What I'd Like to Know about 2105

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Physics in the 21st Century - 100 Years after Einstein's "Annus Mirabilis"
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Almost two years ago, I was invited to this Symposium to give a talk on "Quantum theory: foundations", in the light of Einstein's objections to quantum mechanics. To prove that this was the original plan, let me show you two wonderful things I had dug up in preparation for that talk. [SLIDE: EPR article in NY Times and Einstein's response.]

But last February, the organizers said, wouldn't it be much more fun if I talked about questions I would ask physicists 200 years after Einstein's *annus mirabilis,* if I could be magically transported to the year 2105.

Why me? This came about because five years ago the *New York Times,* whose interest in the frontiers of science hadn't diminished since 1935, in spite of Einstein's rebuke, had an article about "10 Physics Questions to Ponder for a Millenium or Two." The questions were assembled by a panel of judges from contributions submitted by participants at a conference on string theory. According to the *Times,* David Gross, one of the judges (and one of the winners), characterized the challenge as imagining "what question I would ask if I woke up from a coma 100 years from now." He now tells me that this was meant to apply only to his own question, but the *Times,* and other sources that picked up the questions, suggested that they should all be viewed in this light. From that perspective — as questions physicists would like to ask their colleagues in the year 2100 — most of the questions made me uncomfortable. They seemed temporally provincial — too absorbed with issues of the current decade or two. Consider, for example, question 4

4. Is nature supersymmetric and, if so, how is supersymmetry broken?

and question 7

7. What are the fundamental degrees of freedom of M-theory and does the theory describe nature?

It would surprise me and disappoint me if the context and terms of such questions made sense to anybody but historians of science, after the passage of 100 years of research. The only question of the ten that struck me as reasonable under the 100-year test was the question asked by Gross himself:

1. Are the dimensionless parameters that characterize the physical universe calculable in principle, or are some merely determined by historical or quantum mechanical accident, and uncalculable?

Dimensionless parameters are likely to survive all but the most radical upheavals in our conception of the world. Indeed, the cooncept has been with us at least since the hydrodynamicists of the 19th century, and though fundamental ones are a 20th century invention, they have been with us now for the better part of a century. This question, alone among the ten, satisfies all the criteria I'll describe later.

The fact is, I felt uncomfortable not only with most of the questions, but with the whole exercise, as the *Times* presented it. Too many unimaginable things can happen in a century to render our current concerns irrelevant or obsolete. Just think about the century behind us. (*Annalen der Physik* received Einstein's relativity paper on June 30th, 1905, so we still have three more weeks to be living in a century at the beginning of which only one guy understood relativity, as Feynman once put it.)

I write an occasional column in Physics Today, commenting on various peculiarities of our profession, and the pitfalls of devising questions for colleagues 100 years from now struck me as a good topic. So in February 2001 I published an essay inspired by the article in the *New York Times,* giving my own list of ten questions, to highlight the futility of posing questions for colleagues a century ahead of us.

But I seem to have fallen victim to the inverse Cassandra effect. Casandra made true prophecies, but because she rejected Apollo, he arranged that nobody would believe them. I, on the other hand, designed questions for colleagues 100 years in the future to make the point that one should not question colleagues 100 years in the future. But my cautionary questions seem to have been taken seriously. You can find them today at an Irish website (`http://www.qub.ac.uk/mp/questions/index.html`) posted next to the original ten. And now I am supposed to speak about them for an hour, wearing one of the two decent neckties I possess.

To set the stage for making inquiries a century into the future, one cannot do better than to recall the tale of Enoch Soames, as told by Max Beerbohm in 1897. (You can find the entire text at `http://www.gutenberg.org/etext/760`.) Soames is an aspiring poet. He is the author of "Negations" and "Fungoids". Both volumes have been entirely ignored by his contemporaries along with all the rest of his writings.

On June 3rd, 1897 Beerbohm runs into Soames in a Soho restaurant and they have lunch together. Soames remarks to Beerbohm that he would sell his soul to the Devil for the chance to spend the afternoon, 100 years later, in the reading room of the British

Museum, to learn from the card catalog whether posterity has recognized his genius.

