make a fair comparison between the alternatives that are available today for large-scale use.

There are five factors to be considered concerning fossil fuels:

- Political and economic dependence on the countries that happen to have large fuel sources.
- Combustion produces on the order of 20×10^9 tons of carbon dioxide a year, which is one of the many factors that affect the climate of the earth. The mechanism determining the climate is so complicated that one cannot yet say for sure what the result would be of changing one parameter, but we know that a decrease of the average temperature a couple of degrees is likely to trigger a new ice age, and that a slight increase might melt the ices in Greenland and the Antarctic, which in turn would raise the level of the sea on the order of 70 m.
- Fossil fuels have very complicated compositions, and combustion produces a lot of impurities. The effects of sulfur dioxide and nitrogen oxides have caused concern, at least in some areas of the world. Considerable amounts of heavy metals are released, including radioactive ones. A number of organic compounds are among the exhaust gases and some of them, like benspyrene, are known to cause cancer and genetic damage.
- Production and transportation cause large pollution problems. Perhaps most serious is the contamination of the sea by crude oil and petroleum products. On his voyage with Ra across the Atlantic, Heyerdahl found traces of pollution all along the way. Maritime life may be eliminated if we continue to pollute the sea, having serious consequences also for life on land.
- Fossil fuels are really too valuable to be burned up, since they are needed as raw materials for the chemical industry.

Many people are very concerned that the waste problem of nuclear energy is not yet solved, but how many of them are worried about the waste problems of fossil fuels? The wastes from impurities should, in principle, all be removable, but are we willing to pay the unavoidable increase in energy cost? In any case, the main waste, carbon dioxide, cannot be removed. Some people are worried that the supplies of fossil fuels will be exhausted, but it seems that the upper limits for the use of different fossil fuels are set by their influence on the environment.

A possible program for mankind would be:

- Take all opportunities to reduce the demands for energy and try to reduce the consumption whenever possible. The goal must be to reach an equilibrium where a desirable increase in one area is compensated by savings in other areas.
- Let nuclear energy take over a considerable fraction of energy supply and reduce the total use of fossil fuels. Oil and coal should primarily be considered as valuable resources for the chemical industry.
- International cooperation and inspection to prevent secret production of nuclear weapons as well as unallowed releases of oil or harmful combustion products.
- Research over a broad field to develop new energy sources which are less destructive to our environment.

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X-ray laser debate continued

The authors' comments on my letter (July, page 56) mislead the reader on two matters, which are important and simple enough to be set right in these columns.

The authors correctly observe that the photo-electric cross section decreases relative to the elastic-scattering cross section, approximately as the wavelength, as the wavelength becomes shorter. This is irrelevant, however, since the ionization cross section, which Breedlove and I gave in our paper, includes also the effects of Compton scattering, and the ratio of the ionization cross section to the elastic-scattering cross section attains a minimum of $R = 10$ at $\lambda = \frac{1}{2}$Å for the light atoms of biological interest. This is sufficient to prevent the imaging of the atoms in an individual biological molecule, according to the arguments we have presented, if light is the illuminant. It was the early recognition of the virulence of light that led Breedlove and me to consider the limitations imposed by radiation damage on the imaging of atoms in molecules when other natural radiations are used as illuminants.

Secondly, the authors suggest that the fundamental limitations to imaging the atoms in a biological molecule are related to the uncertainty principle. Actually the relation is not very direct. If light is the illuminant then the limitation is due primarily to the radiation damage resulting from the ten or more ionizations per elastically scattered quantum. In general, the zero point and thermal motion make the relative position of neighboring atoms in biological molecules uncertain only to within a few tenths Angstroms. (It is the fact that this uncertainty is small relative to the mean separation, ≈ 1–2Å, which gives the "tinker-toy" or "ball and stick" model of molecules its usefulness.)

