$ defines time travel![8]

The angle θ between two vectors ω^{ν} and v^{μ} is found again using $g_{\mu\nu}$'s yanking ability, in analogy to the dot product:

$$g_{\mu\nu}w^{\nu}v^{\mu} = w_{\mu}v^{\mu} = \cos\theta\,||w||\,||v||$$

In our Solar System, spacetime's geometry bends so that the planets move freely with a constant angle relative to their separation from the Sun. By determining angle, $g_{\mu\nu}$ places the planets into orbit.

The protagonist $g_{\mu\nu}$ who controls spacetime's geometry has been found, but we need to know what actually pushes on spacetime to make it curve! The antagonist now takes the stage, the stress-energy-momentum tensor $T_{\mu\nu}$.

The latter gives the flux of energy and momentum through spacetime. What the heck does that even mean?? Well, energy E is the amount of oomph objects have through time; anything with mass contains energy. Momentum $\overrightarrow{p}$ is the amount of oomph objects have through space; a train hurtling toward you contains a lot more momentum than a train crawling past[9]. Think of energy and momentum together as a fluid substance flowing like a river through spacetime.

Finding *flux through spacetime* involves cutting spacetime into 3D slices with different orientations and measuring the flow of the energy-momentum `fluid' through them. If a cross section perpendicular to the time direction is taken, then `flux' is the same thing as density, or the amount of stuff per spatial volume. The first column of the $T_{\mu\nu}$matrix gives the density of energy and momentum. The other columns of $T_{\mu\nu}$ measure cross sections perpendicular to each spatial direction, where 'flux' means the rate of change per spatial area. The flux of momentum can be further separated into pressure (diagonal terms) and shear stress (off-diagonal terms)[10].

In a stroke of genius, Einstein realised that gravity is an effect from the curvature of spacetime's geometry, as caused by $T_{\mu\nu}$. The protagonist $g_{\mu\nu}$ is joined by their sidekicks, the Ricci tensor $R_{\mu\nu}$ and Ricci scalar R, who describe curvature[11].

Place two marbles on the spacetime sheet in Figure 1 and let them roll freely side by side. The curvature in the sheet sometimes makes the marbles move closer together, and this 'attraction' is what we call gravity. The effect occurs because time and space have bunched up. To quantify this squashing, push a pin into the peak of the hill in Figure 1 and tie a short length of string to it with a pencil attached at the other end. Keeping the string tight and trapped to the surface, rotate it to draw a circle with the pencil and paint its interior. This circle contains less area (uses less paint) than a circle of the same radius drawn on a flat piece of paper, because the string is able to capture more area in flat space than in cramped `positively curved' space. For infinitesimal lengths of string, the difference in area between these two circles is called the Gaussian curvature K.

To find the top-left R_{tt} component of $R_{\mu\nu}$, cut spacetime into the three 2D orientations that contain the t direction, and sum up the K for each of these cross-sectional slices (Figure 1 shows the (t, x) cross-section). The diagonal terms of $R_{\mu\nu}$ give the total K for 2D cross sections containing the νth direction. $R_{\mu\nu}$'s off-diagonal terms do a similar thing, but measure curvature interactions between different directions[12]. This effect can be entirely packaged into a nice single number R, which is like a 4D analogue of K. Instead of tracing out a circle with the pencil, we trace out an infinitesimal 3-sphere, and R gives the difference in its 4D volume between flat and curved space.

We are nearly at the finish line! All of the characters for the equation have

7. This is the exact same machinery as the dot product, which first yanks a column vector into a row vector (with the same components since $g_{\mu\nu}$ is the identity matrix in flat cartesian space) then adds up the products of components, yielding the vector's squared length.

8. 'Forwards in time' can be chosen to have either a positive or negative signature.

9. Energy E/c is equal to relativistic mass γm (the object's resistance to direction-changing forces) weighted by c. $\overrightarrow{p}$ is equal to γm weighted by the object's velocity.

10. The rate of change of momentum is force $\frac{d\overrightarrow{p}}{dt} = \overrightarrow{F}$, and stress is force per area; it is called pressure if it is perpendicular, and shear stress if it is parallel.

11. $R_{\mu\nu}$ and R describe volume-changing curvature caused by internal $T_{\mu\nu}$ sources; the Weyl tensor describes shape-distorting curvature, or follow-on tidal effects from far-away sources, hence does not appear in the equation.

12. The component $R_{10} = R_{xt}$ parallel transports the basis vector $\frac{\partial}{\partial x}$ around infinitesimal parallelograms with $\frac{\partial}{\partial t}$ as one axis, inner products (projects) its deviation onto each parallelogram's second axis, and sums up these projection amounts.

been found, and now they are just missing a script. We will place the source $T_{\mu\nu}$ on the right side of the Equation, so the effect of curved spacetime geometry involving $g_{\mu\nu}$, $R_{\mu\nu}$, and R must be on the left side. The final leg of the race is to guess what combination they appear in.

