define the spreading rate as the rate of change of the radius of the smallest circle enclosing all of the balls. Figure 2 shows the radius of this circle as a function of time for three different power levels. In all three cases the initial point marks the turning on of the light. In each case there are three regimes. The first period is a gradual buildup of the underlying convection cell, during which the radius is essentially constant. The second is a period of linear growth in radius, corresponding to spreading under the influence of the initial cell. The third is an erratic region. Here the spreading is an amalgam of spreading rates from secondary continental breakage.

I located the continental fragments at any given time visually. The bottom of the basin is scribed with a polar grid with radiants 5° apart and circles at radial intervals of 0.5 cm. I sketched the location of the continental fragments on polar graph paper, making an effort to minimize parallax error. It takes 1 to 2 minutes to make such a drawing; movement during this time is less than half a millimeter, less than the overall error.

The radius of the minimum circle enclosing all the balls was found by superposing a circular grid over each sketch and estimating the smallest circle that would include all the particles. The center of this enclosing circle shifts negligibly during the first phase of uniform spreading.

Useful spreading rates are obtained by graphically taking the slope of the steep segment of homogeneous spreading. Within the limits of error of this demonstration experiment, the spreading rate is directly proportional to the power level. This result appears to be consistent with earlier theoretical work (*5, 6*), to the limited extent that the situations are similar.

The model as described is in the same general region of parameter space as the earth (*11*). It is an improvement over the various "kinematic" models and has more flexibility than the other dynamic models that have been explored. It also has simplicity. There remain, however, a number of difficulties that will need to be resolved as the work becomes more quantitative. These include the necessity of quantifying the strength of the continent and the coupling between the continent and the asthenosphere. Even the drag of a partially submerged sphere at low Reynolds number appears not to have been calculated (*12*). Because the temperature contrasts are so small, it appears likely that the variation of surface tension with temperature will be unimportant.

Despite these caveats, I feel the model is sufficiently useful to justify further study, and I offer the following comments on its qualitative resemblance to the picture of plate tectonics. When the total picture of plate tectonics over the last 2×10^8 years is drawn, one can see two features that are apparent in this model, and in no other model of which I am aware (*13*). One is the episodic nature of spreading, in which spreading directions change and secondary spreading episodes take place. One can compare figures 4 and 5 of Dietz and Holden's reconstruction (*13*) with the sequence in Fig. 1. In the Jurassic the North Atlantic has opened by pivoting around a still connected Greenland-Scandinavia; in the Cretaceous the South Atlantic has opened, spreading in a different direction. These events can be compared to the sequence in photos 6, 7, and 8 in Fig. 1.

A frequent objection to the plate tectonic hypothesis is that the fit is not so good as claimed (*14*). I have not quantified the goodness of fit associated with the continents in my model, which I know to have been together, but it is clear from direct observation that internal distortions have made the fit less than perfect, a feature unique to this model.

