

## The *Wirbelrohr's* Roar: A Thermodynamic Curiosity

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The law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations— then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

—Sir Arthur Stanley Eddington, *The Nature of the Physical World* (1915).

### **Summary**

A remarkable device, with no moving mechanical parts or any connection to a source of electrical energy, appears to defy the Second Law of Thermodynamics by simulating a Maxwell demon and producing simultaneous, oppositely directed streams of hot and cold air from an input air stream at room temperature. I learned of the device while playing chess with my father-in-law who constructed such a device (a *Wirbelrohr*) many years earlier after reading about it in a science fiction magazine. But the device is no fiction. My simple analysis shows that the *Wirbelrohr* violates no laws of physics.

### **Fascination of Rotational Motion**

With all due respect to Robert Boyle, there is a 'spring' to the air that the venerable Irish physicist never dreamed of some three centuries ago when he introduced his fellow natural philosophers to the effects of pressure<sup>1</sup>. Air is not merely compressible; it can course and caper through appropriate devices in such ways as to please the ear and titillate, if not confound, the intellect. I learned that first hand from playing.

Most people I have encountered, for whom physics is anything but relaxation, could hardly imagine 'physics' and 'play' in the same sentence—except, perhaps, one denying their equivalence. Yet the same laws that govern the erudite matters to which physicists give their attention also apply to amusement. Indeed, sometimes nature's subtlest wiles may be invested in the simplest child's toy. One of my favourite science photographs<sup>2</sup> shows Wolfgang Pauli and Niels Bohr hunched over the ground observing the behaviour of a Tippetop, a curious little object that, shortly after being spun on its wide bottom, flips 180° and spins on its narrow handle. As far as I know, there may still be no consensus as to how it works.

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<sup>1</sup>R. Boyle, *New Experiments, Physico-mechanicall, touching the Spring of the Air and its Effects* (London, 1660). A discussion of these experiments may be found in R. Harré, *Great Scientific Experiments* (Oxford, New York, 1983) 74-83.

<sup>2</sup>This picture is reproduced in *Niels Bohr: A centenary Volume*, ed. A. P. French and P. J. Kennedy (Harvard University Press, Cambridge, 1985) 177.

When I think about the topic of physics ‘toys’, I find it striking how often the phenomena that puzzle and amuse us involve the element of spinning. As a child, I was entranced by a small gyroscope precariously perched at the end of my finger or horizontally suspended by a loop of string around the rotation axis in apparent defiance of the laws of gravity. The gyroscope still fascinates me even though, as a physicist, I understand how it works. My own children, when they were young, were intrigued by a ‘one-way’ spinner, also known as a celt, which I frequently borrowed from them for use in lectures on chiral asymmetry. It is a four-inch piece of plastic (bearing the words ‘Turn on to Science’) shaped like the hull of a clipper ship with just the slightest asymmetry between port and starboard sides. Spin it counterclockwise and it turns freely; spin it clockwise and it soon wobbles vehemently, stops, and rotates in the opposite sense! A celt is startling to behold and by no means trivial to explain. In fact, a partially satisfactory explanation was provided by the cosmologist Hermann Bondi only some hundred years after this remarkable behaviour was first reported<sup>3</sup>. Bondi’s paper is not bedtime reading.

I have myself often fashioned a ‘two-way’ spinner from a wooden pencil by carving a row of notches along its length and affixing a propeller (a popsicle stick works well) to the eraser with a pin. Stroke the notches with another pencil, and the propeller spins either clockwise or counterclockwise depending on a subtle manipulation by the stroker. How does ostensibly linear motion rotate the propeller? In some way, of course, the strokes must generate elliptical vibrations in the pencil, but the details are hardly obvious.

If the motion of solids, with relatively few degrees of freedom, can be puzzling, one can only begin to imagine the paradoxical possibilities that arise when fluids are admitted. Consider, for example, the simple radiometer found in many a museum gift shop. Illuminated by bright sunlight, the four vanes (black on one side, white on the other), spin wildly about a vertical shaft inside a highly evacuated bulb. Clerk Maxwell, I have been told, was ready to discard his electromagnetic theory of light upon learning that the vane spun the ‘wrong’ way—the wrong way, that is, if one assumes the vanes are driven by light pressure. It is not light, however, but residual gas that lies at the heart of the matter, although exactly how is still, more than a hundred years later, a question for discussion. Maxwell, it should be mentioned, did not remain confused over the radiometer effect for long, but addressed its mechanisms in a seminal paper<sup>4</sup>.

Some years ago, while living in Japan, my family and I encountered near a train station in the town of Hakone the eerie strains of a most unearthly symphony. There, about twenty metres in front of us, a dozen or so Japanese children, whose number was quickly augmented by my own, were feverishly grabbing long flexible coloured plastic tubes from the stand of a streetside vendor and twirling them furiously above their heads like lariats. The tones that emerged from each musical pipe, designated ‘The Voice of the Dragon’ by a sign in English, soared and dropped with rotational speed over what seemed like a good portion of the range of a flute. I have never forgotten this loud, wavering, rich-toned chorus of ‘dragon voices’. Despite the outward simplicity of the toy, the details of its sound production are by no means trivial, and the efforts to understand it provided worthwhile lessons in physics as well as much entertainment<sup>5</sup>.

But when it comes to gases, nowhere are the intriguing effects of rotational motion as counterintuitive, I think, as in the case of the ‘*Wirbelrohr*’<sup>6</sup>

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<sup>3</sup>H. Bondi, The Rigid Body Dynamics of Unidirectional Spin, *Proceedings of the Royal Society of London* **A405** (1986) 265.

<sup>4</sup>J. C. Maxwell, On Stresses in Rarified Gases Arising from Inequalities of Temperature, 1879 paper reprinted in *The Scientific Papers of James Clerk Maxwell*, Vol. 2, ed. W. D. Niven (Dover, New York, 1952) 681-712.

<sup>5</sup>M. P. Silverman, *Waves and Grains: Reflections on Light and Learning*, (Princeton University Press, Princeton, 1998), Chapter 14.