"Permit me to introduce myself" says a "tall, flashy, rather Mephistophelian man" at a nearby table. In Beerbohm's presence, and in spite of his fervent pleas not to do it, Soames makes a pact with the Devil and vanishes from the restaurant, transported to the reading room of the British Museum on the afternoon of June 3rd, 1997.

Beerbohm goes back to the restaurant that evening to find out what happened. Soames returns. He is furious with Beerbohm. He had failed to find a single one of his works in the card catalog. He even failed to find himself mentioned in any scholarly works on late 19th century English literature. Indeed, he had failed to find any evidence that he ever existed.

But in the ultimate humiliation, he found himself mentioned by a late 20th century critic, T. K. Nupton, as a fictitious character in a story by Max Beerbohm about a man who sells his soul to the devil for a chance to spend the afternoon 100 years later in the reading room of the British Museum.

Beerbohm is so clever in exploiting the paradoxes of time travel that you have to read the story a couple of times to get all the jokes. For example, when Soames returns from 1997 Beerbohm asks what the people in the reading room looked like.

"They all looked very like one another."

Beerbohm inquires further: "All dressed in sanitary woolen?"

"Yes, I think so. Grayish-yellowish stuff."

"A sort of uniform?"

Soames nods.

"With a number on it perhaps — a number on a large disk of metal strapped round the left arm? D. K. F. 78,910 — that sort of thing?"

It was even so.

"And all of them, men and women alike, looking very well cared for? Very Utopian, and smelling rather strongly of carbolic, and all of them quite hairless?"

I was right every time, Beerbohm tells us.

Later on in the story Beerbohm deduces that although nobody in 1997 had ever read Soames, they had all read Beerbohm. Although he never says so explicitly, they all looked exactly as he guessed because they were, in fact, carefully reenacting Beerbohm's prediction of what the reading room looked like on the precise day, June 3rd, 1997, that was specified in the story. Imagine their astonishment (described to Beerbohm by Soames) when in the midst of their literary party, Soames actually appears.

I believe that there was, in fact, a small commemorative event at the British Museum on June 3rd, 1997, but I doubt the participants put on grayish-yellow sanitary woolens, and sprayed themselves with carbolic. Needless to say, Soames did not show up. Now that we have passed, the precise date of Soames's appearance in the reading room, we can use his case to examine some of the pitfalls of looking 100 years into the future.

"A hundred years hence!" Soames murmurs to Beerbohm while working himself up to selling his soul to the devil.

"We shall not be here," Beerbohm replies, briskly but fatuously.

"We shall not be here, No," repeats Soames, "but the museum will still be just where it is. And the reading-room just where it is. And people will be able to go and read there."

Well, maybe. By a strange coincidence, 1997 — the exact year of Soames's visit — was the year in which the unthinkable happened. The great reading room in the British Museum, where Marx wrote Das Kapital, was closed, and the space converted into an enormous open circular courtyard where you could eat lunch and buy postcards and souvenirs. The entire library was moved to a new building near St. Pancras station on Euston Road. The old reading room stopped functioning in October, so it may still have been limping along when Soames visited it on June 3rd.

But the card catalog is another story.

No one can blame Max Beerbohm for failing to anticipate the electronic catalog in 1897. The conversion, in fact, is still going on and may not have been very far along in 1997. But, it was literally unthinkable in 1897, and it provides a cautionary example of the utterly unexpected things that can happen in the course of 100 years.

A complementary hazard is to anticipate changes far more radical than what actually happens. Beerbohm expected spelling reform. What Soames actually copied from the essay of T. K. Nupton was this:

> Fr egzarmpl, a riter ov th time, naimed Max Beerbohm, hoo woz stil alive in th twentith senchri, rote a stauri in wich e pautraid an immajnari karrakter kauld "Enoch Soames"–a thurd-rait poit hoo beleevz imself a grate jeneus an maix a bargin with th Devvl in auder ter no wot posterriti thinx ov im! It iz a sumwot labud sattire, but not without vallu az showing hou seriusli the yung men ov th aiteen-ninetiz took themselvz.

