Extraterrestrial intelligence:

The readers respond to Tipler

We compliment PHYSICS TODAY for its stimulating guest comment in the April '81 issue by Frank J. Tipler ("Extraterrestrial beings do not exist," April, page 9). As research physicists in specialties far removed from astrophysics and extraterrestrial biology, but intrigued by Carl Sagan's (and others') unquestioned assertion that numberless intelligent civilizations exist elsewhere in the universe, we have been struck by the paucity of critical response to this hypothesis. This lack being quite an uncharacteristic reaction by the scientific community to what is a controversial proposition.

However, with Tipler's counterpoint, it now appears that an opposite view is alive and well. PHYSICS TODAY and Tipler have provided the required first step for the scientific community's consideration, and the usual and absolutely necessary polemics may now proceed.

The cartoon accompanying the piece reminded us of an essay that appeared in a sci-fi publication right after the probes to the moon, Mars, Mercury and Venus indicated that no life there was evident. That essay was similarly entitled "Where did everybody go?!" and undoubtedly represented the lament of the science-fiction authors, who may have had concern for their livelihood. We trust that Sagan and company would rather respond than lament. We look forward to their reply.

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In the April "Guest Comment," Frank Tipler argues that we are the only intelligent species in the galaxy, and thus it is folly to carry out any searches for evidence of other civilizations in space. His basic argument, asserted by others as well, is that complete colonization of all suitable stars in a galaxy is possible by machines (or creatures themselves) in a time interval short with respect to the age of the galaxy. He submits that what is possible will surely occur; thus the first technical civilization colonizes the entire galaxy. And, since no colonization of the solar system has occurred, the implication is that we are the first, and probably the only, civilization in the galaxy. I believe that there are quite plausible alternative scenarios which would support the idea that there are many technical civilizations in the galaxy, and that substantial searches for them are warranted.

The basic weakness in arguments such as Tipler's is the readiness to assume the possible to be the inevitable. To many people, some physically permissible courses of action seem highly implausible, no matter what level of wealth or technical know-how is imputed to the extraterrestrials. A specific example is the hypothetical colonizing Von Neumann machine as proposed by Tipler. Although the computer portion of this device could have insignificant mass, it would have to carry with it the materials necessary to build a successful mining operation or materials-extraction factory—in either case one which is so general in its abilities that it will be able to produce the necessary structural materials from a host of possible planetary surfaces, many of which may not even be predictable. It must also carry observation devices and rather powerful maneuvering mechanisms so that, as it approaches the target stellar system, it can reconnoiter the planetary system (if there is one), make a decision as to which planet, satellite, or asteroid to land on, and then adjust its trajectory to make such a landing possible. At the proposed transit speed of 100 km/sec, aerodynamic breaking for landing will probably be insufficient—or impossible if the destination has no atmosphere. The vehicle then must carry a great deal of mass to make possible the required deceleration as well as to provide maneuvering ability. The overall mass of such a vehicle, including mining and material processing equipment and mass for deceleration is a matter of conjecture, but hundreds of tons is probably a reasonable estimate of the minimum order of magnitude of mass of such a vehicle and its payload. What we are then describing is a mission whose overall costs will surely exceed those of the Apollo or Space Shuttle Programs.

Now, would anyone expend such resources on anything which may or may not accomplish something 100 000 years hence? Many people think it is very implausible. The greatest temerity I might muster (especially as I approach the Proxmires of the galaxy!) would be to promote such a mission if it were to produce results in perhaps a little more than a lifetime, say 100

Deciphering this binary-coded radio message produces a representation of DNA, humans, the solar system and the Arecibo telescope.

the debate continues

years. But then the inferred velocity is more like 0.1*c*, and simply the initial kinetic energy required by the spacecraft is about 10^{21} joules. Assuming a ten-percent efficiency overall in fuel production and utilization, the basic required energy is about 10^{22} joules, minimum. This is as much energy as is produced by all sources in the US in 100 years. We are then talking about shutting down a country the size of the US for a hundred years or so to launch one mission.[1]

This seems implausible, for there are a lot more appealing (and relatively old-fashioned) things you might do with such resources, even if the resources were cheap and available. Foremost would be to restructure the environment of one's own planet to produce a better life for more creatures. Build cities on the oceans. Transform the polar regions into gardens. Then terraform other planets and build space colonies. One would do a lot of radio searching for other civilizations before embarking on interstellar hegemony via the super-expensive and not very satisfying route of von Neumann machines.