<sup>6</sup> M. P. Silverman, The Vortex Tube: A Violation of the Second Law?, *European Journal of Physics* (1982) 88-93.

## The Wirbelrohr

I am not an avid reader of science fiction, and, in fact, except for the ‘classics’ by such writers as Jules Verne and H. G. Wells, generally avoid this genre of literature altogether. My late father-in-law Fred, however, who for many years was a machinist at the AT&T Bell Laboratories, was a science fiction enthusiast with subscriptions to a number of such magazines spanning at least four decades. I recall in particular one visit to his home when, in the course of a chess game, we began discussing some of the strange devices he had constructed for engineers during his employment at Bell.

Perhaps the strangest device that he had ever made, however, he made for himself, he told me. I asked him what it looked like, and he replied that it was extremely simple: a hollow tube shaped like a  $\square$  with no moving parts of any kind. Upon my enquiring as to what it did, Fred cocked his head, and I could see—or at least imagine I saw—a gleam in his eyes and the faint trace of a sardonic smile beneath his bushy white beard. It was a Wirbelrohr, he explained; you blew into the stem, and out one end of the cross-tube flowed hot air, while cold air flowed out the other. I laughed; I was certain he was teasing me. Although I had never heard of a Wirbelrohr, I recognised a Maxwell demon when it was described<sup>7</sup>. I asked my father-in-law whether he invented the device, to which Fred replied that he first read about it in one of his science fiction magazines. ‘Yes indeed!’ I thought to myself, and the look on my face undoubtedly conveyed my incredulity as if my thoughts were audible. He insisted that it worked; and when it worked really well, the cold air could freeze water, and the hot air could fry an egg!

I saw from Fred’s expression that he was not teasing me. My father-in-law was from Switzerland; he was no physicist, but his skill in making things was exceptional. I had often thought to myself that he could make anything—although I meant, of course, anything real. Maxwell demons were, as far as I knew, imaginary. My curiosity was thoroughly aroused, all the more since I happened to be teaching a course in thermodynamics that same semester.

To my great disappointment, Fred had kept no record of the device he made, nor was he able to recall exactly when or from what magazine he obtained construction drawings. After all, he built the device some thirty years earlier. Nevertheless, having never discarded a single volume of his science fiction library, Fred promised that, as time permitted, he would search for the intriguing story. At the end of the visit, I returned home excited, but by no means convinced that the Second Law of Thermodynamics should be omitted from my lectures.

Two weeks later a copy of the desired article arrived in the mail<sup>8</sup>. There, sandwiched between the last page of 38,000 Achnoid alien carbon people without brain chords, and the first page of encephalographic analysts led by a powerful mental mutant during the dying days of the First Galactic Empire ... (two undoubtedly gripping tales that vividly reminded me once again why I rarely read science fiction) ... were the anatomical details of a Maxwell demon.

My father-in-law had certainly told the truth. He, in fact, did more than that; he machined in his basement workshop a working model which I received from him shortly afterwards. The exterior was more or less just as he had described it: two identical long thin-walled tubes (the crossbar of the **T**) were connected by cylindrical collars screwed into each end of a short section of pipe that formed the central chamber; a gas inlet nozzle (the stem of the **T**), shorter than the other two tubes but otherwise of identical construction, joined the midsection tangentially (Figure 1). Externally, except for a throttling valve at the

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<sup>7</sup> A comprehensive guide to the literature on Maxwell demons is given by H. S. Leff and A. F. Rex, Resource Letter MD-1: Maxwell’s Demon, *American Journal of Physics* **58** (1990) 201.

<sup>8</sup>A. C. Parlett, Maxwell’s Demon and Monsieur Ranque, *Astounding Science Fiction* (January 1950) 105-110.

far end of one output tube to control air flow, the entire device manifested bilateral symmetry with respect to a plane through the nozzle perpendicular to the cross-tubes.

Only someone with the lung capacity of Hercules could actually blow into the stem. Instead, the nozzle was meant to be attached to a source of compressed air. Taking the *Wirbelrohr* to my laboratory, I looked sceptically for a moment at its symmetrical shape before opening the valve by my work table that started the flow of room-temperature compressed air. Then, with frost forming on the outside surface of one tube, I yelled with pain and astonishment when, touching the other tube, I burned my fingers!

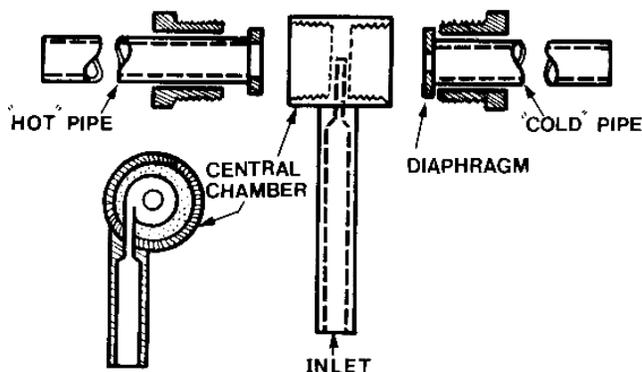


Figure 1: Schematic diagram of a *Wirbelrohr* or vortex tube. Room-temperature compressed air enters the inlet tube, spirals around the central chamber, and exits through the ‘hot’ pipe with unconstrained cross section or through the ‘cold’ pipe whose aperture is covered by a diaphragm.

## Maxwell’s Demon

*Thermodynamics* is different from any other dynamics in physics; in fact, the very word ‘thermodynamics’ is a misnomer. Whereas the term dynamics ordinarily embraced the idea of a system evolving in time under the action of specific forces [e.g. electrodynamics, hydrodynamics, aerodynamics, and chromodynamics (the dynamics of quarks under the strong nuclear force)], the classical theory of thermodynamics is a study of systems in thermal equilibrium—systems, that is, whose macroscopic thermal properties are temporally unchanging. How some physical system has come to be in a state of equilibrium, or how much time is required for the system to go from one equilibrium state to another when external conditions are changed, is outside the principal concern of thermodynamics; for a problem in *this* area, contact a local specialist in kinetics.