To do this, the local conservation of the energy-momentum fluid is imposed: in small regions, energy and momentum cannot be created or destroyed. We need to see how the vectors making up this fluid change over spacetime, but, since vectors live in separate tangent spaces at different points, we can't just use the partial derivatives $\frac{\partial}{\partial x^\mu}$ which are stuck within a single tangent space. Instead, we choose an upgraded version of the partial derivative called the covariant derivative $\nabla_{\mu\nu}$, which can creep around a curved space without twisting[13]. Enforcing the conservation of energy-momentum simply requires that $T_{\mu\nu}$ has zero divergence, or $\nabla_\mu T^{\mu\nu} = 0$[14]. Therefore, whatever is on the left side of the Equation also requires zero divergence for consistency. Here a bit of maths comes in handy. Curvature satisfies certain properties, one of which is the Second Bianchi Identity. By plodding through some manipulations, it can be used to show that the specific combination $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$ has zero divergence. The non-twisting ∇_μ we chose also tells us that $g_{\mu\nu}$ has zero divergence, so a constant multiple of it can be added to the left side. Finally, putting the left and right sides together, we find

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu} \quad (1)$$

After an exotic journey, we have discovered the final spacetime equation! Within its ciphers lies a thrilling drama. The free motion of objects is guided by the geometry of spacetime $g_{\mu\nu}$ and yet the distribution of the universe's objects $T_{\mu\nu}$ pushes on $g_{\mu\nu}$ to make it curve in the form of $R_{\mu\nu}$, setting up an endless conversation between the universe and its constituents. In the words of Wheeler, "Spacetime tells matter how to move; matter tells spacetime how to curve."[15] κ is a constant (a certain number) that controls how sensitive spacetime is to curving. $R_{\mu\nu}$ and R are expressible in terms of $g_{\mu\nu}$ and each index runs through four coordinates, so equation (1) actually describes ten equations in the unknown components of $g_{\mu\nu}$.[16]

Λ is a number called the cosmological constant, which tells its own remarkable story. If Λ is positive and it is placed on the right side of the equation, it acts as a source of constant positive energy in the vacuum of space with negative pressure[17]. It was recently discovered that some unknown energy source called *dark energy* is driving an accelerated expansion of the universe, and Λ may well be this mystery energy.

The equations have been found, but who won the race? Hilbert presented an alternative formulation of the equations via an action-minimising principle five days before Einstein, but Einstein, the originator of the whole program, was the first to publish the equations as presented here (initially without the Λ term).[18] In honour of the physicist who founded the revolutionary theory of gravitational spacetime, or general relativity, these ten equations are known as the Einstein Field Equations.

A sudden idea flashes up and Einstein's mind starts racing. Could it work? He grabs his pen and starts writing symbols in his notebook, scribbling through lines of maths, and... it works. He is already running out the door, rushing to the Prussian Academy of Sciences to present his final equations that shatter the old paradigm of gravity. When Newton's apple fell from a tree, it was being guided by a garment of time and space that ripples and curves in an endless cosmic dance.

References

Many descriptions drew from both the mathematics found in Baez and Muniain's 'Gauge Fields, Knots and Gravity' (1994) and Lee's 'Riemannian Manifolds: An Introduction to Curvature' (1997) and from videos by the Youtube channels 'EigenChris' and 'Physics Videos by Eugene Khutoryansky'. Ville Hirvonen's introductory general relativity course on profoundphysics.com was a helpful starting point. I would like to thank Prof. Geraint Lewis and Dr. Emma Carberry for their feedback on a previous draft.

13. ∇_μ can be chosen in many ways, but there is a unique such choice called the Levi-Civita connection that both preserves the metric and has zero torsion, or 'twisting'.

14. This condition sets up continuity equations for the local conservation of E and $\vec{p}$. We have 'raised the indices' of $T_{\mu\nu}$ by using $g^{\mu\nu}$ to yank its underlying basis covectors into vectors.

15. J. Wheeler 'Geons, Black Holes, and Quantum Foam' (1998)

16. They are highly nonlinear coupled second-order partial differential equations that are notoriously difficult to solve. There are 10 because the tensors are symmetric.

17. In small enough regions spacetime appears flat, so $g_{\mu\nu}$ is the identity matrix except with $g_{00} = -1$, and, like $T_{\mu\nu}$, $-\Lambda g_{\mu\nu}$'s diagonal terms give energy density and pressure.