Where are They? I would venture They are living a good life in their own planetary system, in huge numbers, and if there is to be contact with Others, then it will be by radio communication.

There are those who will find the arguments of Tipler appealing, and those who will find the above arguments appealing. In both cases the arguments are inconclusive. There is a solid and important point, then, which is that we simply have insufficient data to do any hard theorizing about the sociology of extraterrestrial life. We are no more in a position to construct sound theories of the evolution of extraterrestrial societies than Aristotle was to construct theories of physics. SETI is for now an experimental science, and we should carry out reasonable experiments. These include not just searches for radio signals, but other cost-effective approaches which offer the ability to detect even very speculative manifestations of extraterrestrial civilizations.

Reference

1. F. D. Drake, in *Strategies for the Search*

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A biologist looks at the numbers

Leonard Ornstein

In the Guest Comment in April (page 9), Frank Tipler argues that if extraterrestrial beings existed, our galaxy would be so full of their Von Neumann machine proxies that we could not have missed them. Tipler replaces Michael Hart's and James Trefil's humanoid colonizers with machines, to circumvent the costs of humanoid support and humanoid fragility. Francis Crick and Leslie Orgel replace them with cargoes of microorganisms in a revival of Svante Arrhenius' century-old "Panspermia" hypothesis.[1]

I'm concerned that rebuttals of Tipler's argument may refuel the push for a Search for Extraterrestrial Intelligence (SETI) which has been steadily championed by a group of physical scientists led by Frank Drake, Carl Sagan, Bernard Oliver, John Billingham and Philip Morrison. Therefore, I would like to offer less imaginative, but perhaps more compelling, biological arguments against SETI.

Let me say at the start why I believe many scientists are so easily gulled by the intriguing idea of ETI: It's that they simply have faith that the deterministic laws of chemistry and physics assure that all classes of macroscopic processes, including those of biological evolution, *must* be repeated countless times, over the multi-billion-year lives of the galaxies and the vast stretches of the universe. However, such ergodic faith is probably mistaken. Macroscopic Darwinian selection is unparalleled by other physical processes and is much less likely to repeat itself. It tests the environmental fitness of new genetic messages (mutations) that, *prior to* selection, have been generated by microscopic random accidental modifications of pre-existing molecular messages. These molecular messages appear to be otherwise archivally insulated from environmental editing. The full set of messages tested by selection, from the beginning of life, constitute only a minute and probably unrepresentative sample of different possible messages from which the sample has been "drawn." The number of possible messages exceeds the estimated number of atomic particles in the entire universe by some 100 million orders of magnitude![2] Therefore, no matter how prevalent *life* might turn out to be, biological evolution on earth can easily have generated many "inventions," perhaps including intelligence, which are unique in the universe.

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The SETI equation

But let's examine the main arguments put forward by the proponents of SETI and see how convincing they are. Drake has said, "At this very minute, *with almost absolute certainty*, radio waves sent forth by other intelligent civilizations are falling on Earth" (in Ferris,[3] my emphasis). Drake has developed an equation to estimate, as he puts it, the number of communicative civilizations we might find in our Galaxy,

$$N = R_* f_p n_e f_l f_i f_t L$$

(To my knowledge, Drake has not published this equation, and so it appears by attribution, as in Tipler's article, or as a quotation.[3])