With these lessons in mind, I would say that a reasonable question has to meet four criteria:

(1) First of all, for purposes of this Symposium, the question should be about physics,

or at least it should emerge from the attitudes and perspectives with which physicists of today view the world. Here, for example, are some questions that are not allowed, although I would like very much to ask them.

> Do people travel moderate distances in vehicles that can hold no more than four or five of them? If so, what is the energy source? If not, how, other than walking, do people make short (5-10 km) trips?
>
> Do you know what opera is? If so, is it still performed by singers and musicians in front of audiences?
>
> Are there universities at which students meet together in one place to be instructed by professors? If so, is there an academic field called philosophy?
>
> Did the United States of America recover from the presidency of George W. Bush? If not, did the rest of the world?

(2) The answer should, of course, be absolutely fascinating, and not just to the questioner. Think of the ways in which the young Einstein would be amazed by what we know today.

(3) The question should make sense to scientists in 2105. The danger, of course, is that a pressing question of today is likely to make sense only to historians of science, or, worse yet, to specialists in early 21st century issues, prior to the discovery in 2019 of the *chronosynclastic infundibulum.*

(4) The question should have a reasonable chance of not eliciting embarrassed giggles at the early 21st century naivete of the questioner.

So here, after all these warnings, are my own physics questions for colleagues in the year 2105:

1. What are the names of the major sciences? What are the names of the major branches of physics, if physics is still an identifiable science? Please characterize their scope in simple early 21st-century terms, if you can, or try to give me a sense of why my ignorance makes this impossible.

It's hard to guess what the landscape will look like in 100 years, but I can't imagine it will look familiar. Already, for example — at least in the northeastern United States — chemistry is trying to become a branch of biology. At least half a dozen Chemistry Departments, including both Harvard and my own University, Cornell, have changed their names to Chemistry and Chemical Biology.

I have been interested for several years in conceptual — perhaps even philosophical — questions raised by the quantum theory. So when I learned that this change of name had been made at Cornell by the chemists — sorry, I mean by the chemists and chemical biologists — without any consultation with the rest of the university, I asked the Dean whether it would be OK, if I could persuade my colleagues in the Physics Department, for us to change our name into the "Department of Physics and Metaphysics". I never received an answer.

Physics, on its part, seems bent on absorbing biophysics, and, more recently, even economics. A Google on "econophysics" yields a modest 40,000 hits; not much compared with "quantum gravity", which yields 600,000, or supersymmetry, which gets 500,000, but the field is new and the century is still young. "D-brane" gets only 32,000.

Looking backward rather than ahead, what would a physicist from 1905 have made of the term "information science"? How about "nuclear engineering"? (Ten years later it would have made a little sense.)

You might complain that the real content of this question is "tell me everything of interest." But all I'd like to learn is what unfamiliar names are going to be there. And what familiar names are going to be missing.] I am certain that if physics is still a recognized field, it will have subfields whose names will have no more meaning to us than, for example, *Chronosynclastic Infundibulography.*

2. Please show me a widely used, inexpensive device used that will astonish me in as many ways as a laptop computer would have astonished a patent officer in Bern in 1905. At least some of the purposes of by this device should be as comprehensible to me as most of the uses of a laptop would have been to the young Einstein.

The number of different ways in which a laptop would have amazed Einstein in 1905, is itself amazing. Forget about its primary functions. What about the material its case is made of, its cost as a fraction of mean annual income, the source of its power, the precision with which it can imitate a symphony orchestra, its ability to show todays newspapers from all over the world, and all the catalogs of all the great world libraries? Nobody imagined such a thing in 1905. Nobody today can imagine the extraordinary objects that will be found in 2105 in households (assuming there still are households) or pockets (assuming there still are pockets).

You might object that this is a question about technology and not physics, but the technology in a laptop rests on a bedrock of fundamental physics most of which was undreamed of in 1905. I can't imagine what could rival it 100 years from now in the clarity of its purpose and its ability to astonish.

Indeed, I wonder if it may be a mistake to expect advances in physics-based technology in the 21st century comparable to those of the 20th century, which, after all, flowed out of discoveries in physics in the first quarter of that century that are, in some sense, unique in the history of science for their revolutionary character combined with the depth and range of their technological implications.

