How, then, does the deafferented monkey with vision occluded obtain information about its own motor activities, as would be necessary, for example, when learning new movements? In this regard it is worth considering the possibility of the operation of central feedback mechanisms. Intracellular loops located appropriately could provide a means of monitoring central effector activity before it has emerged into the periphery. Several pathways that could fulfill this function have been demonstrated to exist both anatomically and electrophysiologically, with points of inflection involving: afferent collaterals from the medullary pyramids to the dorsal column nuclei (9), laminae 4 to 6 of the dorsal horn (10), and the deep nuclei of the cerebellum (11). Other pathways of a similar nature probably exist elsewhere in the central nervous system. Descending activity could also be converted into a return pattern of signals by electrotonic or ephaptic conduction between descending and ascending fibers in adjacent tracts (12). A number of indications have made the dorsal spinocerebellar tract a subject of interest for current study in this regard. Another possibility is that no topographic feedback whatever, whether of central or peripheral origin, is necessary for the central nervous system to obtain information about movement-producing patterns of discharge. A set of neurons need only fire, and this event by itself would be sufficient to produce the encoding of that information. Feedback return would not be necessary to iterate the data or to report on the consequences of the discharge. These different alternatives need not be viewed as mutually exclusive.

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Electrodynamic Sailing: Beating into the Solar Wind

In a recent report Alfvén (1) suggests and comments upon a novel means of spacecraft propulsion based upon the extraction of energy from the electromagnetic field of the solar wind. He claims that it is conceptually possible to sail upwind by coupling the energy extracted to an appropriate engine, likely an ion engine. His emphasis upon energy is important, but both energy and momentum requirements must be met.

An electrically conducting spacecraft such as Alfvén proposes suffers from two energy loss mechanisms. One is associated with magnetohydrodynamic wave drag, and the other with internal ohmic losses in the unipolar circuit which the system comprises. To make propulsion feasible in the sailing sense of “beating into the wind,” or even a “close reach,” there are two requirements: (i) the spacecraft must be able to do work upon the solar wind in excess of the work done upon it by wave damping and ohmic losses; and (ii) the momentum exchange must favor the thruster (ion engine). It seems possible to achieve the second requirement since an engine ought to be able to partition momentum in the necessary way. However, it appears to be impossible to meet the first requirement, that is, to satisfy the principle of conservation of energy for sailing upwind.

Alfvén’s suggestion that electric propulsion devices be used for attaining high exhaust velocity is basically the means whereby high momentum flux can be obtained while decreasing the fuel mass so that it is not necessary to accelerate as much dead weight of unburned fuel. This mass of unburned fuel which must be accelerated is really the cause of the inefficiency, and it explains why, in the theory of rocket propulsion, the specific impulse is a key parameter. This reasoning also explains why the high exhaust velocities attained in ion engines are so attractive. On the other hand, it has not been possible to design an ion engine capable of yielding the momentum flux required for escape from the strong local gravitational fields such as that possessed by the earth, nor does such an accomplishment seem likely in the foreseeable future.

I would now like to turn in detail to Alfvén’s scheme for “sailing in the solar wind.” The electric field is given by

\[ E = (V \times B)/c \]

where \( V \) is the velocity of the spacecraft seen from a frame co-moving with the solar wind bulk speed, \( B \) is the interplanetary magnetic field, and \( c \) is the speed of light. The production of 10^6 amperes in the example of Alfvén will produce a magnetohydrodynamic bow wave in front (on the upstream side) of his wire and result in wave drag from the production of waves which radiate away from the tips of the wire. Other geometries will produce similar results. The consequence is drag. In effect what takes place is a retardation of the spacecraft by distortion of the interplanetary field lines. This retardation can be viewed as a propulsion mechanism, but only in the sense that the spacecraft tends to come up to solar wind speed as the wind drags it along. Thus, in sailing terminology the spacecraft can only sail downwind (run before the wind) by this means.