R_* is the *r*ate of star formation, averaged over the lifetime of the Galaxy, in units of numbers of stars per year;
f_p is the *f*raction of the stars which have a *p*lanetary system; and
n_e is the mean *n*umber of planets within such planetary systems which are *e*cologically suitable for life.
Drake, quoted in Ferris,[3] informs us:
"f_l is the *f*raction of potentially *l*ife bearing planets that actually do give rise to life. Biochemical experiments on Earth suggest that this number is approximately one, that is, that the chemistry of life is ubiquitous and powerful, and that life tends to arise wherever it has a chance to do so."
"f_i the *f*raction of living systems that evolve *i*ntelligence. The fossil evidence on Earth suggests strongly that this number is also one. We say that because in the fossil record, there is one category of things that constantly improved and that is brain size, which we associate with intelligence."
f_t is the *f*raction of those planets on which intelligence has arisen, which then develop the *t*echniques of radio communication.
L is the average *l*ife-time of these hypothetical civilizations.

Drake estimates the first six variables as one per year, ½, 2, 1, 1, and 1, respectively. He argues that the sethe cephalopod line? The cephalopods are the most advanced members of the phylum Mollusca. A wide variety of eyes are found among more primitive molluscs.[5,6] The eyes of some bivalves illustrate a series of transitional forms[5] that "start" with a primitive verted camera eye with rhabdomeric receptors and "end" with the Scallop's eye, a Schmidt-type camera with catadioptric (reflecting–refracting) optics[7] with an inverted retina with ciliary receptors. In man-made Schmidt cameras, the detector assembly (or a mirror representing it) obscures part of the incoming beam of light. The Scallop's inverted retina also faces a reflecting hemisphere to the rear. In such a design, transparent nervous layers minimize that obscuration. This may reveal the rationale for the origin of inverted retinas. Later conversion back to fully dioptric camera design, as in, for example, the vertebrate line, would leave the inverted retina as a vestigial structure, much more closely related to the verted retina than has previously been suspected.

The coelenterates constitute a phylum which is considered to be more ancient than the molluscs or chordates, and might have contained the ancestors of both. Among the coelenterates are some cubomedusan jelly-fish that have simple, verted camera eyes.[8] Is it possible that an ancestor common to the cephalopods and the vertebrates had eyes similar to the cubomedusan? If that were the case, the observed convergence would hardly be so remarkable; probably much less so than what was surely independent evolution of flight in the vertebrates and the insects. This hypothesis is now testable by protein and nucleic acid sequencing methodologies at a cost much less than that for one year's worth of SETI.

All things considered, my present guess is that f_i is some million times smaller than Drake's estimate.

A reasonable estimate

My somewhat facetious, necessarily uncertain, but perhaps more "reasonable" guesses of the magnitudes of f_l and f_i reduce the likelihood of detecting another civilization a trillion times. Morrison suggests that the SETI project has a "fair chance" of success (in Ferris[3]). But right now, investing in SETI looks more like placing a bet on a dead horse. Surely, unless and until careful studies of the comparative biochemistry of "convergent" camera eyes show that f_i may approach 1.0, no significant social expenditure on SETI is warranted. However, in no way should this argument be construed as a criticism of NASA's rational Planetary Program which is also vigorously promoted by Sagan and Morrison.

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7. M. F. Land, *Sci. Am.* **239**, June 1978, page 126.
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for Life in the Universe, M. D. Papagiannis, ed., Reidel, Boston (1980) page 27.

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After reading Frank Tipler's guest comment regarding the nonexistence of extraterrestial beings, I believe there are some errors that I wish to respectfully suggest.

The first error I noticed was an apparent misreading of the Drake equation, resulting in an erroneous interpretation. The Drake equation, as presented by Tipler, defines the probability P of a communicating, intelligent civilization evolving in any given stellar system independent of all others. Tipler provides this definition, but then proceeds to equate P to $1/N$, the reciprical of the number of stellar systems not younger than 5.3×10^9 years, within our galaxy. However, $1/N$ is the probability of finding, on the first try, evidence of a civilization, given that only one stellar system out of 10^{11} candidate systems has evolved an intelligent, communicating civilization that implements a strategy of exploration with self-reproducing robots. This is not the same as the probability of any given stellar system evolving such a civilization. The error is compounded, however, because although $1/N$ is not Drake's P, neither is it what Tipler interprets it to be: the probability of finding evidence of a communicating, extraterrestial civilization with no assumption on how many such civilizations may exist. If Tipler's claim—that the potential extraterrestial civilizations have failed to communicate in spite of their opportunity to do so—is meant to reduce the possibility of their existence to one, then the entire argument is circular and rendered superfluous by assumption of the result as a condition.

