BEYOND POPULAR SCIENCE

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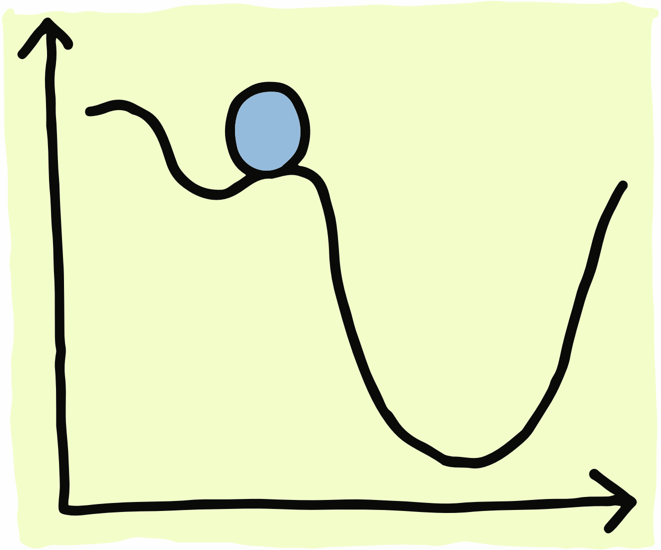
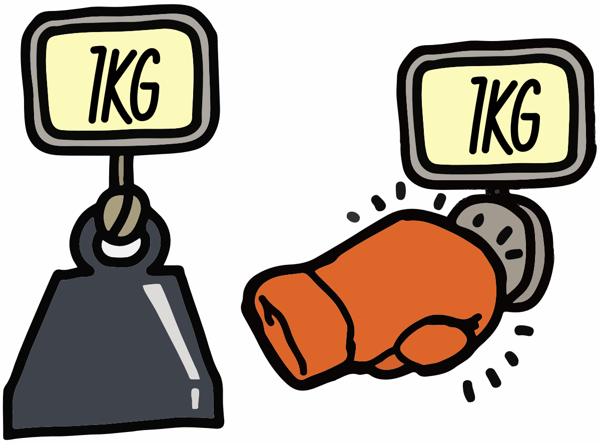
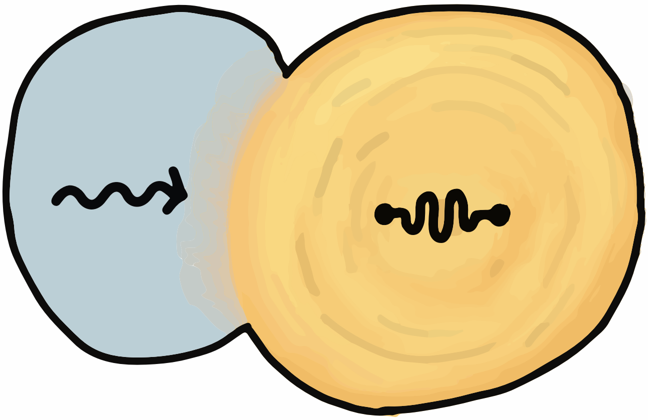
An Empty
Threat

Top (Metastable State): A system stuck in a local energy minimum. Though not at the true lowest-energy state, it remains trapped unless perturbed. The ball resting in a shallow well represents temporary stability—common in physical phenomena such as false vacuum decay or the Sun.
Middle (Inertial vs Gravitational Mass): Both sides read '1KG,' but differ in interpretation. Inertial mass resists acceleration (right), while gravitational mass dictates weight in a field (left). Although equivalent, they arise differently. The Higgs mechanism contributes to inertial mass through interaction with the Higgs field; why gravitational mass follows, remains an open question in quantum gravity.
Bottom (Higgs Mechanism): A particle (left) moves through the Higgs field (right), acquiring mass via constant interaction. The disturbance in the field (rippled line) corresponds to a Higgs boson. The mechanism explains how otherwise massless particles—like W and Z bosons—gain mass while preserving gauge symmetry.







An Empty Threat

Our universe may exist in a false vacuum—a metastable state that could decay through quantum tunnelling, producing a bubble of altered physics expanding at light speed. Current Higgs boson measurements suggest that while such decay is improbable for timescales far exceeding the age of the universe, the possibility remains that reality itself could undergo a phase transition that abolishes matter and forces—with the bonus side effect of no more spam.

