

NONEQUILIBRIUM THERMODYNAMICS

by Aharon Katchalsky

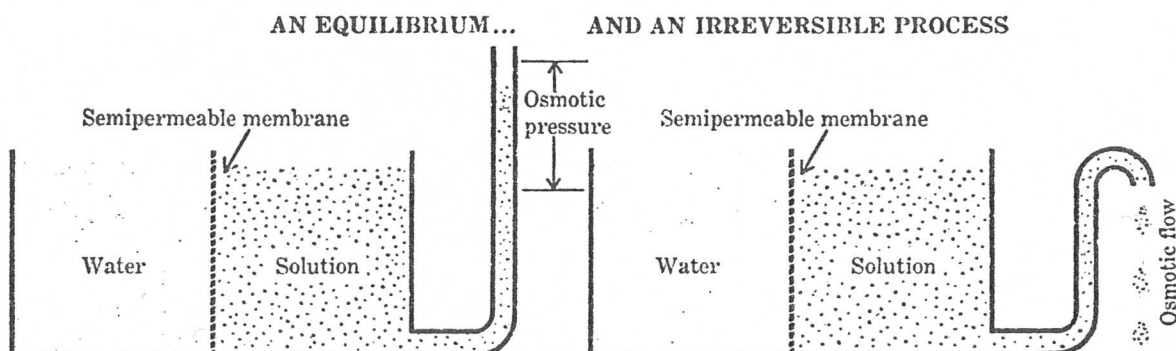
**With a few assumptions about entropy
but without the "graven image" of a model,
thermodynamics can now describe
many irreversible transport processes**

IN BRIEF: *Classical thermodynamics dealt with closed systems in equilibrium, and it could not describe the irreversible transport processes of open systems. Modern insights about the components of entropy production and its relationship to time permit expressing the dissipation of a system's free energy as a function of forces and flows. A flow is seen to be drivable not only by the force to which it is conjugated—current by emf, for example—but also, through coupling, by the forces driving other kinds of simultaneous flows. Onsager's law reduces the coupling coefficients to the number necessary and sufficient to describe process behavior. Workers are still trying to give physical meaning to the coefficients of complicated systems involving many or rapid flows, but the understanding so far achieved of slow and simple systems has already explained old anomalies and predicated new data.—T.M.*

■ The verbal combination of "nonequilibrium" with "thermodynamics" sounds queer to the student of classical thermodynamics. He knows thermodynamics—or more precisely, thermostatics—as essentially a theory of equilibrium states (see Fig. 1). The powerful clarity of its laws and correlations, which has made them the ultimate criteria for the possibility or impossibility of processes, derives to a large extent from the fact that the systems it considers are in a well-defined state—that of equilibrium. One might well wonder whether the logical formalism of thermodynamics really can be extended to embrace the evanescent and transient phenomena of such irreversible processes as diffusional flow and the flow of heat through crystals.

Actually, the great masters who forged the fundamental concepts of the new science of thermodynamics during its first creative period, the nineteenth century, had no intention of limiting its scope to the dead ends of

Fig. 1 CONTRASTING DOMAINS OF THERMODYNAMICS—



The different kinds of systems treated by classical and modern thermodynamics can be created by rearranging the capillary of an osmometer in which a semipermeable membrane separates an aqueous solution from water. In one setup (left), a difference in hydrostatic pressure across the membrane is gradually built up as water molecules replace migrating solute ions, causing the solution level in the capillary to rise above the water level until a state of osmotic equilibrium is reached. The magnitude of the pressure head is derivable from solution properties by classical thermodynamics (thermostatics). If the capillary is bent (right) so that its opening is at the level of the water, the osmotic pressure difference causes an irreversible osmotic flow. Its magnitude is derivable—but only by using both membrane and solution properties and nonequilibrium thermodynamics.

processes—to equilibrium states. They intended to work out a general formalism that would be able to describe real natural phenomena, nonequilibrium states, and irreversible processes. Indeed, the connotation of the fundamental concept “entropy” is evolution, and Clausius introduced it precisely as a universal indicator for the developmental process in a state of irreversible flow.

