September 2006, page 10) present an interesting contrast to an objective reader. Allegations that are forthrightly rebutted, a waspish tone set against reasoned calmness, hearsay versus the protagonist's own words. In sum, an entertaining interlude in a diet of other journals.

The following episode, of which I was a witness, says something about Subrahmanyan Chandrasekhar and his relationship to Arthur Eddington. About two decades ago, Chandra was awarded the Michelson–Morley Prize by Case Western Reserve University. In the public lecture that followed, he spoke about black holes and such. When he had finished and sat down, the chairman invited questions and comments from the audience. A man stood up and made a short, complicated speech ending with "Can Professor Chandrasekhar explain the paradox?" Chandra returned to the podium and, in his characteristically soft voice, said he was reminded of his good friend Eddington, who once told him, "When you really understand physics, there are no paradoxes."

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An adventure in relative time-keeping

I enjoyed Daniel Kleppner's Reference Frame about the relativistic effects of elevation on precise clocks (PHYSICS TODAY, March 2006, page 10). He would be amused with an experiment I did with my kids last year.

The year 2005 was the widely publicized 100th anniversary of Einstein's first paper on relativity and the lesser-known 50th anniversary of Louis Essen's first cesium clock. To celebrate, I created Project GRE^{2}AT (General Relativity Einstein/Essen Anniversary Test), perhaps the first "kitchen science" relativity experiment.

As a collector of vintage and modern atomic clocks, I discovered it was possible, using gear found at home, to convert our family minivan into a mobile high-precision time laboratory, complete with batteries, power converters, time interval counters, three children, and three cesium clocks (see photograph). We drove as high as we could up Mount Rainier, the volcano near Seattle, Washington, and parked there for two days. The trip was continuously logged with the global positioning system; the net altitude gain was +1340 meters.

Given the terrestrial blueshift of 1.1×10^{-16} per meter mentioned by Kleppner and integrating our altitude profile, we predicted the round-trip time dilation to be +22 nanoseconds. This is remarkably close to what we experimentally observed when, after we returned, the ensemble of portable cesium clocks was again compared with atomic clocks left at home (see graph).

Instead of fanciful stories of rocket ships and twins, the kids got a hands-on introduction to general relativity with real clocks and a family road trip. Furthermore, by being at high altitude for the weekend, we experienced more time together, relatively speaking. It was the best extra 22 nanoseconds I've ever spent with the kids.

So, yes, not only do we live in a time when atomic clocks are altimeters, but when relativity is child's play.

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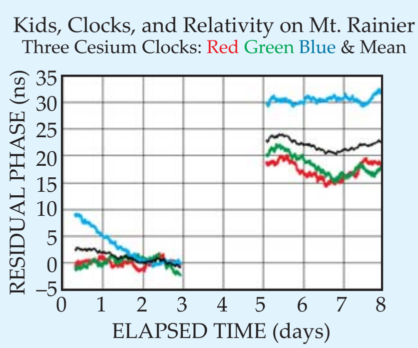

Note on the torsion tensor

In commenting on letters responding to his Einstein article (PHYSICS TODAY, November 2005, page 31, and April 2006, page 10), Steven Weinberg states that he "never understood what is so important physically about the possibility of torsion in differential geometry." He basically argues that torsion "is just a tensor" and could be treated like any additional tensor field in the context of general relativity.

In my opinion, however, a decisive point was overlooked. Torsion is not just a tensor, but rather a very specific tensor that is intrinsically related to the translation group, as was shown by Élie Cartan[1] in 1923–24. In fact, in the Yang–Mills sense, it is the field strength of the translations. Torsion is related to translations and curvature to Lorentz rotations. As one consequence, torsion cracks an infinitesimal parallelogram in the spacetime continuum and gives rise to a closure failure described by a vector (in dislocation theory in solids in three dimensions, it is the Burgers vector).

The simplest gravitational theory with torsion, the Einstein–Cartan theory, is a viable one.[2] Incidentally, torsion could be measured by the precession of nuclear spins, even though the effects are expected to be minute in the present-day cosmos.[3]

References

1. E. Cartan, *Riemannian Geometry in an Orthogonal Frame*, trans. from Russian, World Scientific, Hackensack, NJ (2001), section 87.
2. F. Gronwald, F. W. Hehl, http://arxiv.org/abs/gr-qc/9602013.
3. C. Lämmerzahl, *Phys. Lett. A* **228**, 223 (1997), available at http://arxiv.org/abs/gr-qc/9704047.

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Weinberg replies: Sorry, I still don't get it. Is there any physical principle, such as a principle of invariance, that would require the Christoffel symbol to be accompanied by some specific additional tensor? Or that would forbid it? And if there is such a principle, does it have any other testable consequences?

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