Nor does it take a prophet, or even a lot of chemists, to predict that the major advances in the 21st century will be primarily biological in character. Indeed, it's from that area that I would expect the most amazing gadgets of 2105 to draw their inspiration, so perhaps this question doesn't belong on my list of physics questions. But since Physics Departments will probably all have become Departments of Physics and Physical Biology, the question will then be entirely in order.

3. Are fundamental theories still based on superpositions of states that evolve linearly? Or have the basic principles of quantum mechanics been replaced? If quantum mechanics has survived, do people agree on solutions to the interpretive puzzles that bothered many early 21st century physicists, or have they ceased to view them as problems needing solution? If quantum mechanics has been replaced, has the new theory clarified these puzzles, or do people find it even more mysterious?

Serious people are still worried by quantum mechanics. I quote one mid-century figure:

"We have always had a great deal of difficulty understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it ... You know how it always is: every new idea, it takes a generation or two until it becomes obvious that there's no real problem. I cannot define the real problem, therefore I suspect that there is no real problem, but I'm not sure there's no real problem." (R. P. Feynman, Int. J. Theoret. Phys. **21**, 471 (1982).)

Or, as Einstein wrote to Schrödinger in 1950, "It is rather rough to see that we are still in the stage of our swaddling clothes, and it is not surprising that the fellows struggle against admitting it (even to themselves)."

I worry that this question might nevertheless elicit polite bewilderment, just as a pressing ether-theoretic puzzle at the turn of the 19th century might seem not only irrelevant, but downright incomprehensible to a physicist of today.

There are two possible grounds for 22nd century bewilderment at the question. One is that quantum mechanics will have been discovered, as Einstein always hoped, to be a phenomenology based on a more fundamental view of the world, which is more intuitively accessible. This strikes me as unlikely, because John Bell showed 40 years ago that any such theory would have to allow instantaneous action at a distance. So while the discovery of a more fundamental view of the world during the 21st century seems possible, I'd be very surprised if the new theory turned out to be more intuitively accessible then our current understanding.

An appropriate time scale for the survival of quantum mechanics is set by the fact that its basic conceptual machinery has suffered no alterations whatever, beyond a little tidying up, for eighty years. Not a bad run, when you compare what happened to fundamental knowledge between 1850 and 1930, though not close to the more than two centuries that classical mechanics remained the fundamental theory. So the persistence of exactly the same formalism for another hundred years seems at least plausible. If so, the question might still elicit early 22nd century bewilderment because after several more generations of physicists, chemists, and biologists (as we now call them) have worked with the theory, it has finally, in Feynman's words, become obvious to everybody that there's no real problem. Those early 21st-century people who believed there ought to be a better way to understand the theory will then have been consigned to the same dustbin of history as the early 20th-century ether theorists.

I hope that's not how it works out. It is, for example, now possible to articulate the nature of the wrong thinking that made relativity seem shockingly counterintuitive to many people during its early years. People had simply deluded themselves into believing that there was something called "time" that clocks recorded, rather than recognizing that "time" was a remarkably convenient abstraction — I would even say an ingenious abstraction, except that nobody set out deliberately to invent it — that enables us to talk efficiently and even-handedly about the correlation among many different clocks of many different kinds.

There is now no comparable key to dissolving the puzzlement engendered by quantum mechanics. I would hope that in the next 100 years such a key might be found that almost everybody would agree clarifies the character of the theory, in contrast to today's state of affairs, where no school of thought commands more than 10 percent of the population.

4. Tell me about a state of ordinary bulk matter, unimagined in the year 2005, that's as remarkable as superconductivity was still considered to be in the year 2005. The extraordinary behavior should be recognizable as amazing to an early 21st century physicist.

2011 will be the 100th anniversary of the discovery of superconductivity by Heike Kamerlingh Onnes, and today it is at least as wonderful as it appeared to be in 1911. We now understand the mechanism of its most common forms, though that explanation took almost half a century to be found. More interestingly, finding the explanation took a whole third of a century after the discovery of quantum mechanics, and not for want of trying.