In later years, many thermodynamicists were attracted by the crystalline clarity of thermostatics and built a consistent formal edifice that occupies, in present-day natural science, a place similar to that of logic in general thought. Still, the search for a thermodynamics of irreversible processes continued incessantly in the background.

It was clear that though balance sheets could be worked out at thermal or mechanical or chemical equilibrium, all real processes, whether of an engine or of a living organism, were nonequilibrium, irreversible processes. A suitable conceptual framework and mathematical apparatus had to be developed if a general thermodynamics of natural phenomena were to be an achievable goal.

For more than 80 years, many attempts were made which provided some valuable building blocks for the present-day structure but which did not combine into a consistent science until 1931. That year, Lars Onsager published the fundamental relationship that has underlain all subsequent developments. In 1945, H. B. G. Casimir (see THINKING AHEAD WITH H. B. G. CASIMIR, January 1962, p. 63) removed some inconsistencies in Onsager's treatment and extended Onsager's relationships to cover polar phenomena. Since then, most notably in the postwar years, the new science has grown smoothly. The work of the Belgian and Dutch schools of physical chemistry led by Prigogine and de Groot, of such German physicists as Meixner and Meissner, and of the American Kirkwood has put the treatment of slow irreversible processes, at least, on a solid basis. In many cases—unfortunately not including turbulence—one may discern the beginning of an orderly, indeed “trivial,” treatment of nonequilibrium phenomena.

Whether we like it or not, the ultimate goal of every science is to become trivial, to become a well-controlled apparatus for the solution of schoolbook exercises or for practical application in the construction of engines.

Now nonequilibrium thermodynamics has not yet reached this “classical” stage; its application still requires much ingenuity and profound study in many fields of science, such as the treatment of chemical kinetics and the description of biological phenomena. However, it can quickly become an operational tool that may be used with advantage by the non-specialist.

The basic principles from which nonequili-

rium thermodynamics starts its operations are known and generally accepted. They are the First Law (matter and energy are conserved) and the Second Law (entropy does not decrease) of thermodynamics.

The new trend appears first in the proposition that the laws can be applied locally to every element of a system and second in the assumption that the Second Law is valid also for nonequilibrium systems—if the irreversible changes they are undergoing are sufficiently slow.

The growth of inner entropy

Clausius found that if a system at temperature T exchanges an amount dQ of heat with its surrounding, then the change of entropy dS in the system is larger than or equal to dQ/T ; that is

$$dS \geq \frac{dQ}{T} \quad (1)$$

Clausius himself recognized that dQ/T is the entropy exchanged with the surroundings, or $d_e S$. So, Eq. 1 implies that besides the entropy brought from the outside, there is an additional source of entropy created within the system, or $d_i S$. We may therefore rewrite Eq. 1 in the more explicit form

$$dS = d_e S + d_i S. \quad (2)$$

Now, $d_e S$, the entropy exchanged with the surroundings, may be either positive or negative; that is to say, the system may either obtain entropy from the external world or transfer entropy to external bodies. However, the peculiar property of $d_i S$ is that it can never be negative; it is positive definite:

