primary interest is to analyze the information transfer across several neuronal stages by defining the dynamic input-output relations of the systems rather than to explain the physiochemical basis of interacting subcellular systems.

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References and Notes

1. For cases of systems with "small signal" nonlinearities see, for example, H. Spekreijse (*2*) and J. Levett [*Vision Res.* **10**, 1347 (1971)] and papers on the pupillary reflex system and neutral threshold systems. For the many biological "unidirectional rate sensitivity" systems, see M. Clynes and J. H. Milsum [*Biomedical Engineering Systems* (McGraw-Hill, New York, 1970), pp. 212–316] among many others.
2. H. Spekreijse, *Vision Res.* **9**, 1461 (1969); *Kybernetik* **7**, 22 (1970).
3. N. Wiener, *Nonlinear Problems in Random Theory* (Massachusetts Institute of Technology Press, Cambridge, 1958).
4. A. G. Bose, *Technical Report 309* (Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, 1956); D. A. George, *Technical Report 355* (Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, 1959); J. F. Barrett. *J. Electron. Control* **15**, 567 (1963).
5. Y. W. Lee and M. Sehetzen, *Quarterly Progress Report 60* (Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, 1961).
6. Very few attempts have been made to apply the Wiener theory. The difficulties are that (i) conditions for convergence of the series are not known, (ii) computation time increases almost exponentially with the order of the computed kernel, and (iii) low signal-to-noise ratio and high internal noise are usually encountered in biological systems. See L. Stark [*Neurological Control Systems* (Plenum, New York, 1968)] and J. Katzenelson and L. A. Gould [*Inform. Control* **5**, 108 (1962); *ibid.* **7**, 117 (1964)]. See also E. J. Thomas [*Bell Syst. Tech. J.* **50**, 2797 (1971)].
7. K. I. Naka, *Science* **171**, 691 (1971).
8. F. S. Werblin and J. E. Dowling, *J. Neurophysiol.* **32**, 339 (1969); A. Kaneko, *J. Physiol.* (*London*) **207**, 623 (1970).
9. By a specialized nonlinear technique in which a single, no-memory nonlinearity is assumed (*2*), a similar nonlinearity has been found in the ganglion cell discharge evoked by light in the goldfish retina.
10. K. I. Naka and P. W. Nye, *J. Neurophysiol.* **34**, 785 (1971).
11. We thank Dr. G. D. McCann for his support and B. G. Elgin for his help in the construction of Fig. 1. Supported by PHS grant NB 03627.

13 April 1971; revised 22 November 1971 ■

Sulfur Mobilization as a Result of Fossil Fuel Combustion

An informative comparison of the amounts of trace elements mobilized by weathering processes and those mobilized by the burning of fossil fuel has been given by Bertine and Goldberg (*1*). In the case of sulfur they have made an error in the amount mobilized by fossil fuel combustion which distorts the perspective that they attempt to give. Apparently they overlooked the fact that *most* of the sulfur in coal and oil is converted to SO_2 upon combustion. In Table 1 I list various estimates of the amounts of sulfur emitted as SO_2 from fossil fuels for the world and for the United States at different times. These numbers are to be compared with Bertine and Goldberg's estimates of 3400 × 10^9 g/year for the amount of sulfur produced from the combustion of oil. Their calculation for the amount of sulfur produced from the combustion of coal results from the assumption that, during combustion, 5 percent of the sulfur (and all other elements) is mobilized. The estimate made in this technical comment is based on figures from the Study of Critical Environmental Problems (SCEP) (*2*), which apparently are based on the assumption that about 80 percent of the sulfur in coal is released as SO_2.

Table 1. Amounts of sulfur released as SO_2 by fossil fuel combustion (× 10^9 g/year).

Year	Area	Coal	Oil	Total	Reference
1937	Global	23,300	4,100	27,400	(*8*)
1943	Global	25,700	4,500	30,200	(*8*)
1965	Global	25,500	5,500	31,000	(*7*)
1966	United States			11,000	(*9*)
1968	United States	9,100	2,000	11,100	(*2*)
1968	Global*	45,000	5,000	50,000	This work

* Based on table 7.3 of (*2*) showing that the 1967 U.S. energy consumption from solid fuels is 20 percent of the global value and that from liquid fuels is 36 percent of the global value.