With this misinterpretation, it is not surprising then that Tipler should conclude that $f_l\, f_i\, f_c$ is not more than 10^{-10}. However, this value of 10^{-10} is not a calculation of $f_l\, f_i\, f_c$; it is really a constraining upper bound, necessary only because of the assumption that only one stellar system, not younger than 5.3×10^9 years, has evolved an intelligent, communicating civilization. Suppose that many more than one civilization had evolved.

An intuitive check on this reasoning can be seen by taking the limit of $P(N)$ as $N\rightarrow\infty$, $\mathrm{Lim}_{N\rightarrow\infty} P(N)=0$, which would seem to be unreasonable for the probability of finding such a civilization.

There are other statements in Tipler's paper that I feel are debatable. The statement that none of the potential candidates for having produced an intelligent, communicating civilization have done so is one. The minimum age of 5×10^9 years as a prerequisite for intelligent life is another. The thrust of the article is to prove that we are alone; yet the argument, erroneous though I believe it is, concerns only civilizations wishing to communicate with probes. This is not quite the same thing. Finally, the concluding statement that the number of intelligent, communicating civilizations is 1 ($PN=1$) is circular logic—since P was defined as $1/N$—and therefore does not constitute a proof.

Although this paper expressed no ulterior motive it is reminiscent of other misapplications of statistics I have seen, made in support of religious arguments premised on the uniqueness of humanity as the embodiment of intelligence.

I endorse Tipler's preference for addressing this issue with a statistical analysis of the galaxy as it appears to us, rather than from the perspective of how we feel the galaxy ought to appear to us. However, in this case, perhaps some agreeable middle ground can be found. I would imagine that estimating $f_l\, f_i\, f_c$ could be approached by addressing the problem of estimating the probability of the occurrence of the Earth, the only known planet to be a host to life. This probability estimate may be developed from a theory of planetary origins considering the aggregation of matter in orbit, natural abundances, and other observable phenomena. From this stage, information theory may provide a convenient language for expressing how surprised we deserve to be upon discovering a life-supporting planet as opposed to any other kind.

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. . . The nonexistence of extraterrestrial von Neumann machines in our part of the galaxy does not disprove the existence of extraterrestrial civilizations able and willing to design and manufacture them. This is so because, sooner or later, one or more of the machines would "turn" on their fellow machines and cannibalize them as rich and more easily accessible sources of raw materials needed for self-procreation. The only real question is how long would it take for the initial—computer or otherwise encoded—message of "sibling or species recognition—cannibalism preventing" mechanism to break down. According to the second law of thermodynamics, the design, manufacture and maintenance of information systems[1] requires irreversible energy loss coupled with simultaneous increase of the total entropy of the information-containing structure and its surroundings. The more elaborate the information system, the greater the energy loss and the total entropy gain. If a system is to become infallible, zero defective, or, as Tipler defines it, capable of self-repair (obviously meaning that the repaired item is indistinguishable from the original one), the energy expenditure would become infinite and a corresponding increase in the total entropy would be mandatory. . . .