To those unfamiliar with the subject, it may seem that, by excluding from its domain the intricate details of specific interactions, thermodynamics must necessarily be a weak and ineffective science compared with the other dynamical siblings in the family of physics. This, however, is not the case at all. In autobiographical notes that he merrily designated his ‘obituary’, Albert Einstein, a man who spent a lifetime developing physical theories, wrote<sup>9</sup>

A theory is the more impressive the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression which classical thermodynamics made upon me. It is the only physical theory of universal content concerning which I am convinced that, within the framework of the applicability of its basic concepts, it will never be overthrown...

The strength of thermodynamics, as emphasised by Einstein, lies in its close and simple ties to experiment and observation. Let the whole edifice of chromodynamics—and therefore the theory of matter, itself—collapse because quarks turn out to be nonexistent; the conclusions of thermodynamics would remain as sound as ever.

<sup>9</sup>A. Einstein, *Autobiographical Notes*, in *Albert Einstein, Philosopher-Scientist*, Vol. 1, ed. P. A. Schilp (Open Court, La Salle, Illinois, 1969) 32.

The vast latticework of thermodynamic interrelations rests principally upon two major laws, the First and the Second. The First Law is a generalised statement of energy conservation and is to be found in one form or another in all dynamical theories of physics. In short, energy can be transformed—from mechanical to electrical, or from electrical to heat, for example—but it cannot be created from nothing or destroyed. The Second Law, however, which can be expressed in a variety of seemingly inequivalent ways, is unique to thermodynamics. In its sum and substance, the Second Law affirms the essential irreversibility of natural or spontaneous processes. Phrased somewhat loosely: Energy can be transformed to do useful work...but never at 100% efficiency; some part is always lost to heat, friction, viscosity, or some other irreversible process.

The more tangible versions of the Second Law, attributable in one form to Lord Kelvin and Max Planck and in another to Rudolph Clausius, reveal the historical roots of thermodynamics in the practical problems of machine making. According to Kelvin-Planck no process is possible the sole result of which is to absorb heat and convert it into work. ‘But what about the steam engine?’ someone is bound to ask. True, it operates by heating water to steam which, upon expansion, does work; but that is not the *sole* result; heat is also discarded to the environment. Neither the steam engine, nor any other engine, converts 100% of the absorbed heat into work without in some way changing the state of the rest of the world (including, possibly, itself). According to the different perspective of Clausius, no process is possible the sole result of which is to transfer heat from a cooler to a hotter body. Now, before one is tempted to assert that a refrigerator does exactly that, let him recall again the restricting condition. A refrigerator does take heat from a cool body and pumps it to a hotter body, usually the ambient air, but only upon the input of work in the form of electrical energy. The foregoing two statements of the Second Law are completely equivalent; it is not difficult to show that violation of one implies violation of the other.

Whether it is a tribute to the indomitable spirit, or simply the perversity, of human nature, the interdictions posed by the Second Law have been a red flag before the eyes of many a bullish inventor. Energy is something most people, rightly or wrongly, believe they understand at least to some degree—and the thought of building a device that generates more energy than is employed to run it is probably not seriously entertained except by those entirely ignorant of all science. The content of the Second Law, however, which embodies highly abstract notions for what is otherwise so concrete a science, rests less easily on the mind. It stands as a challenge to the ingenious as well as the ingenuous.

The frustrating thing about the Second Law is that it forbids processes for which energy remains conserved and which one might naïvely hope can be made to work—somehow. But they can’t. A coin dropped from a height above a table top falls down and heats up a little upon impact. No one, I suspect, has ever witnessed a coin spontaneously rise up against the force of gravity at the expense of its own internal thermal energy thereby suffering a drop in temperature. In either case mechanical and thermal energy can be made to balance, but the process occurs in one direction only. In a similar way, the outcome of setting a hot coin on top of a cold one yields a final state of two lukewarm coins. One could wait, as they say, ‘until hell freezes over’ before the time-reversed process, whereby the lower coin becomes perceptibly colder by spontaneously transferring heat to the upper coin, ever occurs, even though the total energy of the two-coin system is again unchanged. The foregoing hyperbolic remark actually serves a purpose: it emphasises an essential part of the unique quality of the Second Law *vis-à-vis* all other physical laws: its statistical validity.

Consider, for example, the First Law, the conservation of energy. Is it conceivable that, although energy appears to be conserved in processes involving macroscopic amounts of matter, that violations nevertheless occur from time to time on an atomic level? In the early 1920s, as physicists struggled to make sense of the structure of atoms and the nature of light, Niels Bohr, Hendrik Kramers, and John Slater published a paper (the notorious BKS paper) rejecting Einstein’s light-quantum hypothesis and holding to the view that the principles of energy and momentum conservation cannot be strictly applied to

individual interactions<sup>10</sup>. Highly controversial, the BKS paper elicited much discussion within the physics community. Einstein and Pauli scathingly criticised it; Schrödinger, by contrast, was fascinated by it. In the end, however, the BKS theory was decisively refuted by experimental studies of the Compton effect, the scattering of light by free electrons. If the conservation of energy and momentum applied only to bulk matter averaged over time, and not to individual quantum processes, then there would be a non-negligible probability that an illuminated electron could recoil in any direction whatever. Within the limits of experimental precision, constrained ever more tightly by new methods and increasing advances in technology, every reliable measurement consistently revealed that individual interacting pairs of electrons and photons strictly conserved both energy and momentum. Although quantum mechanics allows for energy and momentum *nonconserving* virtual processes (such as the ephemeral creation and annihilation of particles in the vacuum), these violations occur over time intervals too short to be revealed directly by experiment; their existence is inferred from theory.

That was probably the last time leading physicists seriously entertained the thought that the basic conservation principles of dynamics were only statistically valid. When in the 1930s the weak decay of elementary particles seemed to reveal violations of energy and momentum conservation, Pauli knew to look for an alternative explanation and predicted the existence of an elusive new particle, the neutrino.