In order that the spacecraft sail up-wind magnetohydrodynamically the sense of current flow must be opposite to that derived from the electric field. In this case radiating Alfvén waves will be produced which tend to propel the spacecraft against the solar wind. Clearly these waves must still feel backward because of the supermagnetosonic speed of the solar wind with respect to the spacecraft, but the body forces

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where \( j \) is the current density and \( A \) is the cross-sectional area of the wire. Furthermore,

\[
  j = \sigma (\mathbf{V} \times \mathbf{B})
\]

whereupon an expansion of the resultant vector triple product gives

\[
  \dot{W}_a = - \sigma (\mathbf{V} \cdot \mathbf{B}) = \left( \frac{\mathbf{V} \cdot \mathbf{B}}{c} \right) A
\]

(2)

(Where \( \sigma \) is the bulk electrical conductivity) which attains a maximum value for \( \mathbf{V} \) perpendicular to \( \mathbf{B} \) for which case

\[
  \dot{W}_a = \sigma E^2
\]

At the same time the system constitutes a closed electric circuit endowed with an effective impedance \( Z \) due to all the individual impedances in series, including those in the solar wind which close the circuit. Thus an additional component of work done upon the spacecraft arises from ohmic dissipation given by

\[
  \dot{W}_\text{o} = (jA)^2 Z
\]

These losses are numerically equal to those associated with the drag, so that the total work done upon the spacecraft has the form \( 2(jA)^2 Z \).

The available power from the solar wind is given by

\[
  \dot{W}_a = jA |V|
\]

so that

\[
  \dot{W} = 2(jA)^2 Z
\]

(3)

The introduction of an engine is made in electrical series with the spacecraft or alternatively by drawing upon the heat generated in ohmic losses. One half of the work done upon the spacecraft appears as an increase in the downstream kinetic energy, whereas the other half is dissipated as heat. Energy can be extracted from the current flowing to drive an ion engine, but the maximum power available is determined by the power transfer theorem which restricts the available power to the amount lost in the remainder of the system. Since that amount is equal to \( \dot{W}/2 \), it seems clear that a net gain in forward kinetic energy can never be attained, since one half is irretrievably lost in wave drag and the other half is partitioned equally (at best) between ohmic losses and the energy needed to drive the engine. In this argument I ignore thermodynamic considerations which would be likely to increase the severity of the restrictions indicated here. Clearly then, even for a thermodynamically perfect engine, it would be impossible to return energy to the solar wind even in an amount equal to that which ends up as heat, which in turn is only half the total lost. Therefore, the energy balance requirement cannot be met.

It should also be noted that the hydromagnetic interaction can be classified as weak, intermediate, or strong. If the interaction is weak, the reaction of the induced field upon the solar wind is small so that the flow field of the solar wind about the spacecraft is not distorted. In this case a nearly undiminished value of \( E \) can be maintained. As the conductivity in the circuit is increased, say, by the introduction of superconductivity, the reaction becomes stronger, the flow field begins to separate, and the net \( E \) is decreased. The solar wind equipotentials tend to spread with the separation of the current flow, diminishing the drop across the spacecraft (4). Ultimately, as the currents grow stronger, the flow tends to separate completely and no further increase in current can be anticipated, no matter how large the conductivity is made (5).

As a large object we would expect this condition to conform to the existence of a bow shock wave. For objects small as compared to the gyro radii of the ions and electrons, it cannot be said with confidence that a bow shock wave will form, but a saturation will still take place, because the saturation limit is imposed by the ultimate mechanical power in the solar wind coupled through the magnetic field. Even though the interaction region is permitted to grow, there must exist a limit upon its size, perhaps where the plasma adjusts itself to permit flow separation to take place.

