Accelerometers Complete Feynman's Gravity Lecture

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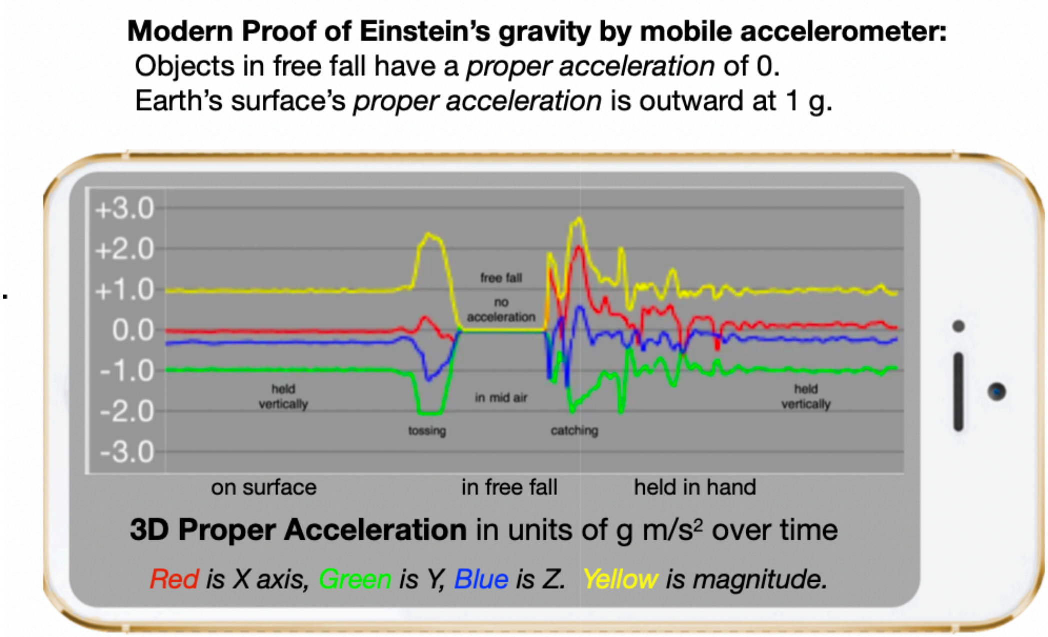
ABSTRACT

We present a new, simpler way to describe and prove Einstein's gravity theory, using modern mobile accelerometers. These days we can easily prove Newton's gravity theory was wrong and Einstein's was correct — using a smartphone.

Professor and Nobel laureate Richard Feynman touched on these issues in his lectures and writing, but his discussion was abbreviated and incomplete. Here we briefly recap his comments on the "possibility" that gravity is a *fictitious* (or *pseudo*) force — that the **real** *proper force* behind a massive object's gravity is due to *the space around it accelerating outward* at a rate proportional to its mass. We can easily confirm this today, using the mobile accelerometers in smartphones that didn't exist in Feynman's or Einstein's day.



The clear *proper acceleration* data compels us to ask: ***How can earth's surface constantly accelerate outward everywhere at 1 g, without the planet's radius in meters getting any bigger?***

The answer, according to the Einstein's spacetime curvature equation, is: ***The lengths of meters themselves (as well as the durations of seconds) grow in scale in the vicinity of matter.*** This captures the geometric and physical meaning behind Einstein's gravity theory. Thus we clarify the simple *non-Euclidean geometry* responsible for everyday gravity.

We describe what Einstein and Prof Kip Thorne call space *warpage* as the *accelerated stretching of volumes of space* — emerging from matter M at a *volume acceleration* of $4\pi GM\ m^3/s^2$ — that result directly in classical phenomena like Newton's Inverse Square Law and Kepler's Law of Orbits. We thus offer a comfortable new bridge between classical physics and relativistic curvature ideas, so they can be more widely understood.