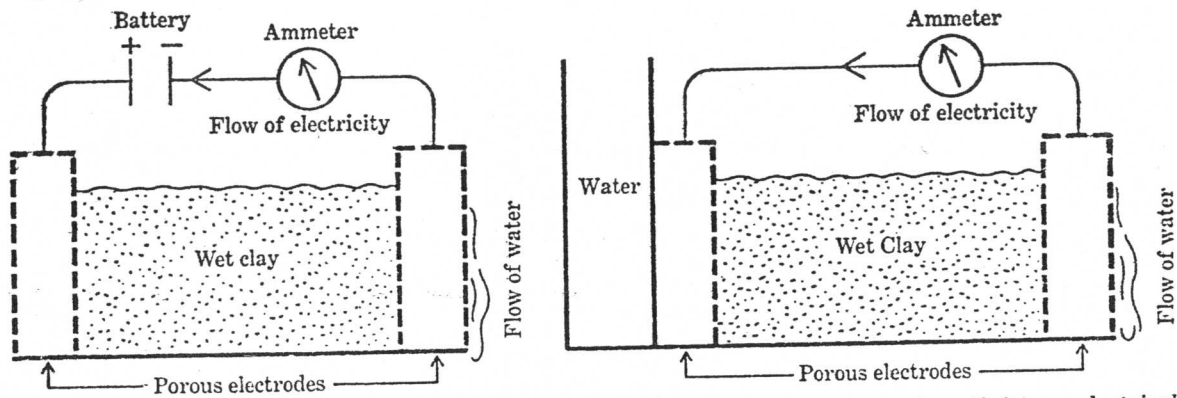
$$d_i S \geq 0 \quad (3)$$

This inner entropy term is due to the dissipation of energy by nonequilibrium processes. Its positivity is another expression of the unidirectional properties, i.e. the irreversibility, of natural processes. The limit of very slow irreversible processes is an equilibrium process during which no energy is dissipated and $d_i S = 0$.

When we say that the entropy grows in natural processes, we imply the positive definite nature of $d_i S$; but we are also expressing another fundamental and striking property of this term: In contradistinction to mass and energy, entropy does not obey a law of conservation. It is a nonconservative quantity whose incessant production constitutes a singular indicator of the progress of natural processes.

This is the reason the thermodynamics of irreversible processes has chosen $d_i S$ as the primary yardstick of all irreversible phenomena. However, an additional step is required to make $d_i S$ a workable scientific tool—the explicit measurement of $d_i S$ per unit of time.

Fig. 2 ELECTROKINETIC COUPLING



The first coupled phenomenon was discovered by Rous in 1808 when (left) an electrical potential drove a flow of water as well as a flow of electricity through a wet clay conductor. In the reverse experiment (right), a pressure head drove not only a water flow but also an electric current. The electrokinetic coupling here is simply the fact that the water molecules are electrically charged.

Philosophers have been concerned with the directional properties of time for many years. Attempts to regard time as another coordinate of a four-dimensional world of events did not remove the mystery from the fact that one can move forwards and backwards in any space coordinate while regrettably one's movement in the time coordinate is restricted to a single direction.

In the flowery language of Eddington, there exists a pointed "arrow of time," and the direction of this arrow was early seen to be connected with the growth of inner entropy in cosmic irreversible processes. For physical purposes, however, we have to jump from general speculations to quantitative relations; we must connect time to inner entropy by a straightforward formula. This we do by writing the differential growth of $d_i S$ with time t ; namely, $d_i S/dt$. This differential is the rate of entropy production by irreversible processes; it is a basic operational parameter of non-equilibrium thermodynamics.

In isothermal systems, which are common both in mechanics and biology, it is often more convenient to consider not the production of entropy but a different though related function, the dissipation of free energy. This function is denoted by the Greek letter phi:

$$\Phi = T \frac{d_i S}{dt} \quad (4)$$

This phi function was introduced by Lord Rayleigh at the end of the nineteenth century as an indicator for the degradation of the working capacity of mechanical systems due to dissipative frictional processes.

Thermodynamic forces and flows

When the fundamental assumptions of the thermodynamics of irreversible processes are put through the mathematical machine of

differential equations, it is possible to obtain an explicit expression for the local entropy production or free-energy dissipation function.

It is found that Φ is the sum of terms contributed by every irreversible process proceeding in the system and that every term is the product of two members—a flow J_i and a force X_i , such that

$$\Phi = \sum J_i X_i \quad (5)$$

where the summation is over the entropy-producing processes.