18. I. Todorov, `Einstein and Hilbert: the creation of general relativity' (2005)

Vacuum Decay: A Simple Blueprint for Cosmic Doom

By Caleb Clark

The end of the universe. It's something humans from all civilisations have pondered. From ancient speculation to modern theories of the Big Crunch or Heat Death of the cosmos on a massive cosmological scale. But what if there were a mechanism for our demise baked into fundamental quantum physics, capable of obliterating us in an instant; and what if I told you that this same mechanism is key for the foundational stages of the Big Bang? What if I told you it also lends a hand to modern developments in a variety of technologies? And best of all, that we can wrap our minds around the core idea of this process through a journey that takes us through the (post-Newton) language modern physics is written in, and alongside one of Feynman's boldest ideas? I'd say you'd be about as stoked as Peter Higgs in 2012 - maybe even more, since you don't need a billion-dollar collider to read this article. Introducing – a classical model for false vacuum decay.

Equipping our toolset

Let's get concrete. The Higgs field, which critically underpins the fundamental physics of our universe, can align into a shape that resembles one of Fig 1 (the symmetric double well) or Fig 2 (the asymmetric double well). In fact, this alignmnent is what breaks the electroweak symmetry in the early universe, giving W/Z bosons their mass. The question of which double well is at the moment not fully resolved, but luckily both problems are reasonably tractable, especially with a simpler approach: instead of considering the 3-dimensional field $\varphi(x, y, z, t)$ as a function of position, we will simply by analogy consider a single function of time $x(t)$.

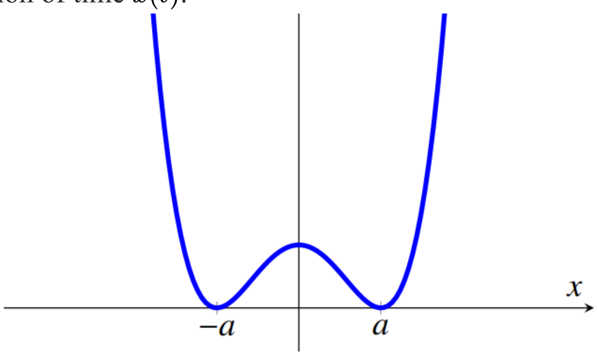


Figure1: Symmetric double well as described by Eq.1, $\varepsilon = 0$

We could write a simple model for this well's potential as

$$V_A\Big(x\Big) = \lambda\Big(x^2 - a^2\Big)\left(x^2 - a^2\right)^2 + \varepsilon x \qquad \Big(1\Big)$$

where x could be the position of a quantum particle, or the value of a field; $a > 0$ is the well's width and $\lambda > 0$ its height, and $\varepsilon \geq 0$ a small parameter characterising a shift from the symmetric well towards asymmetry. For the symmetric double well, we'll address the case $\varepsilon = 0$, and for the asymmetric well we will lift it to $\varepsilon > 0$. Each minimum of the well is a state a particle could be in; for instance the Higgs field's current minimum determines its non-zero vacuum expectation value of $\langle\varphi\rangle \approx 246$ GeV, which in turn gives it the ability to imbue certain particles with their mass.

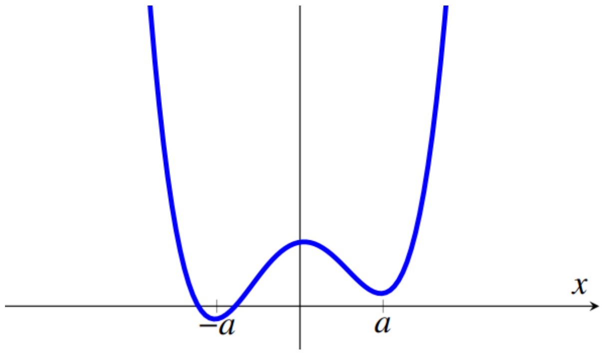


Figure 2: Asymmetric double well as described by Eq.1, $\varepsilon > 0$

Now that we have our potential, we want to ask the question: ***what is the probability that a particle (or field) could transition from one state to the other?*** This question carries a great significance, for if the Higgs field exists in a 'false vacuum' state (i.e. a state that looks stable locally but is not the global minimum of potential, which would be the 'true vacuum') like that of the asymmetric well, there may be a probability of it tunnelling to the lower energy state. This would rapidly expand a 'true vacuum bubble' in all directions, kicking all Higgs fields into the global minimum and activating radically different laws of physics wherever it touches. The subsequent decay that ensues would be 'the ultimate ecological catastrophe' [2], releasing vast amounts of energy, and possibly increasing entropy significantly. The fundamental laws that currently allow our atoms, our cells, and those of stars to be stable would be completely rewritten, and we may dissolve into mere quarks and electrons, or even just pure energy. The double well potential here actually goes far beyond genuinely permitted but sci-fi-sounding armageddon scenarios. It can also be used in quantum gates, information processing, the generalised Josephson effect, or even as recently as 2024, when a genuine vacuum decay of a particular order parameter was observed in ferromagnetic superfluids [3].