The statements made above constitute an informal "proof" that it is impossible to satisfy the principle of the conservation of energy in the proposal of Alfvén. A conceptual laboratory demonstration adds a degree of heuristic conviction. Consider a pair of conducting rails shorted at one end with a movable armature, the rails threaded by a magnetic field. The arrangement constitutes a simple one-dimensional unipolar generator equivalent in principle to the spacecraft in the solar wind. The wind conforms to the rails and shorting section, and the spacecraft to the armature. Clearly a propulsive device drawing its power from the currents which flow cannot

\[
\text{W.}
\]

\[
\text{V.}
\]

\[
\text{H.}
\]

\[
\text{E.}
\]
accelerate the armature. When the
armature is standing, there is no cur-
rent, and, if the armature is initially
carried to move, it seems unlikely that
the armature will be caused to acce-
cerate by the motor which draws its
energy from the motion itself.

But then how can a sailboat move
against the wind? For high-performa-
cyachts, sailing against the wind
(close-hauled) is possible up to angles
between the true wind vector and the
boat direction of about 45°. The sail,
being an aerodynamic section, provides
lift normal to the wind direction; the
lift can be resolved into a component in
the forward direction which does
work in moving the boat forward and
a component to the leeward direction
which does no work in the idealized
case. The leeward component is cor-
corrected by keel "lift." (The boat main-
tains a keel angle of attack to provide
this lift force.) In effect, the keel
provides a force opposing part of the
drag, thus removing the drag from
energy considerations. If the spacecraft
could be placed upon imponderable
rails, then any drag component normal
to the rails would be counterbalanced
by the reaction of the rails, doing no
work, and would thus be removed from
the energy conservation equation;
perhaps some points of the upwind
compass could be attained by this
means. However, the unrecoverable
omnic losses in the electrodynamic
spacecraft have no parallel in the
case for the boat, so that a detailed
comparison seems unwarranted. A
similar conclusion would apply to an
iceboat; if the runners were removed
so that it could slide in any direction
without friction, then upwind sailing
would be difficult at best and likely
impossible. In spite of my arguments,
I am reminded that bees were once
shown theoretically to be incapable of
flight, so perhaps some needed con-
siderations are absent in my argument.

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The first presentation (1) of the sub-
ject of sailing on the solar wind of
necessity was quite short, and a more
detailed treatment (2) is now in press.
Considerable study and development
may be necessary before the technical
feasibility and economic advantage of
solar wind sailing as compared to other
methods of space propulsion can be
evaluated. On the other hand, the
fundamental principles and theoretical
limitations of the method are fairly well
understood since they follow from well-
known laws of physics. Sonett raises
several interesting questions, and, since
they are mainly of a theoretical nature,
they can be answered rather definitely.

The solar wind-powered vehicle (1)
can be imagined in a number of differ-
ent modifications (2). A common fea-
ture of all of these modifications is that
a conducting path is established be-
tween regions of different electric
potential and that the current flowing
through this path is somehow utilized
for propulsion. The conducting path
may be a thin superconducting cable or
a plasma jet or particle beam emitted
from the vehicle.

The simplest type of vehicle could
consist of a superconducting cable with
suitable electrodes or emitters at its
ends to facilitate electrical contact with
the space plasma. The propulsive force
is produced by the I × B interaction of
the current in the cable and the solar
wind magnetic field. As Sonett points
out, the propulsive force will in this
case always have a component in the
downwind direction, that is, away from
the sun. Clearly, a device of this kind
will be most suitable for travel away
from the sun. However, in many cases
it will also be able to sail upwind quite
efficiently in the combined force fields
of the solar wind and gravitation. The
Poynting-Robertson effect (3) is a well-
known example of how even a very
small nonradial force may accelerate
an object toward the sun.

In a more advanced vehicle the elec-
tric power extracted from the wind
may be used to operate a plasma propul-
sion engine. In this way a higher ac-
celeration can be obtained and, at least
in principle, propulsion in any direction
will be possible. In other imaginable
configurations the beam from the plasma
engine, or auxiliary plasma or particle beams, may be used for cur-
rent conduction, thereby avoiding many
problems associated with a long and
fragile cable that must be kept at a
low temperature.

The ability of a plasma-emitting
solar wind-powered vehicle to move
also against the wind may seem para-
doxical, but it is a simple consequence
of the general laws of sailing. Since
these laws seem to be little known and,
since a short literature search has not
turned up any suitable reference, it
seems necessary to clarify some of the
fundamental concepts.