False Vacuum ◦ Higgs Field 246 GeV ◦ Mexican Hat
Potential ◦ Top Quark Mass
Sensitivity ◦ Metastability Edge ◦ Quantum
Tunnelling ◦ Coleman-De Luccia Instanton ◦ Bubble
Nucleation ◦ 10^{100} Year Lifetime ◦ Virtual Particle
Corrections ◦ Renormalization Group Flow

“Darling, there’s a place for us,
Can we go, before I turn to dust?”
— Joanna Newsom, 2006

“כִּי הִנֵּה הַיּוֹם בָּא בֹּעֵר כַּתַּנּוּר וְהָיוּ כָל זֵדִים וְכָל עֹשֵׂה רִשְׁעָה קַשׁ וְלִהַט אֹתָם הַיּוֹם
הַבָּא אָמַר ה צְבָאוֹת„
(“For, behold, the day cometh, that shall burn as an oven; and all the proud, yea, and all that do wickedly, shall be stubble: and the day that cometh shall burn them up, saith the Lord ...”)
— Malachi, c. 400 BCE

An Empty Threat

> The concept of vacuum stability emerged from parallel developments in cosmology and particle physics. In 1980, Alan Guth proposed cosmic inflation to solve the horizon and flatness problems. His model required a scalar field temporarily trapped in a false vacuum state, driving exponential expansion before decaying to the true vacuum. This established that metastable vacuum states could have observable consequences.
>
> Sidney Coleman and Frank De Luccia calculated the decay rate of false vacua in 1980, showing that quantum tunnelling creates expanding bubbles of true vacuum. Their formalism demonstrated that gravitational effects could either enhance or suppress transitions, depending on the energy difference between vacua. The calculation revealed that vacuum decay proceeds through nucleation of critical bubbles whose walls accelerate outward at the speed of light.
>
> The discovery of the Higgs boson at CERN in 2012 promoted the idea of vacuum stability from theoretical speculation to measurable physics. The Higgs mass of 125 GeV, combined with precision measurements of the top quark mass at 173 GeV, placed the Standard Model near the boundary between stable and metastable regimes. Giuseppe Degrassi and collaborators showed in 2012 that these values imply the Higgs self-coupling likely becomes negative at energies around 10^{10} GeV, creating a deeper minimum in the potential.
>
> These calculations depend critically on the running of coupling constants with energy scale. The renormalization group equations track how the Higgs quartic coupling λ evolves from low to high energies. At the measured Higgs and top masses, λ decreases with increasing energy and may cross zero. Beyond this critical point, the effective potential develops a new minimum at large field values where the universe would have different physical laws.

The 2012 discovery of the Higgs boson completed the Standard Model but raised an existential question: precision measurements placed our universe near the boundary between stable and metastable regimes. Our vacuum may be stable for now but not forever.

Classical physics defines vacuum as empty space—the absence of matter. This is not the case in quantum field theory. The vacuum is not emptiness but a specific configuration of fields filling all space. A field assigns a value to every point in space. In quantum field theory, every point contains a quantum state for the electromagnetic field, the Higgs field, quark fields, and others. The vacuum is the configuration where these fields minimise the total energy density.

A quantum field extends throughout all space and determines the probabilities of measurement outcomes. The electromagnetic field carries light waves and radio waves. When this field vibrates in a particular pattern (mode), we observe it as a photon. Similarly, the electron field's vibrations manifest as electrons. Each elementary particle type—quarks, leptons, bosons—corresponds to its own field. These fields exist everywhere, even in 'empty' space. What we call particles are localised excitations, like waves on an ocean that

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pervades the universe. The vacuum is the state where all these fields vibrate with their lowest possible energy.

This lowest energy state is far from inert. The Higgs field has a nonzero value throughout space, approximately 246 GeV. This value gives mass to fundamental particles (Higgs, 1964) through their couplings to the field. Without it, electrons would be massless, atoms could not form, and matter would not exist.

Whether this vacuum state is permanent depends on the field potential—a mathematical term describing the energy associated with different field values. Just as a marble rolls to the bottom of a bowl, fields evolve toward configurations that minimise their potential energy. The shape of this potential determines whether our vacuum is truly stable or merely appears so.