To make our question more precise, we will visit the Lagrangian formalism of classical mechanics. Remember Newton's force law $F = ma$, the foundation for essentially any problem in first-year mechanics involving predicting motion of objects. Now, remember how sometimes it was easier to analyse a problem with respect to energy conservation? The more sophisticated version of this is something called the Lagrangian, and for our purposes it is equivalent to kinetic energy T minus potential V:

$$\mathscr{L} = T - V$$

From this, like how Newton's law would give us a differential equation of motion in terms of x via $\frac{F}{m} = \ddot{x}$, we also extract an equation of motion from the Lagrangian by minimising 'action' (described soon):

$$\frac{d}{dt}\frac{\partial \mathscr{L}}{\partial \dot{x}} = \frac{\partial \mathscr{L}}{\partial x} \qquad (2)$$

and for our potential, this gives

$$\ddot{x} = -V'(x). \qquad (3)$$

Again, this is just a more sophisticated version of $F = ma$, and indeed here it reduces to that case if you plug in the right variables.

Now, if you were to imagine a ball in a 'valley' outlined by Fig 1 or 2, initially sitting still, there is *no classical chance* it could roll from one minimum to another. But we know about quantum tunnelling, where particles of energy E can surmount the odds and cross through a barrier of energy $> E$. There is in fact an easy fix to implement this tunnelling into our theory, but it may shatter your currently established conceptions of space-time. The trick is to \emph{rotate time to become imaginary} (called 'Euclidean time'):

$$t \mapsto it = \tau.$$

If we accept this bit of 'magic', and twist our derivatives to incorporate τ, we see in $\mathscr{L}$ that the relative sign of the kinetic to potential energy flips; equivalently, we could imagine the potential of Fig 1 to be upside down, as in Fig 1. Now it's perfectly intuitive to imagine a ball rolling down from the top of the hill, picking up some speed, and then coming to a stop at the top of the other hill, i.e. our old minima![1]

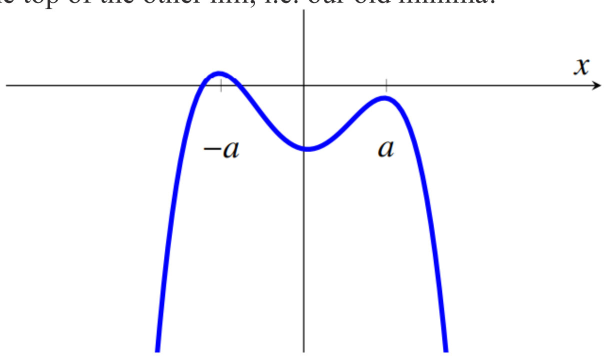


Figure 3: Asymmetric double well as described by Eq. 1, with the same parameters from 2, viewed in Euclidean time, resulting in a flipped potential.

Now for the so-called 'action'. An analogy helps: think of a particle as a submarine, and the Lagrangian as 'amount of fuel used per second'. The pilot of this submarine will of course take the allowed path which minimises the total amount of fuel used, even if there might be many other paths which use more fuel. This total amount of fuel used per path is the 'action'. We can define it mathematically as:

$$S_E\big(\text{path}\big) = \int_{\text{path}} d\tau \mathscr{L}_E \qquad (4)$$

where the subscript E here stands for the fact that we are working in Euclidean ('imaginary') time. Finding the path which minimises[2] this action is directly what gives the equations of motion from before!

Now our final tool needed is the 'Feynman propagator' K_E . Here we throw out the classical notion of a particle only taking one given path, and embrace the quantum notion first introduced by Feynman: *particles simultaneously take an infinite number of different paths*. It's hard to imagine for our submarine, but that's because we have *monkey throw rock* brains, not *photon travel through slit* brains. (Yes, the double slit experiment for particles can be explained by this notion too!)

.. The propagator then represents a transition amplitude from a point x_1 to a point x_2. In Euclidean time, it can be calculated as:

$$K_{E,x_2 \hookleftarrow x_1} = \int \mathscr{D}x e^{-\frac{S_E(x)}{\hbar}} \qquad (5)$$

Here we are integrating over all possible paths with the fancy $\mathscr{D}x$; and the $e^{-\frac{S_E(x)}{\hbar}}$ factor can be interpreted as a probability for each path. This actually explains, from a quantum perspective, why we minimise action to obtain our classical paths: we are taking the quantum $\to$ classical limit $\hbar \to 0$, and the only path that survives is that with the lowest action S_E. Importantly, the physical interpretation of this propagator is that its *square-modulus* $|K_{E,x_2 \hookleftarrow x_1}|^2$ *gives the probability of transition*.