Amid clear and repeatable evidence from accelerometers, this approach lets us fill in the details surrounding Prof Feynman's comments, so the "possibilities" he discussed can be persuasively understood as experimentally proven *facts*. Mobile accelerometer experiments help provide a deeper understanding, a startling new intuitive description, and proof of Einstein's theory of gravity and spacetime curvature.

Keywords: *gravity; general relativity; spacetime curvature; accelerometer, Feynman*

Background: Einstein's Elevator Epiphany, General Relativity and Gravity

Einstein's *general relativity* theory considers the apparent downward pull of terrestrial gravity a *fictitious force* — the term physicists use for a mysterious *apparent* force seen by **observers who don't realize *they're* accelerating**. In the case of gravity, this means an apple in free fall does *not* accelerate downward toward the earth — the surface of the massive earth accelerates outward toward the apple, *pushing* observers upward! Einstein famously realized this while considering his weight change, and related thought experiments, on elevator rides in 1907. He realized, *that's* why objects in free fall near earth's surface all ***appear*** to accelerate downward at the same rate. Exhilarated, he would call it the "happiest thought" of his life.

Einstein Struggled to Understand This

For eight years after his elevator epiphany, Einstein struggled to reconcile his intuitive *fictitious force* idea with the light speed limit and other elements of his previous *special relativity* theory. Bogged down in symbolic math for so long, he mourned that his simple, elegant insight was being buried under abstractions. What happened to the fun and magic of proving how gravity works in an elevator? Worse, he worried that the emerging math of general relativity might be misleading us all. He fumed, "Since the mathematicians have invaded the theory of relativity, I do not understand it myself anymore." (Schilpp p. 102)

Even as the theory was first being proven in 1919 — using a telescope to confirm gravitational lensing of starlight during an eclipse — it was infamous for being hard to describe and understand. Scientists and journalists teased that general relativity is so complicated and mysterious, only two people on earth understood it — including Einstein. But Einstein was convinced it should be easier to explain. He knew intuitively that for gravity, his spacetime curvature theory was profoundly simple. For decades he wrote books aimed at popular audiences about relativity, with "*...That Anyone Can Understand*" in the title. Yet most of its readers couldn't begin to say how spacetime curvature causes gravity.

More than a century after their adoption, many students, physicists and textbooks have trouble grasping and presenting the ideas. In fact, when asked what a mobile accelerometer will report — when it's resting on a table or tossed it in the air — many physics students and teachers get it wrong! Einstein's extraordinary gravity theory is not being properly explained.

Accelerometers and Feynman to the Rescue

Happily, by applying 21st century measurement technology to Einstein's insights, we can explain his extraordinary gravity theory much more clearly and convincingly today.

The approach, presented in the brief article Accelerometer Experiments Clarify Einstein's Gravity Theory, provides an intuitive handle on *spacetime curvature* in general relativity, and how, in contrast with Newton's approach, continuous stretching in the *scale of meters* results in everyday gravity. We can summarize the core idea in two paragraphs here:

In experiments on and near earth's surface, accelerometers' clear *proper acceleration* data compels us to ask: ***How can earth's surface constantly accelerate outward everywhere at 1 g, without the planet's radius in meters getting any bigger?*** The answer — that ***in the vicinity of matter, the lengths of meters are geometrically increasing*** — clarifies the simple non-Euclidean geometry responsible for everyday gravity. *Weight* and the apparent *pull* of gravity are in fact *reactions* to *real* forces, in accord with Newton's 3rd law — equal in magnitude, opposite in direction. In that sense, gravity is an illusion, where weight and the pull of terrestrial gravity should be regarded as *fictitious* or *pseudo* forces.

Thus the *outward stretching of volumes of space* — emerging from matter M at a *volume acceleration* of 4πGM cubic meters /second/second — results directly in classical phenomena like Newton's Inverse Square Law and Kepler's Law of Orbits. The key stretching factor is Newton's G, in units of *volume acceleration proportional to mass* — $m^3/s^2/kg$. Likewise, an increase in the *length of seconds* near matter, known as *time dilation,* causes light to be deflected for a longer *proper time* and "pulled" *more* than slow-moving matter — observed as *gravitational lensing*. Together these simple stretching ideas capture the core geometric and physical meaning behind Einstein's *spacetime curvature* field equation and the experiments that confirm it.