Let us take, as the most general de-
inition of sailing, the motion and
propulsion of a vehicle without internal
energy sources. According to this de-
inition, a "sailing boat" thus may have
all kinds of complicated machinery, the
only requirement being that the energy
for propulsion must originate from the
media surrounding it. Furthermore, all
cases for which the vehicle receives
energy transmitted to it from any kind
of man-made source are explicitly ex-
cluded.

Clearly the propulsion of a "sail-
ing boat" originates from momentum in-
teraction with the media around it. The
case of a boat interacting with a single
medium with constant flow velocity is
trivial. Since the boat can derive its
energy of motion solely from work
done on it by the medium, it must
move with one component of its velo-
city directed downwind. In complete
agreement with Sonett, we conclude
that to move upstream the boat would
have to do work upon the wind, which,
according to the definition above, is
energetically impossible. This is the case
of an iceboat without runners, as dis-
cussed by Sonett. In situations where
the solar gravitation can be neglected,
this explanation applies also to the solar
wind vehicle propelled by the I × B
interaction discussed above.

Far more interesting is the case of a
boat interacting with two media having
different states of motion. In this case
the boat can extract energy by trans-
ferring momentum from one medium to
the other, in a direction so as to equalize
their states of motion. Quantifi-
tatively, the maximum possible energy
• gain is given by

$$\frac{dW}{dt} = v_{rel} \cdot \frac{dp}{dt}$$

(1)

where v_{rel} is the relative velocity of
the two media and dp/dt is the momentum
transfer effected by the vehicle. The
extracted energy can be used to move
the vehicle against the force fields as-
sociated with one or both of the media
and to compensate for frictional losses
associated with vehicle motion.

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Equation 1 seems to be a very general relation covering a wide variety of phenomena, and the word "medium" may mean almost any force field. [As an example, the well-known Fermi acceleration mechanism (4), whereby a particle gains energy by interacting with two moving magnetic mirrors, follows directly from Eq. 1.] It can also easily be generalized to include the case where one of the media is originally inside the vehicle and successively ejected by some machinery. It may be disputed whether such a vehicle should be referred to as a sailing vehicle since its propulsion is possible only as long as matter is available for ejection. In a wide sense the name "sailing vehicle" may be justified, however, since the motion of the vehicle is governed by the law of sailing, Eq. 1.

Clearly, Eq. 1 replaces the simple energy relation governing the motion of a boat interacting with a single medium. Consequently, Sonett's requirement (i) is not applicable to the plasma engine type of solar wind vehicle, which interacts with two different media. Thus, no fundamental principle prevents a solar wind sailing boat of the plasma engine type from moving against the wind. Moreover, there is nothing fundamental about the fact that an ordinary sailing boat cannot go straight against the wind.

One can easily overcome this inability, for example, by supplying the energy from a wind-powered generator to a suitably dimensioned water screw. A suitably designed solar wind vehicle will, at least in principle, be able to move in any desirable direction. On the other hand, practical difficulties such as unacceptable "fuel" consumption or low efficiency for certain types of operation may very well be found to limit its usefulness.

The laboratory experiment proposed by Sonett is fully feasible, and a working table-top device could very well be constructed: An armature with a length of 1 m moving along rails with a speed of 10 m/sec across a field of 2000 gauss would generate a voltage of 2 volts. Let us assume a motor of internal resistance 0.2 ohm mounted in the center of the armature and connected in series with the rest of the loop which may have a considerably lower resistance. The current will then be 10 amperes and the motor will develop 20 watts. The motor is used to drive a piston forcing water (from an internal tank) through a nozzle. If we may assume a motor efficiency of 80 percent, we can eject 500 g/sec at a speed of 8 m/sec relative to the armature. The propulsive force so produced will be 4 newtons as compared to the electrodynamic drag of 2 newtons. Losses higher than those assumed here could be overcome at the cost of increased "fuel" consumption by the choice of a lower exhaust velocity. A net force of 2 newtons is not very impressive, but the scaling laws are very unfavorable for the model. (The drag is here proportional to the velocity, the propulsive force to its square.) The device will not be able to start from zero velocity, a limitation which is also understandable from Eq. 1, where \( v_{rel} \) now stands for the relative velocity of the two media "water" and "the rail system." Once given sufficient velocity, however, the "vehicle" will be able to propel itself and even accelerate. This represents no perpetual motion machine, however, since the motion will stop when all the "fuel" has been ejected. The energy is available initially as the kinetic energy of the water, and the energy of the total system decreases steadily during the motion.