Generally, the flows J_i are perceived intuitively and have a simple physical meaning.

Thus, the flow of matter will be the vectorial transport of a number of moles or a number of grams of substance per unit area per unit time. Or the flow of heat, or of electricity, will be the transport of a corresponding quantity in a given direction per unit area and unit time.

Some of the flows have no direction in space and are merely scalar changes per unit time. An important flow of this type is the advancement of a chemical reaction or the extent of reaction per unit time.

Still other flows have to be specified by a more sophisticated dependence on space coordinates; they require treatment by tensors of second order. Such are the flows in anisotropic systems; e.g., the flow of heat in crystals.

Though the flows of thermodynamics are generally familiar, the forces are generally not the well-known mechanical forces of Newtonian mechanics. Thus the force conjugate to a diffusional flow of matter, the force which drives the transport of a given substance, is found to be the local drop in its chemical potential. The chemical potential itself, μ , is not an elementary concept. It depends in a rather complicated manner on pressure, temperature,

concentration, and electrical potential, so that it is still a rather foreign concept to the practical worker despite its having been covered for many years in textbooks of physical chemistry.

A closer inspection, however, shows that the gradient of chemical potential is rather simple, for it is found to be a straightforward mechanical force per unit substance which drags the diffusing substance in solution.

Some other thermodynamic forces are more familiar. There is no surprise in observing that the force driving the flow of entropy is the fall in temperature, or that the force conjugated to the flow of electricity is the negative gradient of electrical potential.

Presumably the most difficult force to grasp is the force driving the advancement of a chemical reaction. This important force was first described by de Donder and denoted as the affinity of the reaction, A .

Consider a reaction of substance B and C giving rise to the reaction products F and G . If we assign each of the participants a chemical potential, say μ_B , μ_C , μ_F , and μ_G , then the affinity is $A = (\mu_B + \mu_C) - (\mu_F + \mu_G)$, or, more generally, it is the sum of the chemical potentials of the reactants, minus the sum of the chemical potentials of the reaction products. If A is larger than zero, the reaction is driven from left to right; if it is smaller than zero, the reaction proceeds in the opposite direction; but when $A = 0$, no reaction takes place and a state of equilibrium is attained.

Thermodynamic flows and forces have to be carefully assigned to the irreversible processes proceeding in the system; but then they can be fed into Eq. 5 and the dissipation function evaluated.

Dependence of flows on forces

The patient reader who has managed to read my article up to this point will surely stop and ask himself what we have achieved by our deliberation.

Apparently, after a lengthy analysis of flows and forces, the investigator will be able to combine them in a mathematical expression and have the satisfaction of knowing what the entropy production of his system is. But what does he gain by this knowledge? What new information, what clearer insight has he derived from this formal juggling with mathematical symbols?

The scientist or technologist will surely ask for a useful application and will not be satisfied with the mere possibility of adding a non-equilibrium label to the object of his interest.

In order to proceed, we have to supplement the dissipation function Φ with additional relationships, the most important being the dependence of the flows on the forces. The search for such dependences is almost as old as the study of energy conversions that underlies classical thermodynamics.

Already in 1811 Fourier observed that the flow of heat is linearly dependent on the gradient of temperature. Later, Fick noted that the diffusional flow of matter depends linearly on gradient of concentration, while Ohm found that the flow of electricity is linearly proportional to the electromotive force.

All of these cases demonstrated that in relatively slow processes, the rates of which are largely determined by frictional forces, the flow is a linear function of the force and may be written as

$$J_i = L_i X_i \quad (6)$$

where the coefficient L_i is a proportionality factor, not necessarily constant but independent of both J_i and X_i .

But linear dependence is not the whole story. And, as is often the case in the history of science, the more complicated dependence was discovered several years before the simpler linear case.