A minor question for 2105: will people have learned that the last name of the discoverer is not Onnes, but Kamerlingh Onnes, just as the last name of the inventor of the quark is not Mann, but Gell-Mann. Because the Dutch feel no need for hyphens in compound last names, Kamerlingh Onnes seems doomed to go down as Onnes in scientific American articles, textbooks, popular books by distinguished authors, and histories of science. If posterity thought of me as Min (first name Mer), while, like poor Enoch Soames, I'd be delighted to be remembered at all, I'd still be pretty peeved.

Many remarkable phenomena have been predicted before they were discovered. Most famously, perhaps, the non-Newtonian gravitational deflection of light, predicted by Einstein and preliminarily confirmed by Eddington, though the resulting hoopla was incompatible with the size of the error bars. Or, to take another example associated with Zurich, the existence of the neutrino, postulated by Pauli in 1930 but not confirmed by Reines and Cowan for another 25 years.

But I maintain that nobody could have predicted superconductivity. The explanation for the phenomenon — a broken gauge symmetry — is so unintuitive that it would never have occurred to anybody to think about the possibility, much less work out its observable consequences, if people had not been driven in desperation to the explanation by their efforts to make sense of the actual phenomenon. Furthermore, the mean field approximation made to extract anything useful is uncontrollable and, in many other contexts, notoriously unreliable.

In a similar way nobody could possibly have invented quantum mechanics itself, had they not been driven to it by many unambiguous but unintelligible facts. General relativity might be the unique exception to this rule, though Einstein did get an enormous clue from the Eotvos experiments and motivation from his need to extend special relativity to include gravitation.

Like superconductivity, I believe nobody could have anticipated the much more recently discovered fractionally quantized Hall effect. Without the great analog computer of nature to motivate our speculations and calculations, nobody would believe a word of the currently accepted explanations.

I'd love to know some other unpredictable phenomena terrestrial bulk matter is capable of. It would be an unanticipated consequence of the basic laws of quantum mechanics and electrodynamics that govern ordinary matter, but the way in which those laws gave rise to that behavior would simply be too subtle to extract, without our first having learned from Nature what it was we were looking for, and without Nature being available for us to test whatever crude or crazy ideas we came up with in trying to account for the phenomena.

Although only a handful of such examples were found in the 20th century, it would be strange if others didn't thrust themselves upon us as we got better and better at going to lower and lower temperatures, creating stronger and stronger magnetic fields, and fabricating devices with structures on tinier and tinier length scales.

It's an essential part of my question that the strangeness of the behavior should be intelligible to an early 21st century physicist. This might be hard to satisfy. I'm not sure that the extraordinary character of a superconductor would have been evident to a physicist of 1811. Oersted didn't discover the action of electric currents on magnets until 1820. Ohm's law was not enunciated until 1827. Faraday discovered electromagnetic induction in 1831, all within a century of the subsequent discovery of superconductivity. The mystery of superconductivity, even if appreciated in 1811, would have been masked by a constellation of other mysteries. If the extraordinary character of the state of matter exhibited to me in the early 22nd century is that it has absolutely no coupling whatever to the *chronosynclastic infundibulum*, I'm not going to be impressed.

5. Do time and space still play the fundamental roles they did in early 21st-century physics, or have they been replaced by more coherent, less obscure concepts?

I am perplexed at how can people talk about spacetime turning into a foam at the Planck scale. As already noted, the great lesson of special relativity is that the concept of time is just an extremely convenient and compact device for characterizing the correlations between the devices we are able to use as clocks, or the much broader class of physical systems whose behavior we try to correlate with those clocks. But clocks tend to be macroscopic. They have to be macroscopic to communicate with us, which is their only purpose. Indeed, to assert that time, in quantum mechanics, refers to anything more than the time at which a state is prepared or a measurement is made, is to get into deep and murky waters.

Same problem with space. Einstein taught us that distances are usefully viewed as the interval between space-like separated events, and to measure this we need, for example, light signals and clocks. So when we talk about time and space at unthinkably tiny length scales, we literally don't know what we're talking about. There seems to me considerable danger here of imposing on an utterly alien realm a useful bookkeeping device we've invented for our own macroscopic convenience. The only justification (and it's not a bad one!) is that we don't know what else to do.