Before the underlying statistical basis of thermal phenomena was clearly understood, some—Clausius, for example—regarded the Second Law to be rigorously valid in all domains of experience. The proscription that no process can, as a sole result, convert heat to work with perfect efficiency was interpreted strictly to mean *no* process ever. Perception of the Second Law as a manifestation of a law of large numbers was probably first recognised by James Clerk Maxwell, whose pioneering statistical studies of the distribution of particle velocities and associated colligative phenomena would have marked him as a master theoretical physicist even had he never formulated the laws of electromagnetism.

Although the connection may not be obvious, the previous two formulations of the Second Law are equivalent to yet another formulation, more fundamental, in my view, as it is readily amenable to interpretation within the framework of the atomic theory of matter. This third version is expressible in terms of the abstract concept of entropy, a word introduced by Clausius that derives from the Greek root signifying ‘transformation’. Together, energy, which derives from the Greek root meaning ‘work’, and entropy are the two fundamental determinants of an equilibrium thermodynamic state.

From the macroscopic perspective of thermodynamics, the *change* in entropy (which is what one actually measures) associated with the transformation of a system from one equilibrium state to another is related to the heat absorbed or released. From an atomic perspective, however, heat is the energy exchange between physical systems as a result of random molecular motion. In fact, the temperature of a sample of matter in thermal equilibrium with its environment is linearly proportional to, and therefore a measure of, the average molecular kinetic energy. Correspondingly, the entropy of the sample is a measure of the disorder of molecular motion; that is, the number of distinctly different ways in which the particles can be distributed over allowed quantum states and yet still give rise to the specific macroscopic properties (e.g. pressure, temperature, volume) exhibited by the sample. The higher the entropy, the greater the disorder.

Looked at statistically, then, the entropy change for a transformation between equilibrium states is a measure of the relative probability of finding the molecules of the system in the microscopic (quantum) states compatible with the final macroscopic equilibrium state of the sample compared with finding them in the microscopic states compatible with the initial equilibrium state. With this in mind, one can express

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<sup>10</sup>N. Bohr, H. A. Kramers, and J. S. Slater, The Quantum Theory of Radiation, *Philosophical Magazine* **47** (1924) 785.

the third version of the Second Law as follows: in any spontaneously occurring process, the entropy always increases, unless the process is reversible in which case the entropy change is zero.

Imagine a box divided into two sealed compartments of equal volume, one containing a gas, the other vacuum. Between the two compartments is a removable partition. When, by some external means, the partition is removed, the gas spreads into all the available volume until the gas pressure is uniform throughout the box. Wait as long as you please, the gas will never return to the original compartment. What, never? Well, hardly ever! For all the molecules to move in such a way as to recreate a vacuum in the second compartment would require a highly improbable configuration of molecular velocities. Suppose, as symmetry would suggest, the probability of finding a gas molecule to the left or right side of the original partition is  $\frac{1}{2}$ ; then the probability that all  $N$  molecules spontaneously and independently diffuse to the same side is  $(\frac{1}{2})^N$ . At room temperature (20 °C) and 1 atmosphere pressure, a sample of gas initially confined to one cubic centimetre contains about  $2.5 \times 10^{19}$  molecules. This follows from the ideal gas law: (Pressure)(Volume) =  $Nk$ (Absolute Temperature), where Boltzmann's constant  $k$  is  $1.38 \times 10^{-16}$  erg/Kelvin, and the equilibrium conditions, expressed in suitable units, are 1 atmosphere pressure =  $10^6$  dynes/cm<sup>2</sup>, room temperature = 293 Kelvin, and volume = 1 cm<sup>3</sup>. Therefore, compared with finding the gas uniformly spread throughout the entire available volume, the probability that all  $N$  molecules retreat to the initial compartment is roughly

$$P(N) \sim \frac{1}{10^{10^{19}}}$$

The denominator of this fraction is the number 1 followed by *ten billion billion* zeros. Technically, the probability is not exactly zero, but it is certainly indistinguishable from zero for all practical purposes. If we had to wait until 'hell freezes over' for all the molecules to return to the original compartment, how long would that be?

Suppose we consider hell 'frozen over' when, statistically speaking, not a proton remains in the observable universe. Without protons, there can be no neutrons bound in atomic nuclei; free neutrons decay to protons, electrons, and antineutrinos with a lifetime of about 15 minutes. Contemporary theories of the elementary particles predict that baryon number is not rigorously conserved, and therefore protons should decay to positrons, among other things. Positrons and electrons would presumably combine and mutually annihilate. There should be nothing left, then, except electromagnetic radiation and neutrinos. Whether hot or cold, such a universe ought to qualify as a hellish place. What is the probability of this happening? Experiment currently places the proton lifetime in excess of  $10^{33}$  years. Assuming there is any validity at all to the expectation of a finite proton lifetime, let us be generous and set it as  $10^{40}$  years (or about  $3 \times 10^{47}$  seconds). Having on occasion seen the number of protons in the observable universe set at about  $10^{80}$ , I shall again be lavish and estimate the proton count at  $10^{100}$ . After all, what are a few zillion protons more or less? If at some moment there are  $N_0$  protons, the number  $N(t)$  remaining at a time  $t$  later is given by the exponential decay law. On average there will be one proton left after a time interval

$$t_1 = T \ln(N_0) \sim 10^{50} \text{ seconds}, \tag{1}$$

where  $T$  is the mean proton lifetime. Wait another  $10^{40}$  years, or a total time still on the order of  $10^{50}$  seconds, and there is a fair chance that even that last proton will have decayed. Hell is now completely disintegrated, let alone frozen.

Now consider how long on average one must one wait for the gas molecules to evacuate the second compartment.

Let us assume—because it is simplest to do so and because other models will hardly make any difference in the final results—that the molecules can be treated as spherical balls of some specified radius and mass. To be concrete let the mass be that of the proton ( $1.67 \times 10^{-24}$  g) and the radius be on the order of the Bohr radius ( $1 \times 10^{-8}$  cm). It follows from the kinetic theory of gases that under the equilibrium conditions of room temperature ( $20^\circ\text{C}$ ), 1 atmosphere pressure, and a volume of 1 cubic cm, the molecules in the gas move at a mean speed of about  $10^5$  cm/s and undergo roughly  $10^{28}$  collisions per second. I arrived at this number by the following reasoning. The mean speed  $v$  (technically the root mean-square speed) of molecules of mass  $M$  can be estimated by equating the mean molecular kinetic energy  $\frac{1}{2}Mv^2$  and mean thermal energy  $\frac{3}{2}kT$ ; thus  $v \sim \sqrt{kT/M}$ . A single molecule of cross-sectional area  $A$  sweeps out a volume  $Av$  per second of travel within which occur about  $N(Av/V)$  collisions with other molecules in the container of volume  $V$ . Thus, the total rate at which molecular collisions occurs in approximately  $N^2Av/V$  per second, which yields  $10^{28}$  collisions per second.