In 1808, a pioneer colloid chemist in Russia named Rous studied the conductance of electrical current by wet clay (Fig. 2). To his amazement, he observed that imposing an electrical potential difference across the clay led not only to the expected flow of electricity but also to a pronounced flow of water towards the cathode. Since, on *a priori* grounds, a flow of water should be driven by a pressure head, Rous made the converse experiment: he applied hydrostatic pressure to the piece of clay and obtained a flow of electricity.

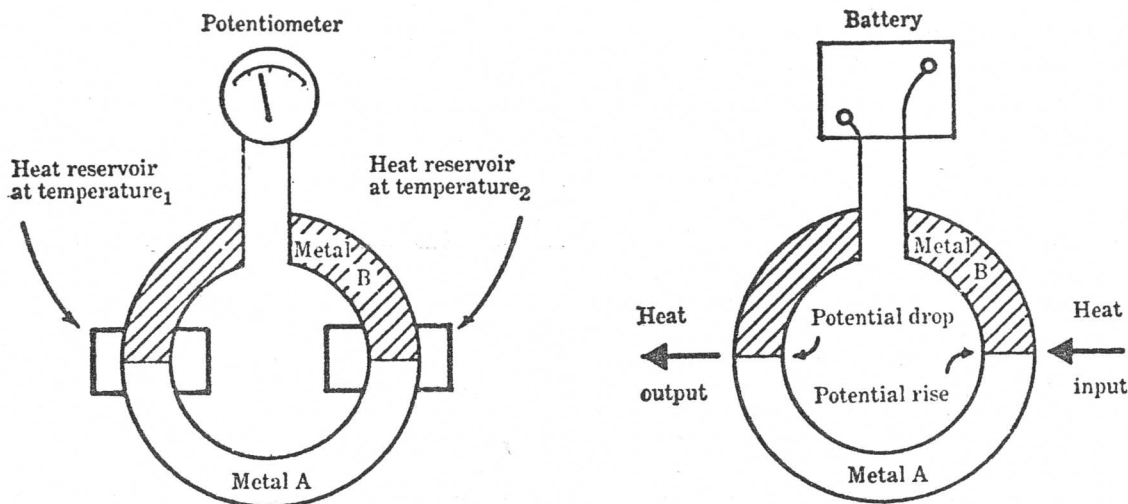
Rous's ingenious electrokinetic experiments were the first to demonstrate the existence of coupled phenomena. They proved that a flow may not only be driven by its directly conjugated force but may also be coupled to other, nonconjugated forces. Thus the flow of electricity is evidently caused by an electromotive force, but it may be coupled to a hydrostatic pressure; and conversely, the volume flow of water may be coupled to an electrical force.

Some twenty years later, another group of coupled phenomena was found in the field of thermoelectricity (Fig. 3). Seebeck in Germany observed that if the ends of a bimetallic couple are heated to different temperatures, an electric potential difference is built up—across the conductor. Conversely, the French watchmaker Peltier observed upon passing an electrical current through the couple, that heat was transported from one junction to the other.

Onsager's principle of matrix symmetry

Neither Seebeck nor Peltier understood what they were doing; but their experiments, with that of Rous, made clear the importance of coupling. The idea that interrelationships between different flows may exist, and often occur in natural phenomena, matured slowly during the nineteenth century but did not find a consistent expression until 1931, in the

Fig. 3 THERMOELECTRIC COUPLING



A bimetallic thermocouple can be used to show two aspects of thermoelectric coupling. In the Seebeck effect (left), a temperature gradient between the junctions causes a flow of current as shown by a buildup of open-circuit e.m.f. The microscopic explanation of such thermoelectric coupling is that some metallic heat conduction is an energy transfer from hot electrons to cool electrons. In the Peltier effect (right), a weak flow causes vectorial heat transport from one junction to the other.

“phenomenological” equations of Lars Onsager.

Onsager assumed that any flow is linearly dependent not only on its conjugate force but in principle on all other forces operative in the system.