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References and Notes

1. A bibliography on plate tectonics is out of place here. See X. LePichon, J. Francheteau, J. Bonnin, *Plate Tectonics* (Elsevier, Amsterdam, 1973). For the minority view, see papers in *Plate Tectonics—Assessments and Reassessments*, C. F. Kahle, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1974).
2. A good summary and extension of theoretical approaches is provided by D. P. McKenzie, J. M. Roberts, N. O. Weiss, *J. Fluid Mech.* **62**, 465 (1974).
3. Experiments include those on freezing wax: D. W. Oldenberg and J. N. Brune, *Science* **178**, 301 (1972); J. W. O'Bryan, R. Cohen, W. N. Gilliland, *Geol. Soc. Am. Bull.* **86**, 793 (1975); those on modifications of convection by heating from below: F. M. Richter and B. Parsons, *J. Geophys. Res.* **80**, 2529 (1975); those on clay in centrifuges: H. Ramberg and H. Sjöström, *Tectonophysics* **19**, 105 (1973); as well as those of Howard *et al.* (*5*) and similar experiments by L. Knopoff, K. A. Poehls, R. C. Smith, *Science* **176**, 1023 (1972).
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6. H. E. Huppert, *Geophys. Fluid Dyn.* **2**, 317 (1971).
7. One may also write the Peclet number in terms of a differential temperature T as $R' = (g\alpha T d^3)/(\nu\kappa)$.
8. T. H. Jordan and W. S. Lynn, *J. Geophys. Res.* **79**, 2679 (1974).
9. The size of the plate, as opposed to the continent, is indeterminate, as some amount of the surrounding fluid surface is included. I hope to explore this using shadowgraph techniques at some future time.
10. Several measurements of flux versus bulb displacement quite close to the bulb, made with an International Thermal Instrument Company thermal fluxmeter coated to absorb radiation, indicate a total available power of 17.2 ± 1.2 watts. Translation of this information to the experimental situation is complicated by the difficulty of making albedo measurements. I calculated the number given in the text, assuming a fraction of 17 watts equal to the area of 61 balls divided by the total area at a distance of 50 cm.
11. One might object to the small lateral extent as compared with the geophysical situation; however, there is no reason why one cannot use more beads. The only difficulty is the tedium involved in assembling large continents. It takes several hours to get a 219-ball continent ready.
12. I have searched *Physics Abstracts* from 1950. Interest in this problem is no doubt limited because flow at very low Reynolds number is relevant to blood flow, for which there are no free surfaces, whereas the flow of objects near a free surface is relevant to naval matters, and these flows have high Reynolds numbers.
13. A typical, and comprehensive, reconstruction is given by R. S. Dietz and J. C. Holden [*J. Geophys. Res.* **75**, 4939 (1970)].
14. A. A. Meyerhoff and H. A. Meyerhoff, in *Plate Tectonics—Assessments and Reassessments*, C. F. Kahle, Ed. (American Association of Petroleum Geologists, Tulsa, Okla., 1974), pp. 43–145.
15. My interest in this problem was first awakened when I was a student at the University of California, Los Angeles, and I thank L. N. Howard, W. V. R. Malkus, and J. A. Whitehead, all of whom were there at that time.

1 October 1975; revised 15 December 1975

Marine *Oscillatoria* (*Trichodesmium*): Explanation for Aerobic Nitrogen Fixation Without Heterocysts

Abstract. *Nitrogen fixation in marine* Oscillatoria *appears to be associated with differentiated cells located in the center of the colony. These central cells exhibit reduced pigmentation relative to peripherally located cells and do not incorporate $^{14}CO_2$ in photosynthesis. Central cells apparently do not produce O_2 which would deactivate nitrogenase. When central cells are exposed to O_2 via disruption of the colonies, N_2 fixation (acetylene reduction) decreases sharply even though individual trichomes remain intact. Disruption of colonies in the absence of O_2 does not cause reduced nitrogenase activity. In the sea, turbulence from wave action apparently separates trichomes allowing O_2 to enter thus decreasing nitrogenase activity. These observations explain how* Oscillatoria *is able to fix N_2 without heterocysts in an aerobic environment and why its blooms virtually always occur in calm seas.*

Oscillatoria (*Trichodesmium*) spp. is a planktonic myxophyte alga inhabiting near-surface waters of tropical and subtropical seas. It is capable of fixing atmospheric nitrogen (*1*). In view of the critical importance of combined nitrogen as a limiting nutrient in the ocean (*2*), it can play a central role in the nitrogen budget of the euphotic zone in some seas. Unlike other N_2 fixing algae from aerobic environments, *Oscillatoria* spp. does not possess heterocysts, thick-walled cells that protect nitrogenase from O_2 inactivation (*3*). Its mode of protecting nitrogenase is yet undiscovered, and little is known of factors affecting its ability to fix N_2 in the sea. *Gloeocapsa* sp. is the only other alga that does not possess heterocysts yet is able to fix N_2 in an aerobic environment (*4*). The mechanism for protecting nitrogenase in this species is also unknown. Other nonheterocystous N_2-fixing species such as *Plectonema boryanum* are able to do so only under microaerobic conditions, which presumably limit the exposure of nitrogenase to O_2 (*5*).

It appears that N_2-fixation takes place in centrally located cells in the colony. A typical colony consists of several hundred trichomes, arranged in parallel, each trichome having about 100 cells. Examination of *Oscillatoria* with the light microscope reveals that those trichomes passing through the middle of the colony have about 10 to 20 lightly pigmented cells in a central differentiated region (Fig. 1) (*6*). As shown by ^{14}C autoradiography, these central cells do not photosynthesize, whereas there is carbon incorporation in the apical cells and in trichomes on the outside of the colony. Since the central cells, like heterocysts, do not fix $^{14}CO_2$, they are unlikely to evolve O_2 in photosynthesis (*7*).