A complete rearrangement of the approximately  $10^{19}$  molecular velocities should therefore occur about once every  $(10^{19} \text{ molecules}) / (10^{28} \text{ collisions/sec}) = 10^{-9}$  s second. However, only one in  $10^{10^{19}}$  rearrangements is likely to yield the desired configuration. Thus the time interval for the molecules to return to the first compartment would be

$$10^{-9} \text{ seconds} \times 10^{10^{19}} \sim 10^{10^{19}} \text{ seconds} . \quad (2)$$

Note that  $(10^{19} - 9)$  in the exponent is still about  $10^{19}$ . The number  $1/P(N)$  is *so* large that the time scale for complete molecular rearrangement obtained from any reasonable model of molecular collisions remains insignificant in comparison.

The time expressed in relation (2) exceeds the putative lifetime of all matter in the universe, estimated in relation (1), to such an extent that the gas molecules in the container will have long since crumbled to photons and neutrinos before totally evacuating the second compartment. Actually, the container, itself, would no longer exist. Note however, that to say that the lifetime of a proton is so many years does not mean that one must necessarily wait that long for the particle to decay. It *might* decay within the next minute although the enormous lifetime indicates that that is highly improbable. The inference of the time interval for evacuation of the second compartment must be interpreted in the same statistical way—that is, the molecules *could* all leave within the next few moments, but most likely they would not.

In contrast to the preceding system of  $10^{19}$  molecules, if the box originally contained only *one* molecule, the likelihood of ‘all’ the gas being found in the original compartment is clearly 50%, and one could expect this configuration to recur over the time interval required for the molecule to traverse the length of the container, namely in about  $1 \text{ cm} / (10^5 \text{ cm/s})$  or about 10 microseconds.

Looked at from the perspective of probability, the Second Law represents, not an absolute proscription, but rather a continuum of possibilities. When few particles are involved, the behaviour of the system is invariant under time reversal—that is, processes can occur in either direction—in keeping with the fundamental equations of motion (such as Newton’s second law or the equations of Schrödinger

and Dirac) that do not distinguish an arrow of time. When, however, the numbers of particles involved are unimaginably huge, the spontaneous transformation of a system proceeds in that direction for which the resulting molecular configuration is overwhelmingly probable, the direction in which entropy increases.

Having understood the statistical nature—and wishing to illustrate the limitations—of the Second Law, Maxwell, noted for his incisive intellect and playful spirit, proposed a mechanism that has since become an integral part of thermodynamic lore<sup>11</sup>:

[The Second Law]...is undoubtedly true as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being...would be able to do what is at present impossible to us.

And so was born the famous (or perhaps infamous) Maxwell demon. What could such a demon do?

Now let us suppose that...a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and closes this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without expenditure of work raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics.

At the time of its enunciation in the early 1870s (at the end of an elementary textbook on heat), Maxwell's little 'being' elicited little interest in several of the major thermodynamicists then alive. Clausius responded that the Second Law did not concern what heat could do with the aid of demons, but rather what it could do by itself. Ludwig Boltzmann, who contended with Clausius for priority in deriving the Second Law from mechanics, also side-stepped the problem by arguing that in the absence of all temperature differences characteristic of thermal equilibrium, no intelligent beings could form. But to discard Maxwell's demon as merely frivolous is to miss an essential point seized upon by later physicists; namely, whether or not an intelligent intervention (not necessarily a demon's) can exploit in some way the naturally occurring thermodynamic fluctuations within a system to circumvent the Second Law.

By about 1914 it was already quite clear that no inanimate mechanisms could do this. Although phenomena such as Brownian motion and critical opalescence showed clearly that large fluctuations in the thermodynamic properties of bulk matter in thermal equilibrium can be made to occur<sup>12</sup>, these fluctuations would also affect any mechanism devised to operate Maxwell's 'trap door' in a way that admitted or rejected molecules selectively. Moreover, the smaller the mechanism, the stronger would thermal fluctuations act upon it, and correspondingly the more uncontrollable would be the outcome.

The final loophole, however, that of a device operated by intelligent beings, was eliminated by the nuclear physicist Leo Szilard whose broad interests also embraced major contemporary issues in the life sciences. In a paper relating the concepts of physical entropy and information, Szilard argued that any intelligent being, even a demon, would have to make a measurement of some kind in order to exploit naturally occurring fluctuations; the very act of measuring would result in an entropy production

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<sup>11</sup>J. C. Maxwell, *Theory of Heat*, 8th Ed. (Longman, Green, and Co., London, 1885) 328-329.

<sup>12</sup>Brownian motion refers to the random movement of small particles in a fluid, for example pollen grains in water, as a result of the spatially nonuniform impacts by the molecules of fluid. Critical opalescence is the onset of a milky appearance in an initially transparent fluid at a temperature and pressure close to those for which a phase change occurs. Large fluctuations in the density, and therefore in the refractive index, of the fluid lead to substantial light scattering at all wavelengths, hence the whitish appearance.

sufficient to prevent violation of the Second Law.<sup>13</sup> The idea was carried further some twenty years later when Leon Brillouin demonstrated more concretely that a Maxwellian demon, working in an isolated system in thermal equilibrium, could not see the molecules.<sup>14</sup> Bathed in a surrounding sea of isotropic blackbody radiation, the demon could never distinguish one molecule from another without recourse to his own source of illumination—and this additional light would generate an increase in entropy.