For example, let us consider a system in which the flows J_1 , J_2 , and J_3 are driven by the forces X_1 , X_2 , and X_3 . We shall now explicitly write the dependence of each of the flows on all three forces, as a generalization of Eq. 6:

$$\begin{aligned} J_1 &= L_{11}X_1 + L_{12}X_2 + L_{13}X_3 \\ J_2 &= L_{21}X_1 + L_{22}X_2 + L_{23}X_3 \\ J_3 &= L_{31}X_1 + L_{32}X_2 + L_{33}X_3 \end{aligned} \quad (7)$$

What these equations state is that while, say, the second flow (J_2) is dependent on its conjugated force X_2 through the so-called straight coefficient L_{22} , J_2 also depends linearly on force X_1 and on force X_3 through the coupling coefficients L_{21} and L_{23} .

You’ll note that the equations are linear; i.e., the flows are stated to depend only on the first power of the forces. This is by no means self-evident and is not always true; the flows may depend on some higher power of the forces or may exhibit still more complicated functional dependences.

It is rather lucky that in a great number of phenomena, at sufficiently low rates of flow (and it is here that we need the restriction of nonequilibrium thermodynamics to sufficiently slow flows), the linear relationships hold very well and nicely describe the observed behavior.

The real trouble with the phenomenological equations lies in the large number of coefficients required to master even the simplest cases. The determination of each coefficient requires a different experimental method, so that for the full description of a three-flow system we need nine independent experimental methods which may be neither available nor practicable.

I think it was Cauchy who said, “Give me five coefficients and I will plot an elephant; give me six coefficients and the elephant will wiggle its tail.” Imagine what Cauchy could do with the nine coefficients imposed upon us in a simple three-flow case!

It is here that we are helped by the fundamental law of Onsager, which is rightly regarded as the cornerstone of nonequilibrium thermodynamics. The statement of the law is rather mathematical; it says, “The matrix of the coefficients is symmetrical” or

$$L_{ij} = L_{ji} \quad (8)$$

For the three-flow system the requirement is that $L_{12} = L_{21}$, $L_{13} = L_{31}$, and $L_{23} = L_{32}$.

In words: those coupling coefficients are equal that are equidistant from the diagonal formed by the straight coefficients.

We shall soon see that this mathematical-looking statement does not merely reduce the number of coefficients required for the description of irreversible processes, it also leads to a series of very valuable and important physical relationships.

The proof of Onsager’s law is based on a

profound statistical-mechanical analysis. Actually there does not yet exist a sufficiently general and complete proof of its validity. However, many great scientific ideas have a range of importance and correctness wider than that originally envisaged by their creators. That this is also the case for Onsager's principle was shown recently by Donald Miller, who analyzed a large number of existing experiments and found that the principle holds in a variety of fields of physics and chemistry. You may therefore accept it as an empirically founded law of nature.

Now let us consider a few examples that will demonstrate how to use Onsager's law and what kind of predictions nonequilibrium thermodynamics makes.

Electrokinetic and membrane permeability

It seems fitting to take as the first example the first observation of coupled phenomena—the experiments of Rous (Fig. 2). The analysis is based on the work of Mazur and Overbeek, who pointed out that in this case we evidently have two thermodynamic flows—the flow of electricity I and the volume flow of water J_V . Then it is intuitively clear—but may be verified by constructing the dissipation function—that the driving force for the electric flow is the electromotive force E , while the force driving the flow of water is the hydrostatic pressure across the piece of wet clay Δp .

We may therefore write Onsager's equation in the form

$$I = L_{11}E + L_{12}\Delta p \quad (9)$$

$$J_V = L_{21}E + L_{22}\Delta p$$

In Eq. 9, the coupling of Rous is brought to light clearly and definitely: we see that even if no electromotive force acts on the clay (that is, if $E = 0$), the existence of a pressure difference will produce an electric flow if the coupling coefficient is nonvanishing. Also expressed is the reverse coupling: when no pressure is applied ($\Delta p = 0$), the action of the electrical force will cause a volume flow of water.

