GENERALLY SPEAKING

Compared with this problem, the original theory of relativity is child's play.

Albert Einstein (1912)

The elevator was the self-operating kind that opens both doors automatically when it stops.

Raymond Chandler (1937)

We were in the position of a librarian whose books were still being arranged according to a subject scheme drawn up a hundred years ago, trying to find the right place for books on Hollywood, the Air Force and detective novels.

Arthur Eddington (1940)

Special Relativity gave us space-time. General Relativity in effect gives us matter-space-time.... It is the matter that bends, or distorts, the fabric of space-time.

John Gribbin (1986)

Physics is once more facing *conceptual* problems: What is matter? What is causality? What is the role of the observer in physics? What is time? What is the meaning of 'being somewhere'? What is the meaning of 'now'? What is the meaning of 'moving'? Is motion to be defined with respect to objects or with respect to space?

Carlo Rovelli (2001)

Maybe at first I thought of this as just a job. Now, though she pays me for the usual 8/5, I find I'm doing more like 18/7. The first train's before five. The last at one. It's not often I'm on both but it does happen. I'm always like this, always driven. Now this mission has my mind in overdrive. It makes it hard to sleep. Some nights I just walk along the beach and play mind games with words. Or, recently, with relativity.

I worry that I can't decide what she's about, why she needs Frank. I'm not doing much; he's doing zilch. Is he some kind of front? For what? It makes no sense.

Another trip. She has me book her ticket and print out her boarding pass. It must match her passport; maybe Birgit *is* her name. A last-minute, first-class, no-discount ticket has her heading off to Paris. So today I'm left to mind the store again. Or to keep on surfing. Surf, it never stops. Not on Kawailoa beach; nor on the Net.

My musing is cut short when he walks in, unkempt as usual. Why do I do the coat and tie? Today's agenda's heavy duty. General relativity's the second of the Big Three theories. Einstein starts out with something like our usual concepts of space and time. He bends them. Space and time, I mean. It's scary stuff.

And she was right although I don't like to admit it. I am finding lots of stuff. Of course it's subject to the usual Web warning: It ain't necessarily so. So says Gershwin; he is hip and he has got it. Some of it is wrong, some is misleading. It needs a careful eye on what's authoritative and what's not. Even when it *is* it may be wrong. But that's less of a problem than it might be since we won't depend upon it either way. We can't. Nobody knows the way to go. I don't need a down with Echobelly so I soar with Mary Carpenter: On with the song.

I suppose it is his job to ask dumb questions, like what's general in general relativity? But I told him this already: GR is general because it's not specific. It covers frames of reference of every kind. So, unlike SR, it includes accelerating or rotating frames. But its name's not helpful. It's not really about relativity; it's more about gravity. And, I tell him, it's also about the fact that you can't tell the difference between acceleration and gravity. Anyone who's used an elevator knows acceleration feels like gravity. Even as a youth Einstein's pragmatic. He heeds facts like that.

In 1853, Elisha Otis doesn't invent the elevator. Someone did that already. He invents a brake to stop an elevator falling when its cable snaps. This gets more people into elevators. It makes him lots of money. So I figure Einstein *could* have thought of GR in an elevator. There were elevators in his city in his time.

Checking, it's not clear that he was ever in one. But I figure elevators got him thinking. His thought experiment uses 'a spacious chest resembling a room with an observer inside [to which] is fixed externally a hook with rope attached.' It sounds like an elevator. With a difference: Einstein puts his chest where there's no gravity—which Otis wouldn't want. He says a person in the chest can't distinguish between weight (when the chest is tugged by gravity) and inertia (when the chest is tugged by rope). His big leap is this: If you can't *tell* the difference, there *is* no difference. This comes to be called 'equivalence'. It is a big deal; before his big leap, weight and inertia are seen as two different things.

The person in the chest leads to a theory of gravity. It describes how matter, space and time behave, everywhere and (almost) everywhen. Heady stuff! Soon its predictions are confirmed. The *New York Times* says that it is 'perhaps the greatest of achievements in the history of human thought.' What the *Times* does not say is that few know what to do with it.

GR's equations show how matter causes curves in space and time. It shows how these curves make matter move. They answer a question that always troubled Newton. *His* equations calculate the force of gravity between two masses—let's say Earth and the Moon—at any given distance. They work well. Newton wonders why. How could the Moon know that there *is* a planet, let alone that it's 250,000 miles away? Einstein says the Moon knows nothing. Newton would be pleased.

