of students from both classes could be interviewed to further ascertain their level of understanding. If students using the consistent histories approach significantly outperform those learning the standard Copenhagen interpretation, it may be worthwhile to develop interactive tutorials similar to those discussed in the article but using the consistent histories approach.

In response to Travis Norsen, we note that we agree with Alan Van Heuvelen, whom Norsen cites, and our approach is consistent with his advice.[3] However, intuition and foundational issues are not exactly the same things. Although a deep understanding of foundational issues may improve intuition, we can help our students develop qualitative, conceptual understanding of many aspects of quantum theory without first having to clarify every foundational issue. Our research suggests that the nature of physical intuition is not well understood, though intuition is important.[4]

As Philip Shemella has suggested, we have used other wordings for the question of interest, including the wording he recommends. Our findings are unchanged. During interviews, the interviewer has often rephrased the question when a student was unable to answer correctly. The responses were qualitatively unchanged.

As Griffiths, Norsen, and Walter Harrison imply, the use of simulations and results from physics education research to address functional issues is just a single prong in what should be a multi-pronged approach to the teaching of quantum mechanics. We agree that addressing foundational issues is just as important.

In addition to the approach taken in textbooks by Griffiths and Harrison, Richard Robinett's quantum text[5] relates pedagogical quantum models to modern experimental realizations of these systems and emphasizes connections to classical mechanics.

We agree with Norman Chonacky that a discussion of the broader role of computation in the physics curriculum is needed. We encourage interested readers to attend the American Association of Physics Teachers topical conference Computational Physics for Upper Level Courses, to be held in July 2007 (see http://www.opensourcephysics.org/CPC/index.html). Its purpose is to identify problems in which computation helps students understand key physics concepts.

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Uncertainty over weakening circulation

Barbara Goss Levi's Search and Discovery story (PHYSICS TODAY, April 2006, page 26) discusses evidence of weakening ocean circulation and its possible connection to global warming. The Atlantic Ocean circulation across 25° N latitude has been used as a benchmark for characterizing the mass and heat transport from the tropics to the northern latitudes. The upper portion of this transport includes the Gulf Stream, which is at least partially responsible for a moderate climate in Europe. A weakening of the Atlantic meridional overturning circulation and of the Gulf Stream might have the unpleasant consequence of cooling Europe's climate.

The PHYSICS TODAY piece is based on analysis of work by Harry Bryden, Hannah Longworth, and Stuart Cunningham,[1] which concluded that the Atlantic meridional overturning circulation slowed by about 30% between 1957 and 2004. Their work inspired speculations that the anthropogenic increase in carbon dioxide may be responsible for the weakening of heat transport from the tropics, and that such an effect has now been detected.

The conclusion that the Atlantic meridional overturning circulation has decreased by 30% does not follow from the data presented by Bryden and coauthors, but is based on an incorrect treatment of measurement errors.

According to Bryden and coauthors, the 1957 transport in a layer shallower than 1000 m was 22.9 ± 6 Sverdrups (1 Sv = 10^6 m^3/s) compared with the transport of 14.8 ± 6 Sv in 2004. The ± 6 Sv represents an uncorrelated error of each measurement. Bryden subtracts the two quantities and presents the results as 8.1 ± 6 Sv (instead of 8.1 ± 12 Sv or ± 8.5 Sv, depending on the character of errors), which is an incorrect result. It is a mystery how such an error was missed by Levi and by the editors and reviewers of the original paper. The observed change of 8.1 Sv is well within the uncertainty of the measurement. The correct conclusion from the data presented in Bryden's paper should have been that no statistically significant change in Atlantic meridional overturning circulation at 25° N between 1957 and 2004 has been detected. Such a conclusion is in agreement with the earlier analysis of essentially the same data (between 1957 and 1999) by Alexandre Ganachaud and Carl Wunsch.[2]

Research also failed to detect any slowing,[3,4] and one of the relevant papers[4] concludes that "there is no sign of any Meridional Overturning Circulation slowdown trend over the past decade, contrary to some recent suggestions."[1]

In defense of Bryden and his coauthors, I must share a comment from a personal communication I had with Bryden shortly after his *Nature* paper was published. Bryden's paper as submitted for publication to *Nature* included a question mark at the end of the title, suggesting only a possibility that the circulation might be slowing down. On the editor's insistence, the question mark was removed, and the title was changed into a positive statement that caused a considerable stir.

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Postscript on Chandra and Eddington

The letters from Arthur Miller and Kameshwar Wali (PHYSICS TODAY, 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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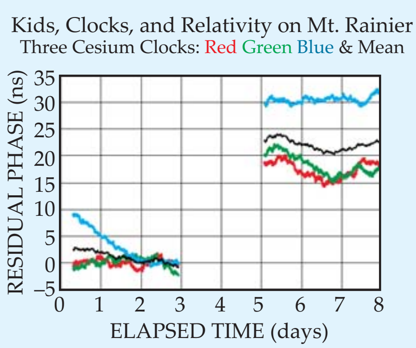

Note on the torsion tensor

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]

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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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