Onsager's law now gives additional and quantitative information. Since by this law $L_{12} = L_{21}$, we deduce that the electrical flow per unit pressure, at $E = 0$, equals volume flow per unit e.m.g., at $\Delta p = 0$, or

$$(I/\Delta p)_{E=0} = L_{12} = (J_V/E)_{\Delta p=0} = L_{21} \quad (10)$$

Observe that Eq. 10 does not say how large is the flow either of electricity or of volume. Thermodynamics alone can not say whether or not L_{12} is zero or, if not, what its magnitude is.

The other example I would like to consider is membrane permeability. Following the work of Staverman, my friend Ora Kedem and I have devoted considerable time to the thermo-

dynamic description of the permeability of nonelectrolytes and of electrolytes through simple or composite membranes. Here, I'll discuss only the very simplest case, of the transport of a single nonelectrolyte solute dissolved in water, through a homogenous synthetic membrane.

Let the membrane under consideration be separating two compartments containing two solutions of equal solute but of different concentrations. Let the resulting difference of osmotic pressure across the membranes be $\Delta\pi$.

Let us further assume that the hydrostatic pressure is unequal on the two sides of the membrane, so that there exists a pressure head Δp .

We now have two forces, $\Delta\pi$ and Δp , and our next task is to evaluate the conjugated flows. Consideration of the dissipation function Φ shows that, as expected, the flow conjugate to Δp is the flow of total solution volume across the membrane, or J_V . The other flow is more intriguing; it is the flow of solute relative to that of solvent: what we call the diffusional flow J_D .

With this information we can write

$$J_V = L_{11}\Delta p + L_{12}\Delta\pi \quad (11)$$

$$J_D = L_{21}\Delta p + L_{22}\Delta\pi$$

Eq. 11 immediately indicates several interesting phenomena. On *a priori* grounds we would imagine that volume flow would be driven only by hydrostatic pressure and that $J_V/\Delta p = L_{11}$ should be simply the filtration coefficient of the membrane. But Eq. 11 shows that even at $\Delta p = 0$, there may exist a volume flow driven by the coupled osmotic pressure. Such flows are indeed known; their magnitude depends on the coefficient of osmotic flow

$$L_{12} = (J_V/\Delta\pi)_{\Delta p=0}$$

A similar statement can be made about the diffusional flow J_D . Evidently, in order for a diffusional flow to exist, there should exist a difference in concentration expressed here as the osmotic difference $\Delta\pi$. But we see from Eq. 11 that even when $\Delta\pi = 0$, a diffusional flow may develop, through the action of the mechanical pressure.

This remarkable behavior is real; it is well-known to the colloid chemist as ultrafiltration. It depends on the capacity of the membrane to distinguish the solute from the solvent and to produce, under pressure, a relative or diffusional flow.

Again, Onsager's law leads to the conclusion that the coefficient of osmotic flow has to be equal to the coefficient of ultrafiltration.

This is another case from which we recognize that Onsager's principle is not a mathematical statement but a law of nature, a statement about real relations between physical phenomena.

Before the advent of the thermodynamics of irreversible processes it was customary to describe membrane permeability by two coefficients—a coefficient of solute permeability (L_{22}) and a filtration coefficient (L_{11}). But Eq. 11 shows that three coefficients are necessary; and indeed, the previous neglect of the coupling coefficient L_{12} did lead to inconsistencies and misunderstanding.

A final observation will stress again the importance of the coupling coefficients. Let us consider from the point of view of nonequilibrium thermodynamics the classical measurement of osmotic pressure depicted in Fig. 1. In that experiment, a solution is separated by a semipermeable membrane from pure solvent, water in this instance. The solvent, driven by a difference in chemical potential, enters the solute compartment and a pressure Δp is built up. When the hydrostatic pressure Δp equals the osmotic pressure $\Delta\pi$, the volume flow stops ($J_V = 0$) and osmotic equilibrium is established.