So far as the principles of quantum mechanics are concerned, we should be able to observe the atoms in the molecule without disrupting it if the accuracy of the position measurements is less than the zero-point and thermal-motion amplitudes of the atoms. For example, scat-

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tering of thermal neutrons might, *in principle*, be used to resolve the individual atoms in a molecule without seriously affecting its biological functioning in a thermal environment.

The other issues mentioned by the authors are more technical and can be dealt with more appropriately elsewhere.

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7/12/76

THE AUTHORS COMMENT: George Trammell asserts that we have given a false impression in our article (June, 1975, page 40) and letter (July, page 57) regarding the usefulness of x-ray lasers for the study of biological molecules. We do not believe that this second letter of Trammell's makes any worthwhile new points.

His point that Compton scattering (rather than the photoelectric effect) is the fundamental—rather than merely practical—constraint when discussing limitations on the things one can do with an x-ray microscope was already mentioned in the first paragraph of our earlier letter. His assertion is simply incorrect that one cannot effectively image the atoms in a biological macromolecule because the ratio of x-ray inelastic to elastic cross sections is never less than 10. Apparently Trammell is unaware of the variety of techniques one can employ to record Angstrom-scale images with Compton-scattered x-rays, either conventionally or holographically.

It is also curious that Trammell asserts that the fundamental limitations imposed on an x-ray microscope by Compton scattering are not directly related to the uncertainty principle, since Heisenberg's original description of the uncertainty principle made use of a thought experiment involving the imaging of an electron with an x-ray microscope (see Heisenberg's *Physical Principles of Quantum Theory*).

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10/20/76

Humanity of physics

In his characteristically beautiful article in your June issue (page 23), Victor Weisskopf made an excellent statement of "Why physics is human," but regrettably failed to put forward any arguments in defense of the mathematical content of physics. Since I once had the honor to be addressed as a "horrible mathematician" by Weisskopf himself, (on the occasion of an after-dinner graduate-student discussion when I made a presentation on SU(3) in 1969) perhaps I could remedy the situation on Weisskopf's behalf.

At the outset I feel that we should remember that mathematics is an essential part of physics at all levels, and that of all the four complaints in Weisskopf's article the second hits closest to the essence of physics. We need only recall Lord Kelvin's famous remark to the effect that when he could measure or quantify a concept, it became much more understandable to him. If, even in the nineteenth century, numbers and mathematics were central to a physicist's view of the world, how much more true this is of the twentieth century.

As Weisskopf points out in his case for his points 1 and 3, nature exhibits form, structure, and patterns of symmetry, and these have fascinated Man from the earliest times. It is here that we can start our apology for mathematics. From the ancient Greeks we have inherited a tradition of investigating the order and beauty in the world. Even before the ascendency of Athens two great themes of nature were recognised: first, that nature exhibits order—in the sense of patterns of events that are not totally random or chaotic, as exemplified by the progression of the seasons and the motions of the plants—and second, that the essence of this order is to be found in mathematics. At Plato's Academy, appreciation and understanding of the beauty of such patterns exhibited by the natural world were regarded as among the loftiest ideals to which a man could aspire, and in his curriculum for the education of philosopher-kings, Plato placed mathematics at a central point. In view of these facts surely we should not feel apologetic for mathematic's role in today's physical sciences. We only need a contemporary statement of the same themes to justify it.

Firstly, we can state that the most esthetic aspect of modern scientific endeavor is to give a clear and concise description of the patterns of symmetry and order in nature and of the mechanics underlying them. Secondly, the clearest and most concise statements of symmetry and order, and therefore the ones that are most elegant and esthetically appealing, are those made in terms of mathematics.

At Maharishi International University in Fairfield, Iowa, concepts similar to these have been used as a central part of extremely popular courses in physics and other sciences (and arts), and it is noteworthy that the four complaints enumerated by Weisskopf have been almost unheard of.

In conclusion I suggest that the best defense of the mathematical content of physics may be made on artistic, and therefore more directly human, grounds rather than by appealing to the intellect and pure reason. I would also suggest that your readers might well find it prof-