I confidently predict that time and space will still be with us in 2105, whatever happens to the British Library. But I wonder if they'll be in evidence at the foundations of the scientific description of nature.

6. Has progress been made in understanding the nature of conscious experience or how the mind (as opposed to the brain) affects the body? Does quantum mechanics or its successor play a crucial role in that understanding? Does that understanding clarify our confusion over the meaning of quantum mechanics?

There are those who say there is no problem of consciousness because the question doesn't make any sense. There are those who say there is no problem because it's all obvious. Physicists further divide into those who say quantum mechanics clearly does or clearly does not have anything to do with it.

The problem of consciousness, of course, has been around for centuries. But the growing sense, at least among physicists, that science has something to say about it doesn't seem to me transparently absurd, even though no two scientists can currently agree on what that something might be.

If you're not bothered by consciousness, it's unlikely that I'll be able to explain to you why it bothers me, but let me try. The notion of *now* — the present moment — is immediately evident to an individual consciousness as a special moment of time, or a brief interval, of order perhaps a few tenths of a second. It seems highly plausible to me that your now overlaps with my now or, if you are very far away from me, with a region space-like separated from my now. On the other hand, I can conceive of it not working this way: that your now is two weeks behind or fifteen minutes ahead of my now.

Physics has nothing to do with such notions. It knows nothing of now and deals only with correlations between one time and another. The point on my world-line corresponding to now, obvious as it is to me, cannot be identified in any terms known to today's physics. Consciousness has a particularity that seems absent from the physical description of the world, which deals only with relations. Consciousness can go beyond time differences and position itself absolutely along the world-line of the being that possesses it.

According to Rudolf Carnap, Einstein himself was bothered by "Now". Carnap reports a conversation with him in the early 1950's, in which "Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics. That this experience cannot be grasped by science seemed to him a matter of painful but inevitable resignation."

An even simpler example of an elementary constituent of consciousness which physics is silent on is the quality of the sensation of blueness. Physics can speak of a certain class of spectral densities of the radiation field, it can speak of the stimulation of certain receptors within the eye, it can speak of nerve impulses from the eye to the visual cortex, but it is absolutely silent about what is completely obvious to me (and I assume to you) — the characteristic and absolutely unmistakable blue quality of the experience of blueness itself.

This point — a banality among philosophers, who speak of *qualia* — is extremely hard, if not impossible, to put across to many physicists. I have sometimes managed to do it by citing a theory I had as a child to account for the fact that different people have different favorite colors. My idea — a kind of chromo-aesthetic absolutism — was that there was, in fact, only one most pleasurable color sensation, common to all human beings, but the reason *your* favorite color was blue while *mine* was red was that the sensation you experienced looking at blue objects was identical to the sensation I experienced looking at red ones. (Having come up with this example in a desperate attempt to get the point across to physicists, I later found it (complete to the choice of colors — only "you" and "me" are interchanged) on a list of possibly meaningless questions in P. W. Bridgman, *The Logic of Modern Physics*, Macmillan (1927), p. 30.)

Many people, some of them quite distinguished, have suggested that the problem of consciousness may be related to the problem of understanding quantum mechanics. I have little patience for people who think that quantum mechanics may contain a solution to the problem of consciousness. Consciousness is too mysterious to find its explanation in something that simple. But I can believe that a resolution might proceed in the other direction: if it were possible to understand consciousness this might resolve some of the puzzles of quantum mechanics. This has to do with the fact that the only statements quantum mechanics makes about the world are relational. If I view myself as a system describable by quantum mechanics, then my state becomes entangled with anything in the physical world I interact with. My conscious perceptions, on the other hand, have a particularity that goes beyond the correlation between those perceptions and what they are perceiving. To account for this by saying that I'm actually having all of the perceptions in a collection of parallel universes strikes me as ludicrously naive. The particularity of human experience is simply outside the scope of contemporary science, just like the nowness of now and the blueness of blue.