This mode of protecting nitrogenase from O_2 inactivation would appear to be relatively fragile since a separation of the trichomes from one another could permit O_2 to enter and deactivate the nitrogenase. This does occur. For example, in February in the eastern Caribbean, we gently collected *O. erythraea* from the sea surface with buckets. Colonies were placed in filtered seawater in 5-ml serum vials, and half of the vials were shaken vigorously by hand for 10 seconds. Nitrogen fixation was measured with the acetylene reduction technique (*8*). For a total of 22 measurements, we noted an average decrease in N_2 fixation of 88 percent ($P < .05$) in the shaken vials. Average rate in unshaken (control) bottles was 2.11 (S.E.M. = 0.25) ng of N_2 per colony per hour, and in shaken bottles it was 0.26 (S.E.M. = 0.13).

On a later cruise to the same area, O_2 was removed from seawater by gently purging with a gas mixture of 99 percent argon and 0.04 percent CO_2, and there was no measurable reduction of the rate of N_2 fixation in shaken samples as compared with that in unshaken controls. However, agitation of the samples in the presence of O_2 decreased N_2 fixation by an average of 69 percent ($P < .005$) (*9*).

Oscillatoria is also sensitive to turbulence in its natural habitat. Wave action apparently can separate trichomes in the colony permitting O_2 to enter and deactivate nitrogenase. When the sea was calm [sea state (SS) = 1], N_2 fixation per cell was greatest at the sea surface (Fig. 2) (*10*). An SS value of 2 is apparently an intermediate condition where N_2 fixation is greatest at the surface or at a depth of about 10 to 15 m. However, at an SS of 3, N_2 fixation is depressed at the surface and clearly is greatest in deeper water at 10 to 15 m. Furthermore, at an SS of 4, damage from wave action extends deeper. Greatest relative N_2 fixation is at about 20 m (25 percent light intensity), and the least is at the surface. The action of cresting waves and entrained air bubbles at relatively low wind speeds has also been shown to break the chains of diatoms. Schöne has observed that wave action at an SS of 4 results in a 25 percent decrease in average chain length for *Skeletonema costatum* (*11*).

Table 1. Chi square contingency table comparing *Oscillatoria* population density as measured by Steven and Glombitza (*13*) at Barbados, West Indies, with local weather conditions. The terms "below" or "above" refer to median trichome density (0.3×10^3 per liter). Unfavorable weather is defined as at least 1 day with wind over 15 knots in the week prior to sampling or total sky coverage from clouds of 0.9 or greater on the day before sampling. Favorable weather is defined as no days over 15 knots in the week previous to sampling and cloud cover less than 0.9 on the day before sampling.

Status	Below	Above	Totals
Favorable	14	24	38
Unfavorable	20	7	27
Corrected chi square = 7.34			
Significance = .0067			

It would appear then, that calm seas would be required for optimum N_2 fixation at the sea surface. Other investigators have observed that *Oscillatoria* spp. blooms typically occur in calm seas (*12*). Additional evidence for this hypothesis can be gathered from an analysis of data on *Oscillatoria* spp. population density, which were collected from 5-m depths at biweekly intervals over a 33-month period 9 km west of Barbados, West Indies, by Steven and Gombitza (*13*). They observed a 120-day pattern of oscillation in population density and postulated that it was free-running since they could not link it with any external mechanism such as the solar cycle or nutrient concentration changes. We have compared these population data with records of wind speed and cloud cover as recorded at the Barbados airport. A simple analysis (Table 1) indicates ($P < .01$) that