Potentials can have multiple minima. A local minimum is a dip surrounded by higher terrain—stable against small disturbances but not the lowest point. A ball in a shallow depression on a hillside stays put even with a deeper valley elsewhere. A false vacuum is a field configuration at a local minimum when a deeper minimum exists. Climbing out requires energy, so the field appears stable despite not occupying the true ground state.

The Higgs field is a scalar field—it has spin 0 and a single degree of freedom at each point in space, unlike vector fields (spin 1) or tensor fields (spin 2).

Spin is an intrinsic quantum property, analogous to but distinct from classical rotation. A spin-0 particle (scalar) has no preferred direction—it looks identical from every angle, like a sphere. A spin-1/2 particle (fermion) requires two full rotations to return to its original state, a distinctly quantum behaviour with no classical analogue—electrons, quarks, and all matter particles have spin 1/2. A spin-1 particle (vector) has a direction, like an arrow pointing in space. The photon, with spin 1, must have its electric and magnetic fields oriented perpendicular to its motion. A spin-2 particle (tensor) has even more complex directional properties—the graviton (hypothetical particle mediating gravity), if it exists, would have spin 2. The spin determines how particles behave under rotations and what kinds of fields they can create. Scalar fields such as the Higgs are the simplest: just a number at each point in space, no direction.

The field's potential at tree level (before quantum corrections) takes the shape:

$$V(\phi) = \lambda(\phi^2 - v^2)^2.$$

This creates a 'Mexican hat' shape: high at the centre, dropping to a circular valley at radius $v \approx 246$ GeV. The field settles in this valley, breaking electroweak symmetry—the W and Z (Weinberg, 1967) bosons become distinguishable from photons by acquiring mass.

From this minimum, all particle masses follow. The W and Z bosons acquire masses proportional to v. Quarks and leptons gain mass through Yukawa couplings to the Higgs. The location in the valley sets the mass spectrum of the Standard Model.

The tree-level potential is an approximation. Virtual particles—quantum fluctuations that briefly borrow energy from the vacuum—modify the effective potential. These corrections depend on energy scale: at higher energies, different virtual processes dominate.

Virtual particles contribute through quantum loops. A virtual top quark can appear from the vacuum, interact with the Higgs field, then disappear. Though fleeting, these processes change the effective potential. Heavy particles such as the top quark contribute most strongly because their coupling to the Higgs is proportional to their mass. The top quark's virtual loops pull the Higgs potential downward at large field values, while the Higgs self-interactions and gauge boson loops push it upward. The competition between these effects determines vacuum stability.

The renormalization group(Wilson, 1971)—a mathematical tool that tracks how physical parameters change at different energy scales—shows how couplings evolve with energy scale μ. The Higgs self-coupling $\lambda(\mu)$ and top Yukawa coupling $y_t(\mu)$ satisfy coupled differential equations. The large top quark mass means y_t is close to 1 (the Yukawa coupling $y_t = \sqrt{2}m_t/v \approx 0.99$), and its contribution drives λ downward as energy increases.

If $\lambda(\mu)$ becomes negative at high scales, the potential bends downward for large field values. A second minimum forms far from the electroweak scale. This new minimum can be deeper than the original, making our vacuum metastable rather than stable.

The Higgs boson mass, measured at 125.25 ± 0.17 GeV, and the top quark mass at 172.9 ± 1.5 GeV, determine the boundary between stability and metastability. These values place the Standard Model near the critical line.

A lower top mass of approximately 2 GeV would strongly favour absolute stability; about a 2 GeV higher top mass would strongly favour metastability with a shorter (yet still astronomically long) lifetime.

This sensitivity transforms vacuum stability from philosophical speculation to experimental physics. Precision measurements of the top mass will determine whether our vacuum is stable or metastable.

The discovery of the Higgs boson at CERN in 2012 added a measurable aspect to this abstract question. Combined with precision measurements of the top quark mass, physicists could finally calculate whether our universe sits in a truly stable vacuum or a metastable one. The result was unsettling: we appear to live on the edge. If our vacuum is indeed metastable, the primary concern becomes quantum tunnelling—the mechanism by which the field could spontaneously transition to a lower minimum despite the energy barrier.

Classical physics forbids transitions between separated minima—the field cannot climb over the barrier. Quantum mechanics allows tunnelling through barriers. In field theory, this occurs via instantons: field configurations (Coleman, 1977) that interpolate between vacua in imaginary time, where time becomes a spatial dimension in the calculation.