So we have reduced our question from the vague "how do we calculate transition probability between minima" into the more computationally tractable "let's perform an integral over all paths to get the Feynman propagator, using Euclidean time". Let's give it a shot!

Symmetry comes first

Firstly, there is some analogy to the classical approach which finds only a single path between two points. The way

1. And don't worry too much about any physical interpretations of this 'imaginary time' - we can just think of it as an equivalent, but much easier computational path to our transition probability.
2. Technically, extremises, since are just asking for the first derivative to be 0.

to think about our approach here, is that we will find a single, classical, 'most probable' path (in Euclidean time), then account for all possible deviations from that path weighted by probability, to give an approximate answer from the rest of the propagator machinery. We will do this first for the symmetric well, and then for the double well.

The most probable path is ironically the exact solution a classical particle living in Euclidean time would take. By solving the equation of motion, to get an absolute minima for the action, we meet the final character of this story: the *instanton*. This is a kink between the two minima (or maxima in Euclidean time) of the potential well, following the shape of a hyperbolic tangent curve:

$$x_{\mathrm{cl}}\left(\tau\right) = a\tanh\left(a\sqrt{2\lambda}\tau\right). \tag{6}$$

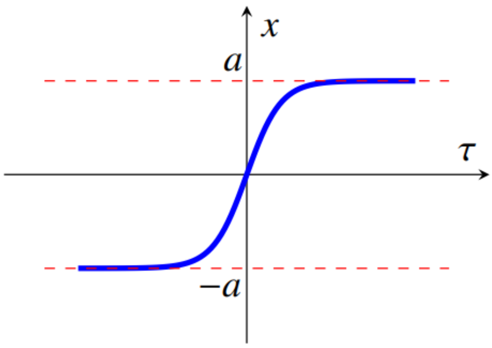


Figure 4: An instanton, described in Eq. 6, moving from -a to a in Euclidean time.

We can calculate the action, and thus the propagator, straightforwardly for this solution, obtaining an action

$$S_{\mathrm{cl}} = 2a^3\sqrt{\tfrac{\lambda}{27}}. \tag{7}$$

Now we can modify the action of a single instanton to incorporate all possible paths (from one minimum to another) in two main ways.

First, once the particle has followed an instanton (I) and established its position at one minima, after a sufficient amount of time, it could follow an 'anti-instanton' (Ai) back to the first minima. And keep doing this, over and over. Each different arrangements A path with I $\rightarrow$ Ai $\rightarrow$ I $\rightarrow$ Ai $\rightarrow$ I is less likely than a simple I, or a I $\rightarrow$ Ai $\rightarrow$ I path with less Ai $\rightarrow$ I pairs; but since we are integrating over *all possible such paths*, we must still include these.

Second, the particle could wiggle a bit along the way to another minima, deviating from the standard instanton curve. To incorporate this we introduce a deviation term y in our new path $x(\tau) = x_{\mathrm{cl}}(\tau) + y(\tau)$, and then integrate over all such y. I won't get into the details of this or any other spicy integration that happens here, but there's a pretty nifty infinite-dimensional generalisation of the Gaussian integral to calculate the final propagator here. As well as this, the fact that we are allowed to expand about our x_{cl} in the first place is essentially the result of the steepest-descent approximation to an integral

$$\int dx e^{-Mg(x)}$$

containing a local minima of $g(x)$ with $M \gg 1$.

Our final result for the symmetric well then ends up with the following form:

$$K_{-a\rightarrow +a} \approx Ae^{-\frac{S_{\mathrm{cl}}}{\hbar}} \tag{8}$$

where to simplify, this A is a constant which absorbs any of the other quantum fluctuations emerging from the above discussion. This form will be of great help to us in the next section as we tackle the asymmetric well.