Reference

1. B. Commoner, *The Poverty of Power*, Knopf, New York (1976), page 7.

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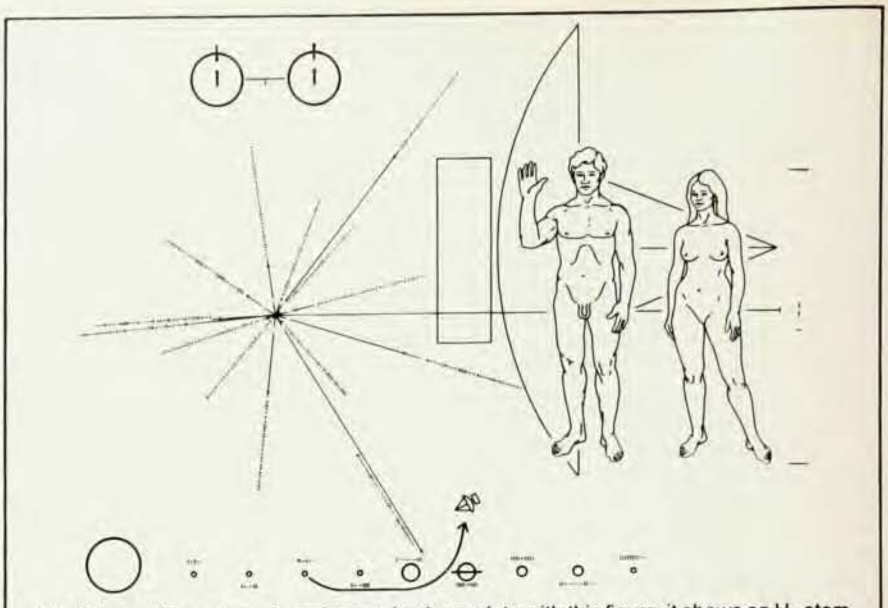
In his article Frank Tipler revives an old argument against the likelihood of intelligent life, other than our own, in the universe. While his ultimate conclusion that we are alone may well be correct, his argument is very weak, for it rests entirely on the assumption that we will be able to build self-reproducing machines capable of turning rocks into rockets. There is no evidence for this.

We know that "von Neumann machines" exist, at least in the form we call life. We do not know if they can exist on a significantly simpler or smaller scale. We have no hints as to how to construct them, and the statements of "experts" that we will discover this in the next century are only whistling in the graveyard. No machine we have built or know how to



The Pioneer 10 spacecraft carries an aluminum plate with this figure; it shows an H_2 atom, the position of the Earth with respect to nearby pulsars, information about the solar system and a schematic view of the spacecraft and its builders.

build is at all intelligent, nor are any of them closer to reproducing themselves than is an abacus. The tip-off is the claimed time scale of 100 years—long enough that one won't be around to be proven wrong, and long enough that "almost anything can happen." But it's not true that "almost anything can happen" in 100 years. Many unexpected things will happen, but certain strongly desired things won't. Antigravity machines and superluminal travel are good examples of things predicted over 100 years ago which haven't happened, and won't in 100, 1000, or 1000 000 years. Our understanding of self-reproducing automata is so poor that we cannot exclude the possibility that we will never be able to construct them.

The problem is worse than just constructing self-reproducing machines. After all, we have available to us a million species of such machines. One species is capable of building rockets, radio telescopes, and computers. To colonize the Galaxy, the machines must be capable of extended space travel and of successful multiplication and colonization in a hostile environment. Anything resembling a modern computer would surely break down, as all computer users know. If Tipler believed humans capable of this he would have suggested using humans. What evidence do we have that synthesized machines could do better?

Finally, Tipler takes the possibility of "O'Neill colonies" too seriously. The question is again that of self-reproducing machines, but the machines are now social and technological organisms, including humans among their components. There is no doubt that a sufficiently large colony is self-sustaining and self-reproducing, at least in the benign environment of Earth. But how small is the smallest such colony? O'Neill might guess 100 people and $\$10^{11}$ of capital, but I prefer to guess 10^3 times larger. The answer is not known.

If Tipler has underestimated the difficulty of building von Neumann machines and O'Neill colonies, as I suggest, then the Galaxy could well be filled with advanced intelligent civilizations in mutual communication.

Jonathan Katz
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Although we agree with Frank Tipler's basic conclusion—that humanity may well be the Galaxy's first technological species—we must confess that colonization of the universe by von Neumann machines sounds very silly (even though Arthur C. Clarke had discussed the concept in his book *Profiles of the Future* and we recognize that disagreeing with Clarke predictions is demonstrably risky). We ask: What self-respecting product of Darwinian evolution would gift the Galaxy to a swarm of sentient machines when the same technology could carry human genes to the stars in the original container? We could ask questions like "Who would pay for such a thing?" and "How could we guarantee the von Neumann machines wouldn't turn on us?" but a far more important point is that when we send sophisticated probes to the stars, human migrants will not be far behind. Human history is quite clear on the point. Monte Carlo simulations of the human interstellar migration suggest that our descendants will fill the Galaxy in no more than 10^8 years.