The earlier article presents these core general relativity concepts in more detail and with additional figures — defining terms like the real proper acceleration and *proper force* behind the illusion of gravity. It describes specific *4-pressure* coefficients in the *metric tensors* that Einstein's field equation uses to describe *spacetime curvature*, the stretching of space and time; the role of Newton's G and how a volume of space can accelerate in *scale* even though it can't have a *velocity* in any direction. None of that detail is needed here.

Feynman on Gravity as a Fictitious Force

The present article focuses on how renowned physicist and Nobel laureate Prof Richard Feynman's lectures and writing — on gravity as a *fictitious or pseudo force* — inform us in a modern experimental context, and help us understand Einstein's spacetime curvature. We'll see why Feynman's ideas continue make him a thought leader in this area, six decades later. Most of the quotations here are from his insightful lectures and his books, such as *Six (Not So) Easy Pieces* in the 1960s.

We'll focus on a quote from early in section 12-5 of his Lectures, **Pseudo forces**. The first paragraph includes a summary of Einstein's elevator thought experiment. I've added bold face and italics for emphasis. Then we'll break down some individual points.

"... One very important feature of pseudo forces is that they are always proportional to the masses; the same is true of gravity. The **possibility** exists, therefore, that ***gravity itself is a pseudo force***. Is it not **possible** that **perhaps *gravitation is due simply to the fact that we do not have the right coordinate system***? After all, we can always get a force proportional to the mass if we imagine that a body is accelerating. For instance, a man shut up in a box that is standing still on the earth finds himself held to the floor of the box with a certain force that is proportional to his mass. But if there were no earth at all and the box were standing still, the man inside would float in space. On the other hand, if there were no earth at all and something were *pulling* the box along with an acceleration g, then the man in the box, analyzing physics, would find a **pseudo force** which would pull him to the floor, just as gravity does.

Einstein put forward the famous hypothesis that accelerations give an imitation of gravitation, that the forces of acceleration (the pseudo forces) *cannot be distinguished* from those of gravity; **it is not possible to tell how much of a given force is gravity and how much is pseudo force**.

It **might** seem all right to **consider *gravity to be a pseudo force*,** to say that **we are all held down because we are accelerating upward**, but how about the people in Madagascar, on the other side of the earth—are they accelerating too? Einstein found that gravity could be considered a pseudo force only at one point at a time, and was led by his considerations to suggest that **the *geometry of the world* is more complicated than ordinary Euclidean geometry**.

The present discussion is only qualitative, and does not pretend to convey anything more than the general idea. ..."

Resolving Feynman's Gravity "Possibilities"