All of this, of course, has not ended discussion of Maxwell's demon. Nevertheless, from the time of Maxwell's proposal around 1871 to the present, no one has ever found or constructed a functioning demon, and it is probably accurate to state, as did Nobel laureate thermodynamicist Percy Bridgman, 'that the entire invention of the demon is most obviously a paper and pencil affair'<sup>15</sup>.

So, what about the *Wirbelrohr*?

### **Mechanism of the *Wirbelrohr***

I withdrew my fingers quickly, shut off the air supply and stared anew at my father-in-law's present. When frost at the cold end melted and the temperature of the hot end dropped, I dismantled the device, half expecting to see some diabolical little creature inside smiling at me. Actually, it was clear at the outset that the *Wirbelrohr* could never have functioned as a Maxwell demon, i.e. in violation of the Second Law. The mere fact that the *Wirbelrohr* had to be fed compressed air signified that initial work was done on the gas. Nevertheless, how the *Wirbelrohr* converted work into such a striking difference in temperature was a mystery to me.

With the few parts of the *Wirbelrohr* laid out on my table, I understood better the significance of the German name, '*Wirbelrohr*', or vortex tube. The heart of the device is the central chamber with a spiral cavity and offset nozzle. Compressed gas entering this chamber streams around the walls of the cavity in a high-speed vortex. But what gives rise to spatially separated air currents at different temperatures? Regarding the pieces closely, I recognised immediately what had hitherto escaped my attention when I had only the story from the science fiction magazine (which scarcely made an impression on me as long as I thought it could be a hoax). Although there were indeed no moving parts of any kind, the internal geometry of the device belied the outward bilateral symmetry. The symmetry was broken by the placement in one cross-tube of a small-aperture diaphragm that effectively blocked the efflux of gas along the walls of the tube thereby forcing this part of the air flow to exit through the other arm whose cross-section was unconstrained.

The glimmer of a potential mechanism dawned on me. Had the incoming air conserved angular momentum, the rotational frequency of air molecules nearest the axis of the central chamber would be higher—as would also be the corresponding rotational kinetic energy—than peripheral layers of air. However, internal friction between gas layers comprising the vortex would tend to establish a constant angular *velocity* throughout the cross-section of the chamber. In other words, each whirling shell of gas molecules within the vortex would exert a tangential force upon the next outer shell, thereby doing work upon it at the expense of its internal energy, while at the same time receiving kinetic energy from the

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<sup>13</sup>L. Szilard, Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen, *Zeitschrift für Physik* **53** (1929) 840. The paper is reprinted together with an English translation in *The Collected Works of Leo Szilard: Scientific Papers*, ed B. T. Feld and G. W. Szilard (MIT Press, Cambridge, Mass., 1972) 103.

<sup>14</sup>L. Brillouin, Maxwell's Demon Cannot Operate: Information and Entropy. I, *Journal of Applied Physics* **22** (1951) 334.

<sup>15</sup>P. W. Bridgman, *The Nature of Thermodynamics*, (Harvard University Press, Cambridge, Mass., 1941) 161.

preceding inner shell. Energy would consequently flow from the centre radially outward to the walls generating a system with a low-pressure, cooled axial region and a high-pressure, heated circumferential region. Because of the diaphragm, the cooler axial air had to exit one tube (the cold side), whereas a mixture of axial and peripheral air exited the other (the hot side).

The presence of the throttling valve on the hot side now made sense. If the low pressure of the air nearest the axis of the tube fell below atmospheric pressure, the cold air would not exit at all; instead, ambient air would be sucked *into* the cold end—which is what I found to be the case when the valve was fully open. By throttling the flow, pressure within the central chamber was increased sufficiently so that air could exit both tubes. Thus this simple, yet ingenious, device transferred energy within its working fluid (air) by means of a mechanism incorporating no moving parts except for the fluid itself.

But even if no demon was at work, did the *Wirbelrohr* violate—or come close to violating—the Second Law? Since it involved a complex, turbulent fluid flow, the operation of an actual vortex tube could not be described strictly by thermodynamics alone. Nevertheless, with some simplifying assumptions I was able to calculate the entropy change incurred by passage through the *Wirbelrohr* of a fixed quantity of gas of known initial temperature and pressure. Under what is termed adiabatic conditions—i.e. with no heat exchange with the environment—the Second Law requires that the entropy change of the gas alone be greater than or equal to zero. The resulting mathematical expression, augmented by the equation of state of an ideal diatomic gas (air is primarily N<sub>2</sub> and O<sub>2</sub>) and the conservation of energy (First Law of Thermodynamics), yielded an inequality

$$x^f \left[ \frac{1-fx}{1-f} \right]^{1-f} \geq \left( \frac{p_f}{p_i} \right)^{\frac{2}{\gamma}} \quad (x \equiv T_c/T_i) \quad (3)$$

relating the temperature  $T_c$  of the cold air flow to the initial temperature  $T_i$  and pressure  $p_i$  of the compressed air, the fraction  $f$  of gas directed through the cold side, and the final pressure  $p_f$  of the ambient gas (taken to be 1 atmosphere). From the First Law the temperature  $T_h$  of the hot air flow can be expressed in terms of  $T_c$  and  $T_i$ .

By setting the expression for the entropy change equal to zero, I could calculate the lowest temperature that the cold tube should be able to reach if the gas flow were an ideal reversible process. The result was astonishing. With an input pressure of 10 atmospheres and the throttling valve set for a fraction  $f = 0.3$ , compressed air at room temperature (20 °C) could in principle be cooled to about -258 °C, a mere 15 degrees above the absolute zero of temperature! The corresponding temperature of the hot side would have been 80 °C. Clearly, the actual performance of the vortex tube, whose operation was by no means a reversible process, was far from any limitation posed by the Second Law. That did not make it any the less fascinating.

Intrigued to know more about the tube, I returned to the obviously nonfiction science fiction article that Fred sent me and tracked down the couple of references provided therein. The first experimental demonstration of a vortex tube seems to have been reported in 1933 by a French engineer, Georges Ranque<sup>16</sup>. Since at the time the device was the subject of a patent application, Ranque provided no drawings or quantitative analysis. Nevertheless, I was pleased to find from the general principles he enunciated that I had arrived at a broad explanation largely coincident with his own.