The process nucleates a bubble of true vacuum within the false vacuum sea. The probability depends on the Euclidean action S_E (the action calculated in imaginary time) of the optimal tunnelling path:

$$\Gamma/V \sim A \exp(-S_E/\hbar),$$

where A is a dimensional prefactor containing field fluctuation modes. For small energy differences between vacua, S_E becomes large, exponentially suppressing the decay rate.

Once a critical bubble forms, energy differences drive its expansion. The true vacuum has lower energy density, creating pressure that accelerates the bubble wall outward. The wall approaches the speed of light, converting false vacuum to true vacuum.

The bubble wall itself is a domain wall—a boundary layer where the field smoothly transitions between the two vacuum values. Its thickness is set by the inverse mass scale of the field, usually microscopic. The energy density in the wall is large, concentrated in this thin shell. As the bubble expands, this energy gets diluted over larger surface area, but the total energy grows as the bubble engulfs more false vacuum volume. The wall accelerates outward under constant pressure, asymptotically approaching the speed of light.

Inside the bubble, physics changes. The Higgs field takes its new value, altering all particle masses and couplings. Electrons might become too heavy to orbit nuclei, or too light to be localised. The balance enabling atomic structure disappears. Chemistry and biology cease to exist through redefinition of all physical laws.

Matter encountering the advancing wall undergoes complete transformation. Particles defined by their interactions with the old vacuum value cannot exist in the new vacuum. The process is not gradual—as the wall passes, particle masses and interaction strengths change discontinuously. Protons might become unstable, quarks might not confine (bind together to form protons and neutrons), electromagnetic and weak forces might merge or separate differently. No information about the previous state survives because the encoding mechanism no longer exists.

For Standard Model–like parameters near current measurements, estimates give $S_E/\hbar \sim 400\text{–}500$, implying an astronomically long lifetime vastly exceeding the age of the universe.

High-energy processes cannot trigger decay. Cosmic rays reach 10^{11} GeV, far above the 10^{10} GeV scale where the Higgs self-coupling runs negative, yet have bombarded Earth for billions of years without incident. The LHC's 1.4×10^4 GeV collisions are negligible by comparison. Vacuum decay requires coherent field excitations over macroscopic regions, not pointlike particle collisions—a single high-energy impact excites fields only locally, insufficient to nucleate the critical bubble geometry needed for tunnelling.

A nuclear war destroys cities but leaves physics intact. Vacuum decay replaces physics itself. The universe continues, but under different rules that may not permit matter, let alone life.

The Unbearable Lightness of Being

Of all existential threats—asteroids, pandemics, nuclear war—vacuum decay offers the ultimate consolation: we'll never know it happened. No final moments of terror, no last goodbyes, no time for regret. The bubble wall travels at light speed, so the universe's rewriting arrives simultaneously with news of its approach.

[Musical Theme: Upbeat, vaudeville-style cabaret]

Verse 1

(Rubato)
When you attend a funeral,
It is sad to think that sooner or
Later those you love will do the same for you.
And you may have thought it tragic,
Not to mention other adjec-
Tives, to think of all the weeping they will do.
But don't you worry.
No more ashes, no more sackcloth.
And an armband made of black cloth
Will some day never more adorn a sleeve.
For if the bomb that drops on you
Gets your friends and neighbors too,
There'll be nobody left behind to grieve.

Chorus

And we will all go together when we go.
What a comforting fact that is to know.
Universal bereavement,
An inspiring achievement,
Yes, we all will go together when we go.

Verse 2

We will all go together when we go.
All suffuse with an incandescent glow.
No one will have the endurance
To collect on his insurance,
Lloyd's of London will be loaded when they go.

Verse 3

Oh we will all fry together when we fry.
We'll be french fried potatoes by and by.
There will be no more misery
When the world is our rotisserie,
Yes, we will all fry together when we fry.

Bridge

Down by the old maelstrom,
There'll be a storm before the calm.

Verse 4

And we will all bake together when we bake.
There'll be nobody present at the wake.
With complete participation
In that grand incineration,
Nearly three billion hunks of well-done steak.

Oh we will all char together when we char.
And let there be no moaning of the bar.
Just sing out a *Te Deum*
When you see that I.C.B.M.,
And the party will be 'come as you are.'

Oh we will all burn together when we burn.
There'll be no need to stand and wait your turn.
When it's time for the fallout
And Saint Peter calls us all out,
We'll just drop our agendas and adjourn.