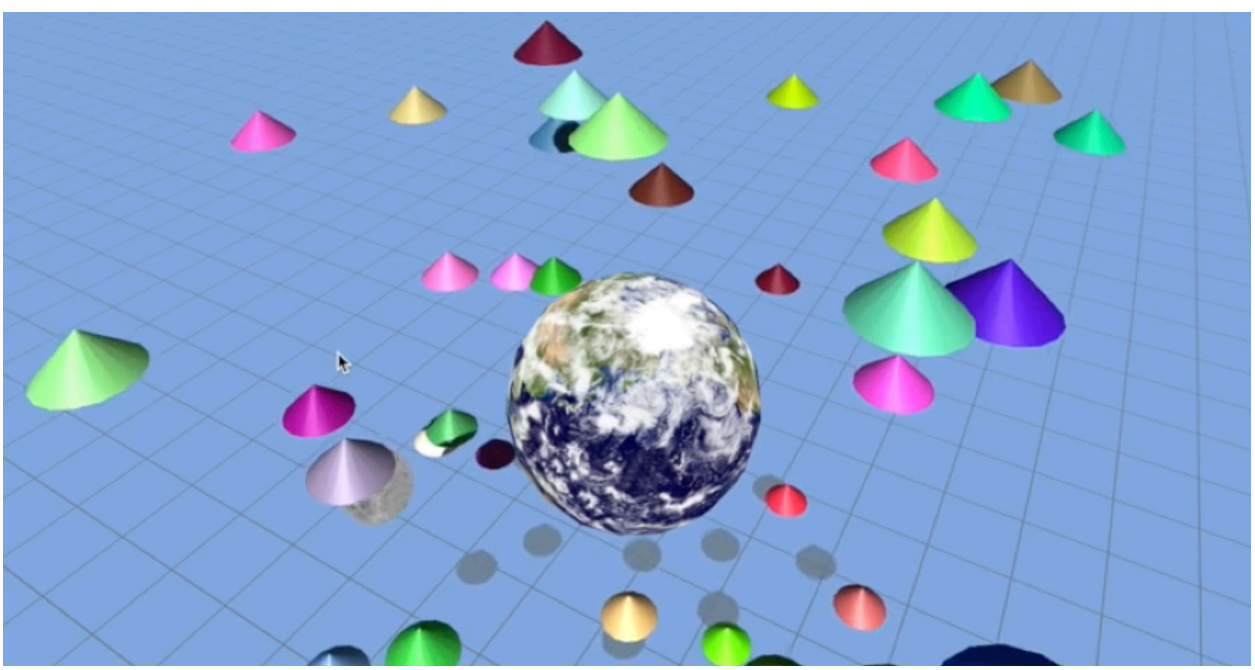
It's notable that Feynman is uncharacteristically cautious as he raises *gravity as a fictitious (or pseudo) force*. He frames the ideas as *possibilities*. And in the end he offers only a "general idea" of the geometry and mechanics of spacetime curvature for gravity.

So these are essentially *questions* Feynman is raising in the 1960s, and in these articles we're filling in details and answering them. Specifically, modern accelerometers let us answer questions about *fictitious* versus easily measured *real* gravitational accelerations.

Animation: Seeing Gravity from Curved and Flat Spacetime Spacetime

Feynman asks: "Is it not possible that perhaps *gravitation is due simply to the fact that we do not have the right coordinate system?*" In other words: '*Might we attain a much more powerful understanding of how spacetime curvature results in what we call 'gravity' if we look at it from different coordinate systems?'*

Feynman's lectures preceded the revolution in fluent 3D animated computer graphics — by over a decade. Today numerous visualizations of spacetime curvature that didn't exist in his day are easily accessible online. We can indeed obtain new insight by following Feynman's proposal and creating multiple points of view on the same scene.



In a simplified 3D animated video here I present gravitational acceleration from multiple points of view — in particular, comparing the *curved spacetime* we unwittingly live in — with its continuously expanding point of view and free-falling objects moving in parabolas — versus the same scene as it would appear in *flat spacetime* — where there is *no* pull of gravity, and inertial objects travel in straight lines, but rigid objects stretch.

Using moving grid lines for the 'rulers', we render *animated coordinate systems themselves*, to see what happens when meters stretch continuously, and what that looks like from different points of view. Even these first crude animated sketches show how continuous increase in the lengths of meters can go undetected and be interpreted as attraction between bodies. This approach to *visually comparing coordinate systems* wasn't available to Einstein or Feynman.

Meters That Stretch

Near the end of his lecture, after discussing gravitational *time-dilation*, Feynman emphasizes the *necessity* of *meters changing scale* in the presence of matter: "Just as time scales change from place to place in a gravitational field, so do the length scales. … It is impossible with space and time so intimately mixed to have something happen with time that isn't in some way reflected in space." (Feynman p. 225)

Thus in the 1960s we find Feynman explaining, rather cautiously, that Einstein's gravity theory is founded on *fictitious force*, meters that stretch, and non-Euclidean geometry.