Tackling asymmetry head-on

Now when we consider the case $\varepsilon > 0$ in our potential from earlier, we find that the minima on the left tilts to a lower potential. Furthermore, both minima shift left from $\pm a$ by $\frac{\varepsilon}{8\lambda a^2}$, so our path must be different. Since this deviation ε is assumed to be small, we can assume our *new 'classical' path* $x_{\mathrm{clA}}(\tau)$ is only a small deviation away from the instanton path,

$$x_{\mathrm{clA}}(\tau) = x_{\mathrm{cl}}(\tau) + \varepsilon f_{\varepsilon}(\tau) \tag{9}$$

where we characterise the asymmetric (A) deviation through the function f_{ε}. Substituting this ansatz into the equation of motion Eq. 3, and neglecting high order terms like ${f_{\varepsilon}}^2$, we obtain a new differential equation to solve for f_{ε} (with overdots being $\frac{\partial}{\partial\tau}$):

$$\ddot{f} = 4\lambda\left(3{x_{\mathrm{cl}}}^2\left(\tau\right) - a^2\right)f + \varepsilon. \tag{10}$$

It turns out to be too difficult to extract any direct solutions from this. Instead, we borrow the classic physics trick of approximate-and-hope-it-works. We analyse separate asymptotic regions: $t \rightarrow \pm\infty$ and $t \rightarrow 0$. Imposing the boundary conditions that our particle does eventually reach the minima despite any deviation along the way, and using a third order power series for the $t \approx 0$ region (the most informative approximation that could be made easily solvable), we obtain three distinct solutions. We can glue these together by setting the boundaries between the regions as $\tau = \pm\frac{1}{a\sqrt{2\lambda}}$ (the same as the instanton width), and enforcing that f_{ε} is continuous and differentiable at these boundaries; the result is seen in Figure 5.

Armed with this classical path we can now move onto calculating the Euclidean action, and then shortly after the transition probability, using the $K \approx Ae^{-\frac{S_{\mathrm{cl}}}{\hbar}}$ approximation of earlier.

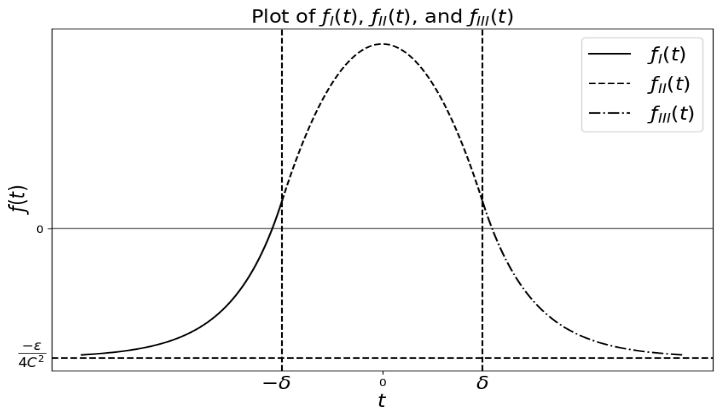


Figure 5: Graph of $f(\tau)$ for all regions simultaneously, showing continuous differentiability at region boundaries $t = \pm\delta$ as well as throughout.

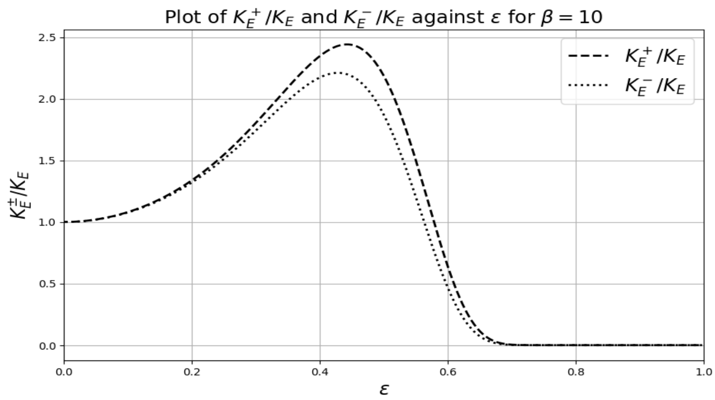


Figure 7: Ratios of propagators to $\varepsilon = 0$ case plotted on a linear scale against ε for $\beta = 10$

Findings of questionable accuracy

However what we can do, which is much more instructive, is to graph the results we get, as a function of ε, and in particular the ratio of our new calculated propagators $K_E{}^\pm$ (where $+$ stands for transitions to the minimum with larger potential energy, and $-$ toward the lower potential energy) against the symmetric K_E. In these graphs β is the amount of time we wait for the transition to occur; i.e. if β has elapsed and still no transition, we pack up and leave, not waiting for any more. All other variables $\hbar$, a, λ are set to 1.

On the whole we see some expected trends, and some unexpected. In Figure 6 as expected, these ratios approximately coincide for $\varepsilon \approx 0$; and one grows while the other shrinks, reflecting the transition probabilities spreading apart as the minima do. However, the graphs have got the order 'the wrong way around', and imply the transition to lower energy is less likely than a transition to higher energy!

Here's an even weirder graph (Figure 7). If we increase the time window to 10, then almost everything looks wrong: the ratios *both* grow above 1, and then *both* drop to 0 for higher ε. So a transition becomes almost impossible if the energy difference is too negative? What? Additionally, tunnelling should surely be more probable, not less, if we have given *more time* for the particles to move.