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Tipler's closing comment seems fallacious. He says:

> John Wheeler and Robert Dicke have argued that if the universe were much smaller than it is, it would terminate in a final singularity before intelligent life would have time to evolve. . . . Thus the universe must contain 10^{20} stars in order to contain a single intelligent species. We should not therefore be surprised if indeed it contains only one.

But I think we indeed should be surprised. The universe needs to be large to persist; having achieved a sufficient age, it is surely more than large enough for a single species.

An analogy comes to mind. Suppose I drill a well because I am thirsty. This may require my going down several hundred feet. I strike water, and I take a drink. A neighbor comes along and asks for a drink as well. What if I were to tell him, "No, there isn't enough. I had to go down 250 feet just to get *myself* a drink."

I doubt that he would believe me.

Charles A. Whitney
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. . . Assume that we are indeed the only intelligence present in the solar system. Does it directly follow that we must be the "first" ones? Suppose intelligence is such that it self-destructs before it reaches the technological capability for interstellar travel. (The probability that the species will attempt travel is then zero.) Based on the experiences of the only intelligence we know about, self-destruction unfortunately does not seem to be such an improbable event. In fact, the best possible news mankind could receive would be evidence that somebody does indeed exist "out there." It would mean we too might have a chance.

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I believe that readers of Frank Tipler's guest comment on the nonexistence of extraterrestrials should consider the following question: How do we know Frank Tipler exists?

Have you ever seen Frank Tipler? Assuming he is an intelligent creature, why hasn't he fallen within our 'realm of influence'? There are only 4×10^9 people on this planet; surely an intelligent creature would find some direct way of making his presence known to at least a sizeable fraction of the population.

Perhaps we haven't seen Frank Tipler because we haven't looked hard enough. If we undertook a *comprehensive* and *methodical* search for him (in New Orleans?) then we may be able to make a definitive decision on his existence.

I use this tongue-in-cheek analogy to demonstrate a common fallacy in SETI—that we now have enough data to decide if extraterrestrials exist. As one who has conducted a SETI, there is no question in my mind that our observational limits are modest at best. I think we should stop indulging ourselves on the *question* of whether ETIs exist. Rather we should get the data (no minor future effort!) and let them decide for us.

N. L. Cohen
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Frank Tipler's piece contains some interesting ideas, though of course he claims too much; his argument says nothing about intelligent aliens who have no technology or no wish to travel. Like all such "proofs," this one makes some unstated assumptions which can be fatal to the conclusion. Consider:

▶ Will biological beings in fact plan for expeditions which yield a return only after 1000 to 10 000 years? Natural selection surely will not prefer beings who have lifespans this long—they would overrun their biosphere if they reproduced often, and if not, they probably would not evolve rapidly enough to have yet attained intelligence. Thus we must consider how probable it is that societies will plan scientific expeditions or programs for times exceeding the individual lifetime by at least one or two orders of magnitude. There is no human evidence for such long-range research goals. Thus Tipler is assuming an important social point without any supporting argument. It is one thing to advocate a manned Moon landing which costs \$30 billion and pays off in a decade, and quite another to propose spending \$30 billion or more which pays off in the year 3000 AD (or 13 000 AD!).