For our purposes here we can simply promote Feynman's "possibilities" as experimentally confirmable *facts*:

- What we call gravity and weight typically ***are*** *fictitious forces*.
- Terrestrial weight **is** an equal and opposite *reaction* to the *real* force (called the *proper force*) that earth's surface exerts on every object in contact with it.

- When objects near earth's surface all *appear* to be attracted to it with an acceleration of 1 g, it's because earth's surface *accelerates outward toward them* with an easily measured ***proper acceleration***.
- Defying Euclid and Newton, meters and rigid objects ***do*** stretch continuously and geometrically in the vicinity of matter at a *volume acceleration* proportional to its mass and to Newton's gravitational constant G, which is in units of (m^3/s^2)/kg, or volume acceleration per kilogram. A planet's surface pushes outward because whereas its *diameter in meters* is constant, in that vicinity *meters themselves* are continuously getting longer.
- Viewed from a continuously expanding coordinate system, the math ***is*** simple. Around a surface containing a point mass M, the space inside stretches with a *volume acceleration* of 4πGM m^3/s^2, in units of cubic meters per second per second. In that stretching space, objects in free fall travel in straight lines.

On Completing Feynman's Lecture

It might seem out of character for the famously plain-talking Feynman to pull his punches and describe the strange core of Einstein's gravity theory as a *possibility* rather than a known consequence of physical law. He briefly addresses some core curvature concepts by analogy, with a discussion of parallel lines on a static sphere that *appear* to be attracted — but also carefully admits the results are counterintuitive:

"… they are not attracting each other—there is just something "weird" about this geometry. This particular illustration does not describe correctly the way in which Einstein's geometry is "weird," but it illustrates that if we distort the geometry sufficiently it is ***possible*** *that* ***all gravitation is related in some way to pseudo forces; that is the general idea of the Einsteinian theory of gravitation****."*

He's saying almost plainly that gravity is a fictitious force—but with enough qualifiers it's as if he knows there is more to say about that, but cuts himself off. He would have had several reasons for doing so.

Part of the answer is historical and technological. As we've seen, our easily repeated mobile accelerometer measurements weren't available to Feynman — or to Newton or Einstein, for that matter. Mobile devices with accelerometers suddenly became ubiquitous around 2007 when smart phones did. Before that, electronic accelerometers were relatively clunky — something we'd be more inclined to carefully plug in than to toss in the air. (For that matter, picture Newton trying to confirm gravity details for objects in free fall using a balance beam that's falling from a tree, or Einstein trying to read a spring scale he has dropped from an apartment window). Clearly viewing, recording and storing accelerometer data with a mobile device is a vastly easier and more repeatable way to measure *proper acceleration*. A scientist today can ask whether Newton's *pull* or Einstein's *push* is the ***real*** force or the ***fictitious*** reaction, and instantly get the answer. Accelerometers prove Einstein correct.

In this context, the case can be made that, to properly understand gravitational forces and spacetime curvature in general relativity, the mobile accelerometer may be as important as the telescope, or more so.

Is *All* Gravity a Fictitious Force?

Another factor that doubtless made Feynman resist simply declaring *gravity is a fictitious force* is: ***not every*** instance of gravity ***is*** a fictitious force! In our initial quotation, he describes general relativity's core *equivalence principle* this way:

It is not possible to tell how much of a given force is gravity and how much is pseudo force.

In the simple cases we think of first, gravity is indeed a fictitious force, as an on-board accelerometer measuring *proper acceleration* would confirm:

- a planet's surface acceleration — responsible for the *weight* of objects in contact with it — is outward and upward
- an object in free fall near earth's surface has a *proper acceleration* of zero
- a satellite in a circular orbit has a *proper acceleration* of zero

So these are all cases of *fictitious force*.

But what about elliptical orbits? The satellite speeds up and reaches a maximum speed at its nearest distance from the mass, then slows down to a minimum at its furthest. So there's clear non-zero acceleration along its axis of travel, which an on-board accelerometer will confirm as well — a *real* force.