Alternatively, the device could start from zero velocity if the rail system were instead moving. Seen from a reference frame attached to the armature, an electromotive force will then be induced in the shorting section at the end of the rails. This potential will drive a current through the armature and the motor, thus producing motion. Let us turn now to the real solar wind vehicle. An evaluation of its capabilities involves a certain amount of guesswork. For a solar wind electric field \( E \), the highest potential difference that can be tapped by a wire of length \( L \) is \( E L \). A field of 2 mev per meter and a 500-km cable would give 1 kv. By suitable arrangements at the ends of the cable a current \( I \) is made to flow through the cable. From laboratory experiments it is known (5) that vacuum arcs of many kiloamperes strength can burn with voltage drops as low as 10 to 25 volts. Similarly, a plasma jet can be expected to conduct considerable currents with quite moderate voltage drops. Therefore, a current of the order of 1 ka does not seem unrealistic. The power so extracted is used to operate the plasma propulsion engine. Assuming that a fraction \( \eta \) of the total power \( IEL \) can be transferred to the translational energy of a plasma beam, we have

\[
\eta IEL = \frac{1}{2} qw^2
\]

where \( q \) is the mass emitted per time unit and \( w \) is the ejection velocity.

The propulsive force so produced is

\[
F_{prop} = qw = \frac{2\eta IEL}{w}
\]

The electrodynamic drag finally will be \( f \cdot IBL \), where \( f \) is a factor that may be larger than unity if the solar wind magnetic field is piling up in front of the cable. It is not certain that this will be the case since the cable and the volume occupied by the magnetic field of the current \( I \) is thin as compared to the ion gyro radius.

It is at present difficult to comment in detail on the effects of the flow field interaction on the extractable power and the drag force. Equation 1 seems to indicate that they should vary in approximate proportion to each other, but part of the power may possibly leak through the compressed plasma in front of the cable. Detailed studies and experiments will be necessary before the exact values of \( \eta \) and \( f \) can be stated. Since the "source impedance of the solar wind plasma and the cable" hopefully will be much lower than that of the plasma engine, the power reduction by a factor of 2 (or 4) foreseen in Sonett's discussion is not explicitly taken account of. The factor \( \eta \) of Eq. 2 may be taken to include such effects as well, if important.

The net force when the vehicle is flying against the wind is found by combining the previous expressions and \( E = vB \), where \( v \) is the solar wind velocity:

\[
F_{net} = IBL \left( \frac{2\eta v}{w} - f \right)
\]

From Eq. 4 it follows that we can always beat the solar wind by using an exhaust velocity

\[
w < \frac{2\eta}{f} v
\]

Since \( v \) is of the order of 400 km/sec, it is obvious that a considerable reduction of efficiency can be afforded before the exhaust velocity, and thus also the "fuel" economy, becomes comparable to that of a conventional rocket.

A study of a solar wind vehicle where a long plasma beam is instead used as current conductor leads to similar conclusions. The success of such a vehicle also depends critically upon the feasibility of long, well-confined plasma beams. We will not comment on this idea any further here.