Flatfoot Frank has never had a problem knowing there's a planet pushing on his shoes. But he seems to like the story of the Moon. GR says Earth's mass makes curves in space. The Moon goes with the curves it finds. They keep it, like a roller- coaster on its rails, in orbit around Earth.

It takes days of heavy-duty thought to bend my brain around the concept of the curvature of space. So he may take a while. It takes Einstein some time too. Then it takes him years to do the math. Why? Well, for two reasons. One, he is not by trade a mathematician so he has to work at it. Two, the math is hard. Frank can't hope to understand it. Nor can I. But maybe he can see the reason *why* it was so hard.

Before 1915 math for things that move in space is well established. It has ancient roots in India and Persia. Newton and Leibniz independently create its modern form. It's called calculus, a word that sets an audience a-shrieking for the exits. But it's an easy idea. As one might expect from India, it's about elephants. Everybody knows the one that goes:

> Q. How do you eat an elephant?
>
> A. One bite at a time.

In calculus you take small bites you *can* solve from a problem that you *can't* solve. The key is to cut down the bite size to no size at all. Then add them up. That solves the problem.

Einstein doesn't have a problem with the calculus itself. He has a problem with its space. Newton's calculus is based on plain vanilla space that everybody takes for granted. Frank's eyes are already rolling. Think of it this way, I tell him: On a sheet of paper draw a diagram of a 2-D calculus problem. Like find the area under a curve. The kind of problem kids bring home to put their parents in their place, as Mead would say. It's simple. Well, sort of simple, because the paper's flat. But that's why this won't work for GR.

As I already told him, GR is about how gravity controls the shape of space. In GR there *are* no flat sheets of paper. And its problems are not 2-D like a sheet of paper. They're 4-D like . . . well, like Spacetime. It's like trying to draw a picture in soft chewing gum that's scrunched in someone's pocket. To make matters worse they're on the move; its shape is changing while he tries to draw. And as it's a 4-D problem, it's not just the shape of space that changes; time's shape changes too. Just to think about it is enough to bend my brain.

This is where Einstein gets lucky. Gregorio Ricci-Curbestrato is an Italian mathematician. In the 1890s he develops math that Einstein needs to work this cranky kind of problem. He and a student write a book about it with the catchy title *Méthodes de calcul différentiel absolu et leurs applications.* He has a pen name: Ricci. Rhymes with peachy. For some reason his full name is fast forgot. Then *he* gets lucky: After 1915 GR starts to sell the book for him. But its math is not easy for Einstein. A friend, Marcel Grossmann, helps with his homework.

What good's all this to Frank? Well, first thing he needs to understand about GR is that he doesn't need to understand it. It's no good to him anyway. It can't say how the universe began. If it could it would have done so long ago. But he does need to understand some things *about* it. Why? Well, because almost every physical cosmologist since Friedmann uses GR to investigate the early universe. Belgian physicist Georges Lemaître does. Einstein does. Lots of others do and there's no sign they will be stopping soon. So he needs to know *why* GR can't say how the universe began. In other words he needs to know: What's wrong with it?

The first thing that's wrong is that GR assumes that space and time exist. Well, strictly, just some aspects of them. I can already see that this will be a problem. Frank can't assume things. His Beginning must explain them. He can't do that with a theory that assumes them.

Second, like SR, GR assumes an object has a position relative to other objects and this position changes smoothly over time. The technical term is 'continuously.' It means with no discontinuities or jerks. Why does Einstein assume this? Well, that's what tensor calculus is all about. In this he doesn't have a choice. No one has the math for jerks. Not then; not now. But my reading says the early universe may jerk.

The third thing is it seems the early universe was tiny. GR doesn't work with very small.

However, when it comes to cosmology—and we soon will—GR puts SR in the shade. SR deals with Frames of Reference. In a Frame of Reference space is fixed. But in GR it's not. Billions of cosmic masses—planets, stars, black holes, galaxies—bend it out of shape.

A dramatic confluence of circumstances rockets GR onto the world stage. It's not exactly tuned up for ten-second clips, yet overnight it launches Einstein into unanticipated orbit. He isn't only the most famous scientist; he's the *only* famous scientist. As the world emerges from amaze, GR soon seems of little use. Then Penrose and Hawking find a perfect problem: black holes. GR is exactly what they need. It and its underlying math evolve. But to this day it cannot answer: What *is* a gravitational field?

Now Frank and I step back to 1917. Einstein's eye turns to the universe. Singlehandedly—as usual—he creates cosmology.