At equilibrium, we put $\Delta p = \Delta\pi$ so that we can measure osmotic pressure by hydrostatic pressure. To our surprise, however, Eq. 12 shows that at $J_V = 0$, Δp is not equal to $\Delta\pi$ but rather $\Delta p = -(L_{12}/L_{11}) \Delta\pi$! (Exclamation, not factorial.)

Our surprise diminishes if we consider that Δp should equal $\Delta\pi$ only for an ideally semipermeable membrane. In that case indeed $-L_{12}/L_{11} = 1$; but in real membranes, which are permeable to both solute and solvent, $-L_{12}/L_{11} < 1$ and the maximum pressure is smaller than the ideal.

Now we begin to recognize the importance of L_{12} as a measure of the selectivity of the membrane. We denote the ratio $\sigma = -L_{12}/L_{11}$ as the selectivity coefficient of the membrane. When $\sigma = 1$, the membrane is ideally semipermeable and distinguishes clearly between solute and solvent. When $\sigma < 1$, the distinction is less precise and solute may pass through the membrane. Finally, when $\sigma = 0$, there is no selectivity, and solute can not be separated from solvent by a membrane process.

Almost needless to say, a quantitative measure of selectivity is of primary interest for the characterization of membranes. A clear grasp of this important parameter has been achieved only through the application of nonequilibrium thermodynamics.

Stationary states

Throughout our discussion we imposed no restriction on flows and forces. However, there are cases that deserve special consideration for their importance both in nature and in technology. Of these, the most important are the stationary states, which are attained whenever the forces applied are constant.

Consider for example a bar of metal to the ends of which we apply different but constant

temperatures. The temperature difference will induce in the bar a flow of heat that will cause a change in all local temperatures. After a while, though, a constant distribution of temperature will be attained and the flow of heat will become steady.

The state of steady flow and of constant distribution of the parameters characterizing a system is the ultimate state of irreversible systems under constant forces. They play the same role in nonequilibrium thermodynamics as is played by states of equilibrium in classical thermostatics.

Steady states are typical of smoothly running engines, and, what is more intriguing, they are the stable states of living organisms. Indeed, most organisms, including man, undergo a process of rapid development in their youth, then reach a steady state at maturity—the well-known state of middle age. Living organisms have a special control system, the system of homeostasis, which corrects minor deviations from steady state, and, to be sure, modern engines are endowed with man-made homeostats that keep them producing at a constant rate.

Since all the parameters of a system are constant during a stationary state, the entropy is constant too, not changing with time. This means, in accord with our first equations, that the entropy created by steady flow is equal to the entropy given off to the surroundings.

Thus, only systems open to exchange of entropy with their environments can reach a steady state. A fully isolated adiabatic system can end up only in equilibrium or in explosion. This is the thermodynamic reason why all living beings are open systems, capable of stable existence in a stationary state.

Several years ago, Prigogine pointed out that steady nonequilibrium systems produce entropy at a minimal rate. This remarkable conclusion from Onsager's law sheds new light on "the wisdom of living organisms." Life is a constant struggle against the tendency to produce entropy by irreversible processes. The synthesis of large and information-rich macromolecules, the formation of intricately structured cells, the development of organization—all these are powerful anti-entropic forces. But since there is no possibility of escaping the entropic doom imposed upon all natural phenomena under the Second Law of thermodynamics, living organisms choose the least evil—they produce entropy at a minimal rate by maintaining a steady state.

I hope that my brief introduction has disturbed your own steady state and will encourage you to dig deeper into the formalism, interpretation, and application of nonequilibrium thermodynamics.

Which you can begin to do by turning to the evaluative bibliography on page 117.