Table 2. Estimates of present rates of sulfur mobilization (× 10^9 g/year). The first two items give a new comparison of rates of mobilization based on fossil fuel combustion and weathering. The third item includes the components of sulfur from river runoff as detailed in the text.

Source of sulfur	Rate
Fossil fuel mobilization	50,000
Weathering mobilization	42,000
Sulfur entering rivers from:	
Soil application	26,000
Deposition from the atmosphere	50,000–70,000
Volcanism	8,000
Total river runoff (from above)	126,000–146,000
Mobilization from nonfuel industrial sources	14,000
Pollution sulfur mobilized (air)	64,000
Total pollution sulfur mobilized (air plus water)	90,000

Further refinement of the comparison of fossil fuel emissions can be made on the basis of a recent estimate made by Berner (*3*) that, on a global basis, 42,000 × 10^9 g/year of sulfur is contributed to rivers from rock weathering. Bertine and Goldberg's estimates of 140,000 × 10^9 g/year of sulfur mobilized by weathering apparently is the total rate of river runoff estimated from average concentrations of SO_4^{2-} in river waters and annual river flow rates. This value is in agreement with my calculations (Table 2).

Berner (*3*) uses concentrations of SO_4^{2-} in rivers given by Livingstone (*4*). The total rate of river runoff from these data amounts to 120,000 × 10^9 g/year. The data compiled by Livingstone covered a period from 1848 to the mid-1950's. Eriksson (*5*) estimates that in 1960 about 10,000 × 10^9 g/year of sulfur entered rivers from the application of fertilizers to soil. It is doubtful that the total rate of river runoff given above accurately reflects the fertilizer component for 1960. Indeed, it is difficult to estimate an appropriate amount, since undoubtedly some fertilizer component is represented in the river water data for SO_4^{2-} concentrations. In this technical comment I assume that a total rate of river runoff of 120,000 × 10^9 g/year is applicable for 1960.

From data presented in the SCEP report (*2*), I have calculated that between 1960 and 1970 the global use of fertilizer nutrients increased by a factor of 2.6. By assuming that the proportion of sulfur in the fertilizer has not changed over this period, I estimate that the present contribution of fertilizer sulfur to river runoff is 26,000 × 10^9 g/year. This would bring the estimated present total amount of sulfur in river runoff to 136,000 × 10^9 g/year.

The sulfur compounds emitted into the atmosphere eventually are deposited on the surface of the earth. Various investigators (*5–7*) have constructed global models for the sulfur cycle in which estimates of the atmospheric sulfur component entering river runoff range from $50{,}000 \times 10^9$ to $70{,}000 \times 10^9$ g/year.

Berner (*3*) also gives an estimate of the annual rate of emission of volcanic sulfur (from volcanoes, fumaroles, and hot springs) which enters rivers. This amounts to about 8000×10^9 g/year.

Table 2 shows that the total rate of runoff of sulfur from rivers estimated by summing the components is in quite good agreement with the rate estimated by the use of Livingstone's (*4*) data corrected for the present rate of fertilizer application. The two numbers are not wholly independent, however, because the sulfur cycles (*5–7*) are artificially balanced.

On the basis of information presented here, it may be seen that, in fact, the rate of mobilization of sulfur in the environment by man is approximately twice that by natural weathering processes. Furthermore, it is evident that the proportion of sulfur in the global environment from pollution sources is increasing. Because of the errors in the computations, the report by Bertine and Goldberg gives the impression that the rate of anthropogenic sulfur emissions is much smaller (by a factor of 40) than the weathering rate. Clearly this is not the case.

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References

1. K. K. Bertine and E. D. Goldberg, *Science* **173**, 233 (1971).
2. Report of the Study of Critical Environmental Problems, *Man's Impact on the Global Environment* (M.I.T. Press, Cambridge, Mass., 1970).
3. R. A. Berner, *J. Geophys. Res.* **76**, 6597 (1971).
4. D. A. Livingstone. *U.S. Geol. Surv. Prof. Pap. 440–6* (1963).
5. E. Eriksson, *J. Geophys. Res.* **68**, 4001 (1963).
6. C. E. Junge, *Air Chemistry and Radioactivity* (Academic Press, New York, 1963).
7. E. Robinson and R. C. Robbins, in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Springer-Verlag, New York, 1970).
8. P. L. Magill, F. R. Holden, C. Ackley, Eds., *Air Pollution Handbook* (McGraw-Hill, New York, 1956), pp. 2–45.
9. F. A. Rohrman, B. J. Steigerwald, J. H. Ludwig, *Power* **111**, 9 (1967).