Our spacetime curvature theory says the satellite is traveling through space that's *expanding at different rates depending on how close it is to the mass*. So these are ***real*** forces associated with gravity — responsible, for example, for the famous "slingshot" strategy for accelerating rockets to high speeds by shifting their heading near a planet, for a launch deeper into space without much fuel. Sometimes these are referred to as *tidal* forces, and indeed such forces affect our ocean tides since the liquidy earth is not strictly a sphere.

So when we speak of *fictitious forces* we don't mean to imply that none of those forces exist! Only that they're a result of the dynamic stretching of lengths and of space itself, and that their origin is in a way the opposite of what Newton and the rest of us thought, as in all those other cases.

Still, the terminology of *fictitious force* seems to be the best way to capture the core difference between Einstein's gravity theory and Newton's. For students who clearly see, "ah yes — the force that *feels like* it's pulling a passenger *backward* when really they're in a vehicle that's accelerating *forward*" — this provides the most helpful image. By contrast, two recent articles with video which attempt to describe Einstein's gravity and curvature, by Veritasium and by Professor Sabine Hossenfelder — *both* with "Gravity is not a force" in the title — leave some audiences confused and skeptical. Since they know there are easily measured forces in there somewhere, they quickly reject what seems to be a claim by cloistered academics that gravity doesn't exist. By contrast, *fictitious force* is a widely understood term from elementary Newtonian physics that doesn't suffer that problem. Use of the term *fictitious* force demands we look out for a corresponding *real* force of the same magnitude in the opposite direction — leaving us less vulnerable to omissions and unintentional misdirection.

The Implausibility Problem

The deeper, often unspoken problem is that fundamentally, Einstein's idea that earth's surface accelerates outward — that lengths and meters themselves stretch so much that they cause gravity — simply seems absurd, weird, and implausible, and thus is barely discussable or teachable. And Einstein's worries were well-founded — it's ordinarily presented so abstractly that the math confounds and misleads both the students *and* the physicists, and buries the ideas themselves!

In the 1960s Feynman wound up discussing it without really explaining it — and skipping that obscure math — while acknowledging the geometry is "weird". And *that* is completely in character for Feynman — his fictitious force "possibilities" were his way of confessing that he didn't yet understand gravity as fully as we might some day. He was as usual demonstrating his curiosity, humility, and playfulness — for him the cornerstones of science.

Today, as we review the simple, profound experimental confirmation of Einstein's *fictitious force* approach to gravity and spacetime curvature, I've returned to Feynman because, even amid his caution, he was more forthright and articulate about this topic than most of his peers and most modern textbooks. Standard general relativity textbooks seem to avoid the topic, often with **no** index entries for ***fictitious force*** (or ***pseudo force)***, ***proper force*** or ***proper acceleration*** — the essential physics vocabulary for explaining Einstein's epiphany from that elevator, or describing how accelerometers might measure and explain gravity.

Not even 1973's *Gravitation,* the relativity bible by Misner, Thorne and Wheeler, gets around to mentioning those terms — in its over 1000 pages! Thus a student or professor seeking a qualitative analysis of the physics behind Einstein's experience in the elevator will find more clarity in a modern 2-page abstract that dares to use those terms.

Conclusions

Modern accelerometer experiments offer key answers to many of Feynman's questions about gravity. They provide new perspective and clarity regarding general relativity's *spacetime curvature*, by putting into stark relief the question:

How can earth's surface constantly accelerate outward everywhere at 1 g, without the planet's radius in meters getting any bigger?

The ability to acknowledge and answer this winds up being a *requirement* for any spacetime curvature theory that credibly explains gravity. And Einstein's approach offers a simple answer:

Earth's surface accelerates outward that way when meters are getting longer.

Einstein's general relativity field equation and its well-named *metric tensors* were designed to meet that requirement — as well as elegantly describing electricity, magnetism, the Lorentz light speed limit, gravitational lensing and the rest. Classical gravity is in general a *fictitious force* resulting from spacetime curvature. Concepts like *volume acceleration* derived directly from Newton's G help to explain it all in one brief article.