Many of my colleagues seem seriously to believe that when computers get fast enough and acquire large enough memories, they too will be conscious. I find this preposterous. My guess would be that in building consciousness, natural selection managed to tap into something that we don't have the slightest clue about. Perhaps the *chronosynclastic infundibulum.* The only thing I'm sure of is that we won't tap into it by building bigger and better computers. The claim that computers some day can be conscious strikes me as every bit as ridiculous as the claim behaviorist psychologists used to make that dogs can't be.

There's a wonderful quote from Schrödinger (yet another famous resident of Zurich) that captures some of this feeling that something is missing from the scientific description. Democritus, Schrödinger remarks, realized that "the naked intellectual construction which in his world-picture had supplanted the actual world of light and color, sound and fragrance, sweetness, bitterness and beauty, was actually based on nothing but the sense perceptions themselves which had ostensibly vanished from it. ... He introduces the intellect in a contest with the senses. The intellect says 'Ostensibly there is color, ostensibly sweetness, ostensibly bitterness, actually only atoms and the void'; to which the senses retort: 'Poor intellect, do you hope to defeat us while from us you borrow your evidence? Your victory is your defeat.' You simply cannot put it, says Schrödinger, more briefly and clearly."

The risk of this question eliciting giggles — then *and* now — is substantial, but I'll take my chances. I'd love to know whether the question will be viewed as vexing, as silly, or as solved by 2105.

7. Is the structure of matter still being probed at shorter and shorter length scales? If so, is the study still based on tracking the debris emerging from high speed collisions? If so, how are the high energies produced? If not, can you explain the alternative investigative tools? What length scales have you reached? Has new structure been found at all intermediate length scales?

For nearly a century almost everything we know about matter at small length scales has come from hurling things at each other at higher and higher energies, so this technique is certain at least to be remembered a century from now, even if it is no longer used. But as the energy goes up so does the cost, and the size, both geographical and human, of the investigation.

We seem to be reaching the limits of feasibility of this method in the early 21st century. By the early 22nd century will the quest to probe deeper have ended, as journeys to the moon have ended today? Or will entirely new methods of investigation have emerged? In the latter case, will things settle down to patterns that persist over many length scales, as they do between 10^{-10} and 10^{-15} meters, or will new structure and therefore new questions continue to emerge as new length scales are reached.

And will any of this — if there is any of this — make contact with the world-view emerging from string theory? Or will the latter be viewed as a spectacularly beautiful manifestation of early 21st century decadence, a kind of scientific analogue of the pre-

Raphaelite English painters of the late 19th century.

8. Is controlled nuclear fusion an important part of your technology? Are room-temperature superconductors?

This question might well appear temporally provincial from the perspective of 2100. But the quest for controlled fusion has been going on for about 60 years; and the need for a clean, readily available source of energy is more acute than ever and will only intensify.

Materials that superconduct at liquid nitrogen temperatures and higher have only been around for 20 years, making this part of the question even more risky. But the 5-fold increase in temperature above absolute zero took everybody by surprise, so nobody can reasonably claim that there couldn't be another 3-fold increase. The consequences for power transmission, electronic devices, wonderful toys, would be immense. Since the broader subject of superconductivity has been with us now for almost a century, and has produced one surprise after another, it doesn't seem unreasonable to guess that it could be of central importance in the technology of the early 22nd century.

So I'm fairly confident that the question will make sense in 2105. The real worry is that other technological miracles will have been devised that have made these two potential technologicals so obsolete as to elicit the dreaded giggles. For example *positive chronosynclastic infundibulatory feedback.*

When I was a child, the most expensive department stores had networks of pipes. When you purchased something, information about the sale was written on a piece of paper. The paper, together with your money, was put into a cylinder with felt bushings at either end. The cylinder was put into a pipe and propelled by air pressure to a central office. In a little while the cylinder came back, popping out of another pipe into a basket, and there was your change. The whole thing made wonderful whooshing and banging noises — particularly at places where the pipes took 90 degree turns. I can imagine somebody in 1945 speculating about the amazing advances in pneumatic tubing that were likely to take place by the year 2045.

9. Are there quantum computers that can factor thousand-bit integers? What else are they used for? Do most homes have one?