Bridge 2

You will all go directly to your respective Valhallas.
Go directly, do not pass Go, do not collect two hundred dolla's.

Final Chorus

And we will all go together when we go.
Ev'ry Hottentot and ev'ry Eskimo.
When the air becomes uranious,
And we will all go simultaneous.
Yes we all will go together
When we all go together,
Yes we all will go together when we go.

— Tom Lehrer

(from tomlehrersongs.com, public domain since 2022)

False Vacuum Decay: Mathematical Formulation

Higgs Potential and Vacuum Stability

The Higgs potential in the Standard Model takes the form

$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4,$$

where ϕ is the Higgs field, $\mu^2 < 0$ for spontaneous symmetry breaking, and $\lambda > 0$ for stability. The vacuum expectation value is $\langle\phi\rangle = v = \sqrt{-\mu^2/\lambda} \approx 246$ GeV. Up to an additive constant, this is the Mexican-hat form $\lambda(\phi^2 - v^2)^2$ with $\mu^2 = -2\lambda v^2$.

However, renormalization group running modifies the effective potential at high energies. The quartic coupling evolves as

$$\begin{aligned}(16\pi^2)\,\beta_\lambda = 12\lambda^2 &+ (12y_t^2 - 9g^2 - 3g'^2)\lambda \\ &- 12y_t^4 + \frac{9}{8}g^4 + \frac{3}{4}g^2g'^2 + \frac{3}{8}g'^4,\end{aligned}$$

where y_t is the top quark Yukawa coupling, g and g' are the SU$(2)_L$ and U$(1)_Y$ gauge couplings, and Q is the energy scale. For Higgs mass $m_H \approx 125$ GeV and top mass $m_t \approx 173$ GeV, λ runs negative at scales $Q \sim 10^{10}$-10^{11} GeV, creating a second minimum at large field values.

Coleman-De Luccia Instanton

Vacuum decay proceeds via bubble nucleation described by the Euclidean action

$$S_E = \int d^4x \left[\frac{1}{2}(\partial_\mu\phi)^2 + V(\phi)\right].$$

The critical bubble solution has $O(4)$ symmetry in Euclidean space, satisfying

$$\frac{d^2\phi}{d\rho^2} + \frac{3}{\rho}\frac{d\phi}{d\rho} = \frac{dV}{d\phi},$$

where $\rho = \sqrt{x_1^2 + x_2^2 + x_3^2 + x_4^2}$ is the four-dimensional radius.

The nucleation rate per unit volume is

$$\Gamma = Ae^{-S_E/\hbar},$$

where A is a prefactor and S_E is the Euclidean action of the bounce solution. For the Standard Model, current estimates give $S_E/\hbar \sim 400 - 500$, making spontaneous decay negligible over cosmic timescales.

High-Energy Triggers

Local few-particle collisions (in colliders or from ultra-high-energy cosmic rays) are not expected to nucleate the required $O(4)$-symmetric critical bubble. Observed cosmic rays reach energies up to $\sim 3 \times 10^{20}$ eV without any indication of catalysed vacuum decay, consistent with the nonperturbative, extended nature of the tunnelling process.

Bubble Dynamics

Once nucleated, the bubble wall accelerates due to the pressure difference between vacua. The wall Lorentz factor obeys

$$\gamma^2 = \frac{1}{1 - v^2},$$

where v is the wall velocity. In the thin-wall limit, the pressure difference ϵ across the wall drives v rapidly toward the speed of light ($v \to 1$) as the bubble expands; the detailed dynamics depend on the surface tension σ, the energy difference ϵ, and the background spacetime.

Renormalization Group Uncertainty

The stability analysis depends critically on precise measurements of Standard Model parameters. The most sensitive quantities are:

$$\begin{aligned}m_t &= 173.1 \pm 0.9 \text{ GeV} \\ m_H &= 125.25 \pm 0.17 \text{ GeV} \\ \alpha_s(M_Z) &= 0.1179 \pm 0.0010.\end{aligned}$$

An increase of order ~1 GeV in the top mass would shift the stability assessment toward instability, while a ~3 GeV increase in the Higgs mass would favour absolute stability.

References:

Coleman and De Luccia, *Phys. Rev. D* **21**, 3305 (1980).

Degrassi et al., *JHEP* **08**, 098 (2012).