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<sup>16</sup>G. Ranque, Expériences sur la Détente Giratoire avec Productions Simultanées d'un Echappement d'air Chaud et d'un Echappement d'air Froid, *Journal de Physique et Radium* 4 (7) (1933) 1125.

Little more was apparently heard of this device until about thirteen years later when, after the Second World War, detailed experimental investigations of German physicist Rudolph Hilsch came to the attention of an American chemist, R. M. Milton, of Johns Hopkins University who had Hilsch's work published in English<sup>17</sup>. In Hilsch's hands, proper selection of the air fraction  $f$  (approximately  $\frac{1}{3}$ ) and an input pressure of a few atmospheres gave rise to an amazing output of 200 °C at the hot end and -50 °C at the cold end. Hilsch, who was the one (not my father-in-law) to coin the term *Wirbelrohr*, used the tube in place of an ammonia precooling apparatus in a machine to liquefy air.

What alerted the author of the science fiction article to the existence of Hilsch's work was an initially brief report in the news section of an American chemical engineering journal<sup>18</sup> in 1946. The information was apparently furnished by Milton who had visited Hilsch's laboratory and brought back (or perhaps constructed later) a small model of the vortex tube. Milton, according to the journal report, was not satisfied with the interpretation of Hilsch and Ranque that frictional loss of kinetic energy produced the radial temperature distribution. Upon requesting journal readers to submit their own interpretations, the reporter soon found himself inundated by a flood of letters from all over the world, a few excerpts of which appeared in a second report, also in 1946. Then, signing off cheerily with the hope that the information might provide a solid basis for further investigation, the reporter ceased all mention, as far as I knew, of the vortex tube.

Left with a farrago of explanations and a slim collection of old references, I looked wistfully at my *Wirbelrohr*. Did anyone really know how it worked?

### Acoustic Streaming

Faced with other more pressing matters, I put the tube aside except for occasional classroom demonstrations. Some time afterward, when the *Wirbelrohr* was all but forgotten, I experienced one of those serendipitous twists of fate that make life interesting. Standing in a corridor of a convention centre and biding my time between sessions that interested me at a physics conference, I scanned a pile of papers strewn over a nearby table. Suddenly, one of the papers, an abstract of a talk to be given (or quite possibly already given) at a different scientific society than the one then convening, caught my eye; in its title I saw the words 'Ranque-Hilsch Effect'. Upon returning home, I wrote to the first author of the abstract who kindly sent me a copy of his papers<sup>19</sup>. What was proposed therein, supported by experiment, was a mechanism far different from anything that I had seen proposed before.

According to a story often told in connection with Wolfgang Pauli, an eccentric genius whose acerbic criticism could be devastating (Ehrenfest called him 'Die Rache Gottes'—the wrath of God), Pauli presented a new theory of elementary particles before an audience including Niels Bohr. Bohr, by contrast known for his gentle qualities, could nevertheless rise to the occasion when critical remarks were required. 'We are all agreed that your theory is crazy', he allegedly replied. 'The question which divides us is whether it is crazy enough to have a chance of being correct. My own feeling is that it is not crazy

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<sup>17</sup>R. Hilsch, The Use of the Expansion of Gases in a Centrifugal Field as Cooling Process, *Reviews of Scientific Instruments* **18** (1947) 108; translation of an article in *Zeitschrift der Naturwissenschaft* **1** (1946) 208.

<sup>18</sup>R. L. Kenyon, Maxwellian Demon at Work, *Indus. Eng. Chem.* **38** (5) (1946) 5; The Demon Again, *ibid.* (12) 5-14.

<sup>19</sup>M. Kurosaka, Acoustic Streaming in Swirling Flow and the Ranque-Hilsch (Vortex Tube) Effect, *Journal of Fluid Mechanics* **124** (1982) 139; M. Kurosaka, J. Q. Chu, and J. R. Goodman, *Ranque-Hilsch Effect Revisited: Temperature Separation Traced to Orderly Spinning Waves or 'Vortex Whistle'*, Paper AIAA-82-0952, presented at AIAA/ASME 3rd Joint Thermophysics Conference (June 1982).]

enough'<sup>20</sup>. While the paper that I read was certainly not crazy, it seemed to me sufficiently strange and original to have a chance of being correct.

With a loud roar air rushes turbulently through the *Wirbelrohr*, just as it does through a jet engine or a vacuum cleaner. Buried within that roar, however, is a pure tone, a 'vortex whistle' as it has been called, that emerges from the selective amplification of background noise. Although high-pitch whistles are often associated with the swirling flow of gas in turbomachinery with rotating shafts and blades, the vortex whistle can be produced as well by the tangential introduction and swirling of gas in a stationary tube. It is this pure tone or whistle, whose frequency increases with the velocity of swirling and hence with the pressure of the compressed air, that is purportedly responsible for the spectacular separation of temperature in a vortex tube.

The Ranque-Hilsch effect is a steady-state phenomenon—i.e. an effect that survives averaging over time. How can a high-pitch whistle—a sound that, depending on air velocity and cavity geometry, can be on the order of a few kilohertz—influence the steady (or, in electric terms, the dc) component of flow? The answer, so the authors contended, was by 'acoustic streaming'. As a result of a small nonlinear convection term in the fluid equation of motion, an acoustic wave can act back upon the steady flow and modify its properties substantially. In the absence of unsteady disturbances, the air flows in a 'free vortex' around the axis of the tube; the speed of the air is close to zero at the centre (like the eye of a hurricane), increases to a maximum at around mid-radius, and drops to a small value near the walls of the tube. Acoustic streaming, however, deforms the free vortex into a 'forced vortex' within which the air speed increases linearly from the centre to the periphery, like the rotation of a rigid body. Acoustic streaming and the production of a forced vortex, rather than mere static centrifugation, engender the Ranque-Hilsch effect.

If this explanation was valid, then my own thermodynamic argument of years before had hypothesised correctly that the angular frequency of the gas molecules throughout the central chamber was constant, as this in fact was a feature of a forced vortex.