This is by far the most rash of my questions. The whole subject of quantum computation is so new that it all may well have evaporated by 2015. The question would then make sense in 2105 only to a few historians of science.

There are two major obstacles to the existence of quantum computers in 2105. The first is technological. To factor a thousand bit integer on an ideal quantum computer, you need at an absolute minimum two thousand qubits. Quantum error correction, which it's hard to imagine won't be an essential component of such a device, multiplies this number by a factor of seven, so we're up to a couple of tens of thousands of two-state systems, whose interactions with external fields and whose pairwise interactions with each other must be controlled with exquisite precision, and whose interactions with anything else must be reduced to an extremely low level, so quantum error correction can be effective. At the moment it's a technological triumph to produce half a dozen qubits — almost enough for one error-corrected logical qubit.

Is this a worry? Half a century ago I had a summer job at IBM on Madison Avenue in midtown Manhattan. My job was to write a program to invert a matrix of complex numbers on the very newest computational wonder, the IBM 704. We wrote in assembly language. We were told that somebody was working hard to develop a more intuitive but incredibly inefficient language called FORTRAN, which was being written for people who were too stupid to write their programs in the vastly more efficient assembly language.

The 704 occupied half a city block. If somebody had told me that within half a century there would be vastly more powerful computers that you could carry in your pocket that cost less then ten 1956 dollars and ran off a battery the size of an American penny that lasted for many years, I would have sent them off for psychiatric care. So I am inclined to dismiss my first concern, as symptomatic of a chronic lack of vision that has afflicted me all my life.

The second obstacle may be more serious. The only practical task that a quantum computer would be exponentially better at than a classical computer (according to our current understanding of classical algorithms) is efficiently determining the period of certain periodic functions, notably $f(x) = a^x (\mathrm{mod}\ N)$. Other applications are closely related to this one. (Lov Grover's famous search algorithm gives only a square-root speed up over a classical search.)

The ability to solve this problem efficiently permits one efficiently to factor N, and this, in turn, compromises the security of the widely used RSA scheme for encrypting secret messages. (RSA encryption can also be broken directly by an efficient period-finding machine, without the detour into factoring.)

While only a fool would expect that by 2105 human morality would have risen to a stage where it was no longer necessary to keep secrets, it isn't rash to expect that some time before then, other forms of encryption will be found that are not vulnearable to an attack by period-finding. Indeed, individual qubits, carried by the polarization states of photons, provide a method for replenishing one-time code pads that's already proved feasible with contemporary technology, and it's entirely plausible that in another 100 years this will be the dominant means for exchanging secret messages, in the (unlikely) event that no better classical procedure has been discovered.

Should this happen, the financial backing for research into quantum computers will suffer a precipitate decline, making their practical realization even less feasible. This would be a pity, since quantum computation is one of the most beautiful, surprising, and illuminating applications of quantum mechanics to have arisen in the second half of the 20th century.

10. Have intelligent signals of extraterrestrial origin been detected?

There's little to say about this one. It's not terribly expensive. The technology for searching is bound to get better and better. So I hope somebody keeps on looking for at least another century, not so much because I think the odds of success are high, but because it would be so wonderful if we did succeed. It would be an great comfort to know that if we managed to eliminate intelligent life from Earth — either by deliberate acts of war or terrorism, or an inability to control the mindless greed that threatens to make the planet uninhabitable — that we would not have destroyed something unique in the universe.

I know that 10 is the canonical number of questions to ask, but with the example of Enoch Soames in mind, I cannot refrain from concluding with an eleventh:

11. Is my book on Special Relativity published by Princeton University Press in late, 2005, still in print?

Or, better yet, will it be in the process of being reissued in a special centenary edition?

Of course the question rashly assumes there will continue to be such things as books. I fear it is hopelessly naive. More likely, there will be 10 peta-byte crystals people carry in their pockets containing permanent copies of everything ever published, updated continuously, and readable through special eyeglasses powered by ambient illumination. Yes, my book will have survived. Everything will have survived.

Nevertheless, this view of the future, like all the views I have expressed in the last hour, is probably hopelessly wrong. So I would urge you to watch your bookstores in the fall, and buy a copy while you still have a chance.