▶ Even if we grant civilizations that plan on this scale, is unleashing a flock of self-reproducing machines a smart move? These machines will mutate, just as life does, because no template can assure certain fidelity in reproduction. Cosmic rays will sleet through them, bringing steady "genetic" alterations. The machines could malfunction and change their motivations. they could become competitors for the raw materials in other solar systems, if the home world ever tries to expand into the galaxy. Or perhaps one of the machines could become deranged, returing to the home world with an irrational aggression and a suicidal plan to destroy the biosphere of the home planet. *Anything* could happen. The point here is that Tipler's whole argument hinges on the awesome power of unlimited doubling. A wise society will think through these matters long before it attempts interstellar travel. (For example, we will confront the unforeseen troubles of self-reproducing machines in the next century, when they could work their exponential magic on the Earth. Freeman Dyson pointed this out years ago.) A society that can plan for 1000-year research programs will surely take precautions to avoid letting its machines gobble up the galaxy. (They would do so either to protect their future interests, or to avoid using up all the industrial materials and thus doom future life to a low level of development.) Even if they launch such machines, they will have to exert some control to avoid potential longterm catastrophe. This means keeping them "in the neighborhood," which I would guess would mean within a few hundred parsecs of home. There might be thousands of such "spheres of self-interest" in our galaxy, without much overlap. Here we see that radio communication has a definite advantage over self-reproducing machines—it doesn't endanger the future resources of the whole galaxy.

▶ On a lighter note, put yourself in the place of the first society in the galaxy that wants to communicate. Someone there makes Tipler's argument and everyone is convinced. Thus they don't listen to their radios and they don't explore—there's no point, they're alone. So they—and every subsequent civilization which accepts Tipler's "proof"—do nothing. Unless they expand for economic reasons and find another ostrich-like society, they'll never know what a simple error they have made. If we buy Tipler's argument, will we be but the $N + 1$st civilization to do so?

It is worth noting that a number of these ideas have been mulled over in science fiction for decades, to good effect. The argument deserves serious though, but making it quantitative, as Tipler has, does not protect it from the danger of the hidden assumption. Let us remember that aliens may well differ from us most profoundly in qualitative ways, not quantitative ones.

Gregory Benford
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Frank Tipler's article about what extraterrestrial intelligent beings would have to be like (if they existed) and what they would have to be doing (that is, building spaceships and forming imperial colonies) was so anthropomorphic in its assumptions that it is surprising he didn't also conclude that extraterrestrial beings would have to drive Chevys, eat Wonder Bread, and belong to the Southern Baptist Church.

John Daugman
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Frank Tipler's argument has one flaw: He assumes a probability of nearly 1 that any species with a serious interest in interstellar communication will be willing to spend about 30 billion dollars to launch a few self-reproducing interstellar probes, since "Some information on other systems would be guaranteed in 10^4 years, even if other intelligent beings are not discovered." Considering how difficult it is to get our species to spend 30 billion dollars on projects that are likely to produce interesting results in 10 or 20 years (controlled fusion, interplanetary exploration, high-energy physics, for example), I can easily believe that the probability of any species spending such a sum on a project that will not pay off for 10^4 years is less than 10^{-10}. In this case, it is possible that every inhabitable planet in the galaxy has evolved an intelligent species; though perhaps none of these species, including ours, should be described as having a *serious* interest in interstellar communication.

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The author comments: The above criticisms of my views can be divided into two classes: (1) those of a technical nature, and (2) those which deal with the sociology of possible extraterrestrial intelligent beings. Most of these criticisms I have discussed in the three *Quarterly Journal* articles[1,2,3] of which the PHYSICS TODAY paper was but a précis. Here I will reply briefly to those criticisms that were answered in the *Quarterly Journal*; my critics are referred to those papers for more detail on the points in question.