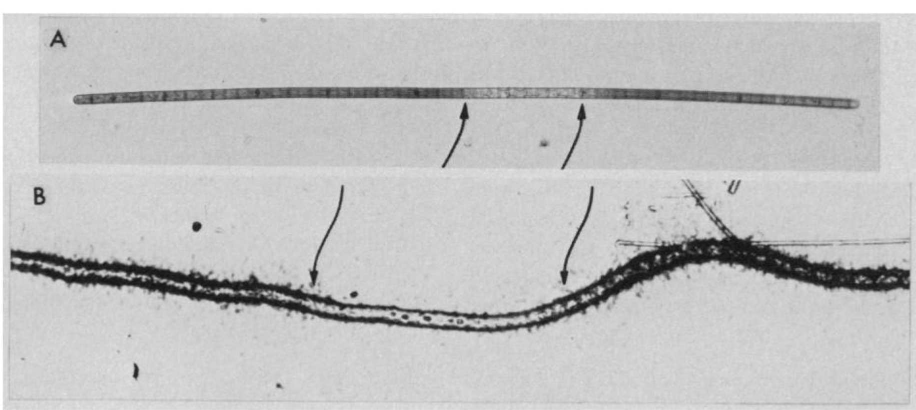

Fig. 1. (A) Central trichome of *Oscillatoria erythraea* as seen in the light microscope. The diameter of cells was 8 μm. The cells (between arrows) in center of trichome are lightly pigmented. (B) ^{14}C autoradiograph of single central trichome of *O. erythraea*. Central cells (between arrows) do not incorporate $^{14}CO_2$.

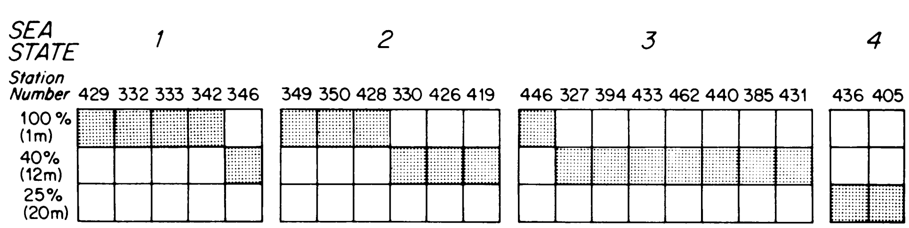

Fig. 2. Maximum N_2 fixation (darkened squares) rates from (acetylene reduction) measurements made at 100 percent, 40 percent, and 25 percent incident solar radiation on cells located at depths of 1 m, 12 m, and 20 m in the Caribbean and southern Sargasso seas. Immediately after collection and the addition of acetylene, samples were incubated on deck in neutral density screening at light intensities and temperatures equal to the depth from which they were collected. The sea state was recorded by the mate on watch. To ensure that conditions of light were the same from one date to another, we only used station data collected under "broken clouds."

greater population densities are associated with low wind speed and, as would be expected, light sky cover. These field measurements are consistent with laboratory observations that N_2 fixation occurs in the central cells of *O. erythraea*.

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6. Marine *Oscillatoria* have been assigned to one species by F. Drouet [*Monogr. Acad. Nat. Sci. Philadelphia* **16**, 1 (1968)]. At the same time, A. Sournia [*Nova Hedwigia* **15**, 1 (1968)] reviewed the marine *Oscillatoria* and described four species. Our investigations were carried out on *O. thiebautii* as described by Sournia; however, in the broader taxonomic scheme outlined by Drouet, the species would be referred to as *O. erythraea*.
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9. Data were tested with a three-way Model 1 analysis of variance where mean N_2 fixation rates (in nanograms of N_2 per colony per hour) were as follows: with shaking and with O_2, 1.73; without shaking and with O_2, 5.60; with shaking and without O_2, 5.47; without shaking and without O_2, 6.44. The sums of squares for differences among the four means was 79.22 (3 d.f.). Differences between the mean with O_2 and shaking versus the rest of the means treatment as a unit has a sums of squares of 75.89 (1 d.f.). The sums of squares for differences among the other three means is only 3.33 (2 d.f.).
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14. We thank David Wall for making the photo for Fig. 1a, and we thank W. K. Smith for statistical advice. Supported by NSF grant GA 37993. This is State University of New York, Stony Brook, Marine Sciences Research Center Contribution No. 139.