In this context, the case can be made that, to properly understand gravitational forces and spacetime curvature in general relativity, the mobile accelerometer may be as important as the telescope, or more so.

We also used animated 3D computer graphics to show something tricky: what gravity would look like if we could somehow escape the curved spacetime we live in, and see that objects in free fall travel in straight lines, and the surfaces of massive objects stretch.

I've shared these ideas in articles and lectures with teens, seniors, physicists and audiences with no advanced math background. They're often delighted to feel they finally understand the concepts, for the first time. I've begun to think these are some of the simple explanations of relativity Einstein thought were possible.

I suspect Feynman would learn plenty experimenting with mobile accelerometers, and would enjoy these articles. Devices that his generation didn't have now let us easily demonstrate, explain in some detail, prove, and in a way, complete the prevailing theory of gravity he was outlining.

And Feynman would welcome the democratization of science embodied in a new kind of laboratory — personal mobile devices. After all, he writes:
"You cannot get educated by this self-propagating system in which people study to pass exams, and teach others to pass exams, but nobody knows anything.
You learn something by doing it yourself, by asking questions, by thinking, and by experimenting."

We Have Trouble Accepting This

The previous article touches on *intuitive* reasons many of us find gravity as a *fictitious force,* and the dynamic stretching of meters, so hard to accept — and why that denial can stubbornly persist despite Einstein's field equation, Feynman's arguments, and our clear gravity measurements.

Intuitively we're quite certain: if say, the scale of meters and rigid objects all around us was doubling many times a day, wouldn't we ***see*** that happening? But the answer is ***No****, not directly* — not from a vantage point near earth's surface. We would just observe peculiar accelerations of surfaces and objects, as if there was a *pull* of gravity.

We don't see it directly because:
• the increase is continuous over time;
• the rate is continuous in space, affecting every ruler and rigid object around us — with the ***local scale of meters*** continuously growing at the same rate equally out to the horizon; and
• the scale of *our own point of view* accelerates at that same rate, masking the scale changes

Rigid objects around us absolutely *don't appear* to be stretching in any way, relative to us or to one another.

Combine this with our strong Newtonian biases, and **we're utterly, profoundly certain that meters and rigid objects are constant in scale** — even if we've been studying relativity and should know better!

The illusion of the downward pull of terrestrial gravity is persistent and stubborn. Like any great illusion, it relies on misdirection, however unintentional. I've seen many physics students, professors and books struggle to describe the path of an object in free fall as some kind of *geodesic curve* while failing to notice the elephant in the room — never acknowledging or suspecting that it's really the huge *surface of the planet* that's accelerating. We don't even see Feynman directly mention it.

This cognitive dissonance and denial is naturally the biggest hurdle in widespread understanding of Einstein's spacetime curvature theory. It can be insurmountable. I know physics professors who don't care what accelerometers show, or what Feynman pointed out, or what Einstein's field equation says about space stretching and meters varying in scale — they emotionally can't accept it.

As we grow to understand this area better, the potential for new science and technology is vast. This is the tip of an iceberg regarding how spacetime actually behaves, and better ways to understand and visualize it. If today's scientists still aren't very good at predicting how a simple accelerometer will behave, what other more significant, unexpected consequences of spacetime curvature might we soon discover?

Einstein's Dream

When Einstein complained, "Since the mathematicians have invaded the theory of relativity, I do not understand it myself anymore," I suspect he wasn't joking or exaggerating. He felt he had lost his way. He hadn't found a simpler, more elegant way to convey the gravity ideas, and somehow the complicated math his colleagues were using was making it worse. Since from beginning to end, science is driven by experiments and data, it's easy to imagine that devices that clearly show *the surface of the earth is accelerating outward* might have led him toward simple, elegant ways to present the same core curvature theory. That's what I've attempted to do with these articles: to more easily share the thrill of Einstein's happiest thought, about the illusion of gravity, with the wider world.

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