12 August 1971; revised 15 November 1971

In his criticism of our report Friend (*1*) has overlooked our basic premise in the development of the amounts of material potentially mobilized about the environment as a result of the combustion of fossil fuels: "Thus far, we have assumed that the elements are accommodated in either the fly ash or the bottom ash during the combustion process and are not introduced as volatile species to the atmosphere. Clearly, selective volatilization can introduce the readily distillable materials into the atmosphere at concentrations far above those indicated in Table 1" (*2*, p. 233). We reemphasized our concern on this point later in the report: "Such elements could be introduced in amounts as much as 20 times greater than those shown in Table 1, if the effects of selective volatilization override the two correction factors" (*2*, p. 234).

Our intent in the report was to demonstrate the impact of fossil fuel combustion on a large number of elements, not to treat each element individually. Obviously, such elements as sulfur, phosphorus, and arsenic will be dispersed in much higher amounts than indicated in table 1 of (*2*) in view of the ready volatility of their compounds.

It is curious that Friend does not cite the paper by Koide and Goldberg (*3*) which precedes the paper given as his reference 3, and treats the dispersion of sulfur in detail. In the paper by Koide and Goldberg the calculation given in Friend's table 1 is made, and, in addition, an argument is presented that the combustion of fossil fuels is now introducing slightly more sulfur into the atmosphere than such natural processes as volcanism and the oxidation of hydrogen sulfide derived from organic matter. This latter process cannot be neglected in any consideration of man's impact on the sulfur cycle such as that given by Friend.

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References

1. J. P. Friend, *Science* **175**, 1278 (1972).
2. K. K. Bertine and E. D. Goldberg, *ibid.* **173**, 233 (1971).
3. M. Koide and E. D. Goldberg, *J. Geophys. Res.* **76**, 6589 (1971).

20 January 1972

An Improved Treading Device for Tethered Insects

A useful actograph ("orientometer") has been described recently (*1*), which employs a revolvable Ping-Pong ball that is supported on three ball bearings (*2*) as the moving substrate on which a tethered insect can walk. A drawback of the apparatus is the relatively high friction at the bearings, which creates drag and slows the responsiveness of the ball and which may lead to premature exhaustion of the insect. Even larger, potentially more powerful insects are handicapped, because they rest with their weight on the ball and add to the load on the bearings. Moreover, on its three-pronged prop, the ball is unstable and a larger insect suddenly activated may simply kick it away. These limitations can be overcome by supporting the ball on an air cushion, generated by directing an airstream through a funnel onto the ball from beneath (Fig. 1). If the rate of airflow is adjusted to compensate precisely for the added weight of the insect, the ball can be maintained in suspension, stably afloat, freely rotatable, and almost free of drag. Thus modified, the apparatus lends itself well to measurement of directional tendencies and response times of tethered insects (*3*).

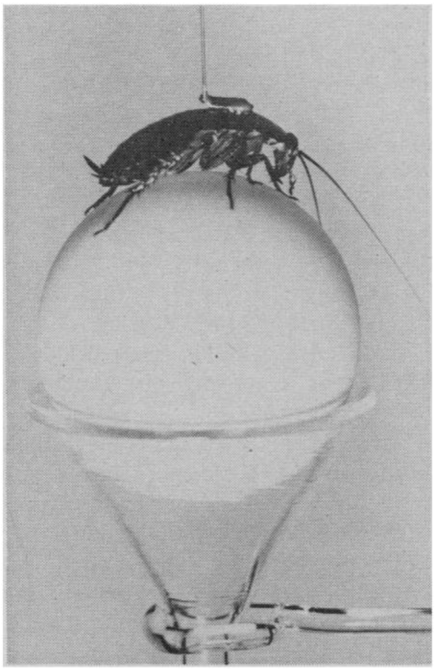

Fig. 1. Tethered insect "walking" on a revolvable Ping-Pong ball suspended on an air cushion (the airstream, directed on the ball from beneath, "floats" the ball just above contact with the funnel). The wire tether glued to the insect is inserted loosely (*1*) into the open end of a capillary tube.

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Reference and Notes

1. W. B. Kerfoot, *Science* **162**, 477 (1968).
2. They are tips of ball-point pens.
3. Supported by NIH grant AI-02908 to T. Eisner.

18 January 1972