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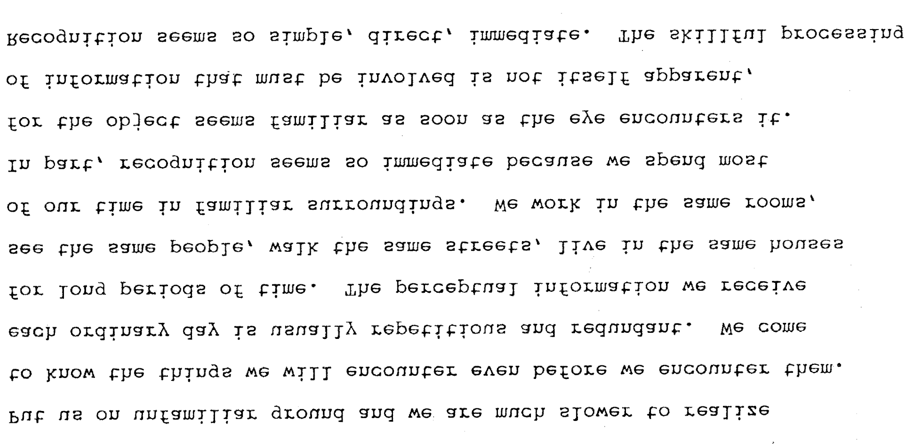
Pattern-Analyzing Memory

Abstract. *College students reread text after an interval of 13 to 15 months more rapidly than they read new matter taken from the same sources. The results implicate a memory system at the level of pattern analysis that seems to be distinguishable from memory of syntactic and semantic features of text.*

Most reading is directed at the semantic content of text. The reader usually wants to know what he is reading about, what the message is; except for such specialists as the compositor concerned with typography and layout and the proofreader concerned with orthography, the semantic aspect is considered to be the message of the text. So pervasive is the concern with the semantic aspect of literacy that most modern theories are directed at it almost exclusively (*1*). The pattern analysis that the skilled reader applies to text has, therefore, often been overlooked as a significant aspect of literacy. A common view emphasizing the semantic component is that the skilled reader extracts the semantic content of the text, reduces it to its propositional form, and stores for the longer term only that form, discarding other aspects of the text. This view has been challenged by demonstrations that typographic features of text can be found in memory of college student readers many days after reading even in the absence of instructions to attend to them (*2*); it is further challenged by this report of an aspect of memory for visual pattern analyzing operations.

In an earlier study eight college students each read 160 pages of typographically unfamiliar material, acquiring considerable skill at the task. Initially, they required about 15 minutes to read a page, compared to about 1.4 minutes to read a page of normally oriented text, on the average. The 160th page of transformed typography was read in 1.7 minutes, however, more than a ninefold increase in reading speed (*3*). After 13 to 15 months, six of the eight students read 98 pages in the transformed typography, 49 for the first time, the other 49 from the set of 160 that had been read earlier. This report concerns both overall performance on the second testing, and the differential performance on pages read for the first and second times.

The participants in the test were male undergraduates at the University of Toronto. They were assessed for lateral dominance by tests of sighting for eyedness and questions regarding preferred hand for eating, writing, and throwing, and preferred foot for kicking; in all, the right side was dominant. The typography they mastered was connected English discourse, each line



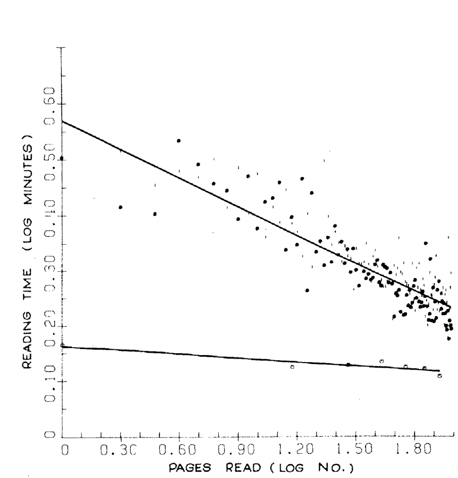


Fig. 1 (left). An example of geometrically inverted text. Fig. 2 (right). The logarithm of reading time plotted against the logarithm of successive pages for inverted text (inclined line) and normal text (line parallel to abscissa). One page of normal text was read at the beginning of each test session; these are shown at abscissa values corresponding to the 1st, 15th, 29th page, and so on. Strokes represent pages read for the first time in this experiment; closed circles represent pages first read a year earlier and reread in this experiment. Each point on the inclined line represents between one and six observations, and the line is the least-squares fit of the data points.