The question of the ability of a vehicle to move against the wind as
discussed here may be largely academic. Most long-range space in the foreseeable future flights will certainly be unmanned, and, when it sometimes becomes desirable to bring back a vehicle, this can often be done by propelling the vehicle at right angles to the solar direction so as to decrease its orbital angular momentum. When this is done, gravitation will quickly bring the vehicle back. Certainly far more important is the ability of a propulsion system to offer a reasonable acceleration in combination with an acceptable fuel consumption. Although it is too early to state the merits of solar wind sailing, it seems to offer sufficient possibilities to encourage further studies.

Note added in proof: We have just learned that some of the ideas proposed in (1) and (2) have already been discussed by Moore (6). Our results are in general agreement with those of Moore, and we regret very much our ignorance of his work.

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26 September 1972

Time Reversal and Irreversibility

Sachs (1) has presented a thought-provoking article on time reversal. However, I find that his introductory arguments regarding the "flow of time" and the origin of irreversibility are somewhat captivated by traditional thinking in statistical mechanics. Among other things, the author states that irreversibility is introduced in the averaging process over the detailed molecular motions.

In a previous article (2) I demonstrated that the introduction of statistics does not by itself produce irreversibility. The origin of irreversibility, time asymmetry, or the law of increasing entropy, as given by any of the statistical mechanical "theorems," is not to be found in the mathematical formulations, but rather in an a priori choice made by the statistical physicist of a probability that is actually asymmetrical in time. This can be related to the empirical fact that blind statistical prediction is "physical," whereas blind statistical retrodiction is not. Thus, one can calculate the probability that something physical will happen, but not the probability that something physical did happen. This should be recognized as an imposed direction of time or an imposed initial condition on symmetric probability theory. It is a selection which is usually undeclared but which is essentially equivalent to an a priori introduction of the essence of irreversibility (and the so-called second law) into what is widely (and wrongly) believed to be a deduced statistical time asymmetry, statistical law of the increase of entropy or mixing, and so forth. Consequently, I stress that statistical (classical or quantum) mechanics fails to deduce the origin of irreversibility and time anisotropies in nature.

Without any other convincing arguments as to the origin of irreversibility, an increasing number of scientists are now convinced that the only explanation presently acceptable is that of the new astrophysical school of thermodynamics (2–4). Also, weak violations of the invariance of the laws of motion under time reversal (T-invariance) or space reversal and charge conjugation (CP-invariance) can now be explained by the astrophysical school (2, 4, 5).

My last remark is related in part only to semantics. The use of the conception flow of time has in the past produced logical havoc for physics. This conception also vitiated Bridgman's objections to Eddington's thermodynamic account of the anisotropy of time (6). The term flow of time should be replaced by a term such as anisotropy of time.

I stress that these remarks do not affect the contribution of Sachs' article. I hope that it will provoke all of us to reexamine the "fundamental" concepts in some of our theories.

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Gal-Or's reference to the statement that "irreversibility is introduced in the averaging process over the detailed molecular motions" takes it out of context. I introduced the concept of averaging to give a loose definition of the macroscopic (thermodynamic) variables of a complex system in terms of the microscopic motions, which are reversible. My complete statement places the emphasis on the incredibly small probability for attaining the initial conditions required for exact reversal of the motion if one can fix only the macroscopic conditions.

This emphasis on the role of initial conditions, which is to be found throughout my discussion, does not seem to be in disagreement with Gal-Or's remarks. However, I do disagree with his suggestion that there is a time asymmetry to be explained. If a complex system is initially in an ordered state, the probability is overwhelming that it will behave symmetrically in time; that is, if the detailed microscopic motions are followed either forward or backward in time from that initial moment, the corresponding thermodynamic variables determined by averaging over the particle motions will change irreversibly.

My article is not intended to be a discussion of the laws of irreversible thermodynamics. My only purpose in bringing up the subject at all is to show, in as naive a way as possible, that there is no contradiction between the time reversal invariance of the laws of motion and irreversibility of the variations of the thermodynamic variables.

Although my arguments may be "captivated by traditional thinking," they are given in connection with a traditional problem in physics which yields to traditional answers. The problem arises not in trying to determine the answers but in trying to phrase them in terms suitable for a wider audience.

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