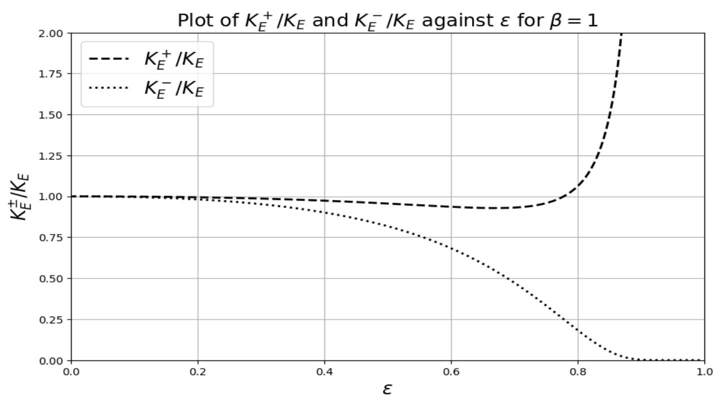


Figure 6: Ratios of propagators to $\varepsilon = 0$ case plotted on a linear scale against ε for $\beta = 1$

So we perhaps followed through on some promising algebra, but when all was calculated and done, we have some blatantly unphysical results. It is therefore *blindingly obvious* some error in calculation has occurred, whether it be in the various approximations made, particularly that of assuming Eq. 8 would hold for the asymmetric case, or just in one of the endless pages of algebra. At best it is a lesson that not everything works out as expected the first time in science, that throwing approximations haphazardly at a calculation won't necessarily yield a stable result, and that evaluating a result is always a crucial check; at worst a message to me to return to kindergarten and start my education from scratch.

But let this not extinguish the flame of wonder within your heart for scientific progress. You now have some powerful tools for tapping into the quantum and classical world alike. And how remarkable that these allow us to analyse the fate of the entire universe! The calculations herein may be inaccurate, but still they give us a glimpse into possibilities of cosmic significance: that the Higgs field of the vacuum itself could destabilise and unravel physics as we know it, and with this, reality itself. A simple jump between two local minima could result in the entire universe being destroyed in an instant.

So perhaps you feel implored to carry the torch forward and re-think these calculations, or perhaps to explore some new universal consequences of quantum effects entirely; the choice is yours. But I hope you leave here with this new understanding: with science we venture close to understanding the deep fabric of reality, and the most profound questions that still elude the human race - questions that could, in the end, determine if our universe is permitted to continue at all.

PS: You may be reassured to hear that using a full, field-theoretic model, but still no shortage of assumptions, that the probability of this universe-ending decay was found to be exponentially suppressed (very small); though some uncertainty does certainly remain! [1].

Acknowledgements

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- Analogies about Lagrangian mechanics are largely due to enlighteningly intuitive discussions with Peter Lavilles. I think he has a cool article you can go read now for the $n+1$'th time :

References

1. Sidney Coleman. Fate of the false vacuum: Semi-classical theory. *Phys. Rev.* D, 15:2929–2936, May 1977.
2. Sidney R. Coleman and Frank De Luccia. Gravitational Effects on and of Vacuum Decay. *Phys. Rev.* D, 21:3305, 1980.
3. A. Zenesini, A. Berti, R. Cominotti, C. Rogora, I. G. Moss, T. P. Billam, I. Carusotto, G. Lamporesi, A. Recati, and G. Ferrari. False vacuum decay via bubble formation in ferromagnetic superfluids. *Nature Physics*, 20(4):558–563, 2024.

And that is a wrap for another issue of The Physics Society's home-grown magazine, Jeremy! Whether it was from questioning the essence of thermodynamics, to understanding the fabric of spacetime a little more, or even finding interest in cosmic doom, we hope that you enjoyed this read!

Join us soon for another fascinating issue later during the semester!

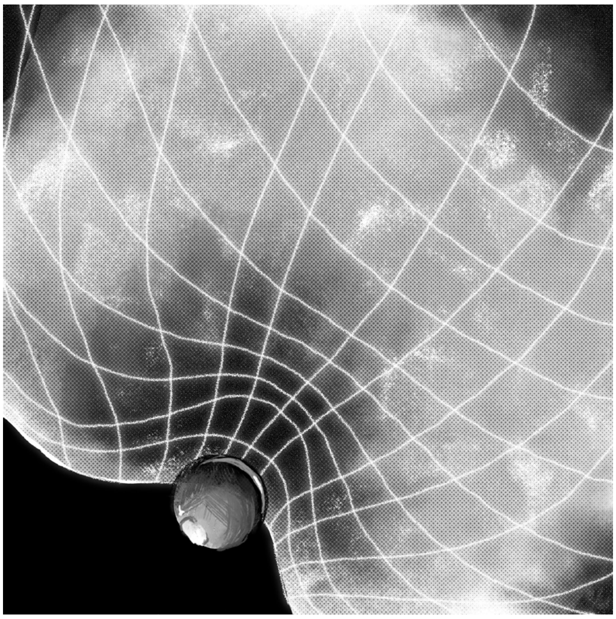
And don't forget to follow our socials on Instagram and the PhySoc website.