Let us consider the technical issues first. I must confess that I am astonished at Frank Drake's computations of the cost of interstellar travel. Not only does he not seem to have read my papers where I present my cost estimates in conjunction with a specific interstellar flight plan,[1] but he seems equally unfamiliar with the fairly extensive literature on relativistic rocket propulsion. In my flight plan I explicitly assumed that the speed of transit between the stars would be $10^{-4}\,c = 30$ km/sec, and that braking would be by rocket engine. The Project Daedalus calculations[1,3,4] indicated that a self-reproducing probe would require a payload mass of 10^3 tons, a figure Drake also obtains. This probe would never be intended to land directly on a planet of the target stellar system. As Drake says, planetary environments are too unpredictable, and it is not even known if planets are commonly found around stars. According to present-day theories of star-formation, however, we can expect to find smaller bodies (asteroids, comets, and so on) in orbit around all stars. These would be the targets of the probe, for they would be the source of the material from which other probes would be constructed. To reach such targets, it is only necessary for the probe to have sufficient fuel to stop in the outer part of the target stellar system. Maneuvering inside the stellar system can be done with solar sails, or similar low-mass propulsion systems. Launching such a probe from the surface of the Earth via contemporary rockets would require a mass ratio of 10^3 to reach a transit speed of $10^{-4}\,c$. A further mass ratio of 10^2 would be required to slow it down in the outer reaches of the target stellar system, giving a total mass ratio of 10^5. Actually, it's rather silly to launch an interstellar probe from the surface of an inhabited planet. I would imagine that any intelligent beings capable of constructing such a probe would have previously colonized their own solar system, and would therefore launch their interstellar probe from the outer part of their own system. If so, they would need a mass ratio of only 10^4, using our rocket technology. Assuming that the cost of the rocket and payload is dominated by the cost of the fuel, and assuming the cost of the fuel is equal to the present cost of gasoline, a probe would cost between 3 billion and 30 billion dollars, depending on where the probe is launched. My reasons for thinking that the cost of the probe would be dominated by the fuel cost is detailed in reference 1.

Drake has overestimated the cost of accelerating a 10^3-ton probe to $10^{-1}c$ by two or three orders of magnitude. The detailed estimates have been given by Freeman Dyson[5], and by the Daedalus Study Group[4]. Drake is correct in asserting that a probe with a mass of 10^3 tons moving at $10^{-1}c$ would have a kinetic energy of about 10^{21} Joules, but he errs in assuming that this energy must be obtained from power sources that supply Earth-based industry. A much better source—in fact the source proposed by both Dyson and the Daedalus group—is a series of thermonuclear explosions generated by a pulse rocket. According to both Dyson and the Daedalus group, the cost of such a probe would be dominated by the cost of the thermonuclear fuel, which would be either deuterium or helium-3. I pointed out in my first article that if a 10^3-ton von Neumann probe were accelerated by nuclear pulse rocket to $10^{-1}c$ and decelerated by the same means in the target solar system (the deceleration adds greatly to the cost), the total probe cost would be about 10^{14} dollars, assuming that the fuel cost was the same in an advanced civilization as it is in ours. However, it is likely that the high cost of thermonuclear fuels is due to the low demand for such commodities in our economy. Once thermonuclear reactors become common, the prices should drop drastically. Except for temporary fluctuations such as the 1973 OPEC oil-price increase, the price of all raw materials relative to wages has been dropping exponentially for two centuries, with a time constant of between 20 and 50 years. If this trend continues—and the economist Julian Simon explains in detail why it should in a recent series of books[6,7]—then in 400 years, the cost of such a probe would be 10^{11} dollars. But in such an advanced economy—encompassing a solar system, say—there would probably be many more people than there are in ours. If the number of people were larger by a factor of 10 to 100, we would expect government budgets and total GNP to be larger by the same factor. Thus, finding funds for a $10^{-1}c$ interstellar probe in such an economy would be as difficult as finding the money for a project costing between 10^9 to 10^{11} dollars in our present-day economy. Even the higher figure could be raised: The 1982 US defense budget is 2×10^{11} dollars; the lower figure would be still easier to raise.

I'm afraid I do not understand John Wilburn's criticism of my statistical methodology. He asserts that $1/N$ is the probability of finding, on the first try, evidence of a communicating civilization that implements a strategy of exploration with self-reproducing robots. However, if one accepts my arguments, this probability for finding such a civilization is not $1/N$, but rather 1, because such a civilization would have already contacted us with a von Neumann probe. Thus we have in effect sampled N stellar systems in our galaxy that could have produced such a civilization but failed to do so. For simplicity I equated N with the total number of stellar systems that are older than 5.3×10^9 years, but as I have emphasized, one should more accurately equate N with the number of stellar systems older than 5.3×10^9 years that could have evolved intelligence within 5.3×10^9 years after the formation of the system. In either case the best statistical guess for the probability of the evolution of such a communicating civilization is some number less than or