Also do not hesitate to contact us via **jeremy.physoc@gmail.com** for ideas, article submissions, or anything else.

Catch you later everyone!

@jeremy_usyd

Website



All in-text art by Lydia Zhang

Guess the rebus!

-

(Clue: Famous Physicist)

Make sure to follow the Puzzle Society, who kindly gave us puzzles for this section

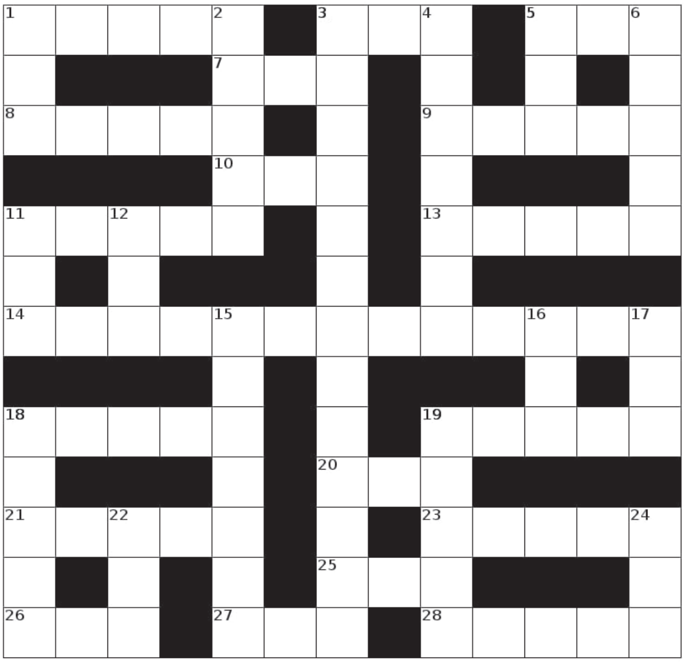
Geocaching Puzzle

The University of Sydney is home to a lovely courtyard, nestled between the new Sydney Nanoscience Hub (opened in 2016) and the Physics building (opened a little less than a century ago in 1926). Here, you are welcome to use the shaded benches and tables to enjoy some much-needed outdoor time.

Clue: Follow the commute of the setting sun. No ladders (or spaceships) needed. (Bonus: send us a photo of your completed geocache for limited edition Jeremy merch!)

Crossword of the Issue

Follow our socials
@jeremy_usyd
for the solution to the puzzles!



ACROSS

1. File them by 31/10
3. Tip of a caligraphers implement
5. ____ giant, or greenhouse ___ for example
7. You may wear this with a suit
8. Nigel Farage went on a binge of this
9. Normal type pokemon that looks like goo
10. The hard core of some fruits
11. An easier to hold sandwich
13. There are iron, gold and netherite varients of this in minecraft
14. Some solvers may do this course after undergrad (or already be doing it !)
18. There is a million dollar prize for a proof regarding an equation that governs this
19. A quality of confectionary, normally
20. Great _ _ _, part of a spheroid geodesic
21. The lowest point
23. A band that reformed last year
25. _ _ _ ME IN,_ _ _ ME IIIIIIIN!!!; Meme with Eric Andre
26. Opposite of 28A, you let sleeping dogs do this
27. If its not the _ _ _ date it isnt the do date
28. Opposite of 26A, you swear to tell it

DOWN

1. _ _ _ by sea, cha by land
2. Baby _ _ _ _!, Unhelpful encouragement as I get my code to only partially work
3. Desk-toy named for famous phycisist
4. Most uni students ignore theirs
5. Ubiquitous tool for version control in code
6. Highly non-standard unit of length, created by an MIT undergrad who became the chair of ISO
11. Measure of typing speed
12. The disease that killed stephen hawking
15. If you have lasted through hardship you have _ _ _ _ _ _ _ hardship
16. What may be put on sushi
17. Tree creatures in The Lord of The Rings
18. Terminal
19. Tom _ _ _ _ _, or Great _ _ _ _ _ !, for example
22. Way to colour wool in minecraft
24. Cambridge contraction for "something"

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PHYSOC