The experimental test of the acoustic streaming theory could not have been any more direct. Remove the whistle—and *only* the whistle—and see whether the radial temperature distribution remains. To do this, the authors first monitored the entire roar with a microphone and sent the resulting electrical signal to a signal analyser that decomposed it into composite frequencies of which the discrete component of lowest frequency and largest amplitude was identified as the vortex whistle. Next, they enclosed the central cavity of the *Wirbelrohr* inside a tunable acoustic suppressor: a cylindrical section of Teflon with radially drilled holes serving as acoustic cavities distributed uniformly around the circumference. Inside each hole was a small tuning rod that could be inserted fully (i.e. until it touched the outer shell of the *Wirbelrohr*) to close off the cavity, or withdrawn incrementally to make the cavity resonant at the specified frequency to be suppressed.

To simplify their experimental test, the authors sealed off one output of the vortex tube and monitored with thermocouples the temperature difference between the centre and periphery of the cavity (which was effectively equivalent to monitoring the temperature difference between the two output tubes). In the absence of the suppressor, an increase in the pressure of the compressed air produced, as I myself had noticed when experimenting with my own vortex tube, a louder roar and greater temperature difference. When, however, the acoustic cavity was adjusted to suppress only the frequency of the vortex whistle (leaving unaffected the rest of the turbulent roar), the temperature *difference* plunged precipitously at the instant the corresponding input air pressure was reached (Figure 2). In one such trial, the centreline

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<sup>20</sup>W. H. Cropper, *The Quantum Physicists*, (Oxford University Press, New York, 1970) 57.

temperature jumped upward a total of 33 °C from -50 °C to -17 °C. With further increase in air pressure, the frequency of the whistle rose and, as it exceeded the narrow band of the acoustic suppressor, the temperature difference began to increase again. Additional evidence came from a striking transformation in the nature of the flow itself, discernible with a touch of the hand. Before the frequency of the vortex whistle was suppressed—and while, therefore a significant radial temperature separation was produced in the tube—the exhaust air swirled rapidly near and outside the tube periphery in the manner expected for a forced vortex. Upon suppression of the whistle, however, the forced vortex was also abruptly suppressed, and the air, now quiescent at the periphery, rushed out close to the centreline.

So the ‘demon’ in the *Wirbelrohr* did not merely roar—it whistled, blowing hot and cold air simultaneously out different sides of its mouth. Thermodynamic analysis has shown that the Ranque-Hilsch effect is not particularly efficient at producing cold air. I have estimated the coefficient of performance, defined as the amount of heat removed from a mole of gas divided by the amount of work done on the gas, to be ideally just under unity, e.g. about 0.9, whereas the corresponding performance of a reversible machine (a Carnot heat pump) operating under the same conditions is about 5. The actual performance of Hilsch’s tubes ran at or below 0.2. But who could be so crass as to talk about the efficiency of a remarkable phenomenon?

For all I know, the case of the mysterious *Wirbelrohr* is largely closed although, science being what it is, future versions of that device may yet hold some surprises in store. I have sometimes wondered, for example, what would result from supplying a vortex tube, not with room-temperature air, but with a quantum fluid, like liquid helium, free of viscosity and friction.

The exorcism of the demon in the *Wirbelrohr* will not, I suspect, dampen one bit the ardour of those whose passion is to challenge the Second Law. Despite the time and effort that have been frittered away in the past, others will undoubtedly try again. On the whole such schemes are bound to fail, but every so often, as in the case of Maxwell’s own whimsical creation, this failure has its positive side: when, from the clash between human ingenuity and the laws of nature, there emerge sounder knowledge and deeper understanding.

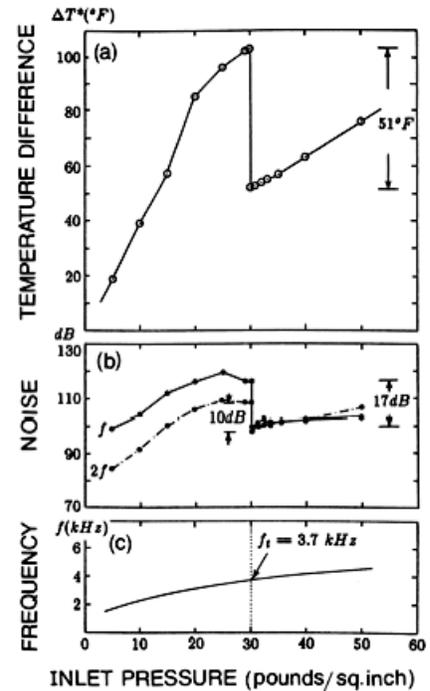


Figure 2: Relation of the vortex whistle to the Ranque-Hilsch effect. Increasing the pressure of the compressed air raises the frequency  $f$  of the vortex whistle [plot (c)]. When the frequency of the whistle corresponds to the tuned frequency  $f_t$  of the acoustic suppressor, the contribution of the whistle (and its first harmonic at  $2f$ ) to the acoustic noise is greatly diminished [plot (b)], the temperature at the centreline of the central chamber jumps upward, and the temperature difference between what is effectively the ‘hot’ and ‘cold’ pipes falls precipitously [plot (a)]. The temperature difference grows again as  $f$  is made greater than  $f_t$ . [Kurosawa *et al.* Ref 24]

### Internet Discovery: Nest of ‘True Believers’

In the years following publication of *And Yet It Moves* I had again put the vortex tube aside and concerned myself with other matters. Always curious, however, I could not help wondering in the midst of preparing the book *A Universe of Atoms, An Atom in the Universe*, whether acoustic streaming as an explanation of the hot and cold air flows stood the test of time, or whether other mechanisms had been proposed and tested. Having then at my disposal the internet, which was not available to me when I first began to write *And Yet It Moves*, I typed into my search engine a few key words and sat back in anticipation of what I would find.

I did not have long to wait—0.05 seconds to be exact. The very first item on the relatively short list of returns bore a somewhat cryptic URL (universal resource locator) with truncated, tantalising excerpts of text promising an interesting result. I clicked the hypertext title and up popped an official-looking memorandum directed to a scientific news group concerned with fusion. Fusion? What could possibly connect the vortex tube to nuclear fusion? I looked further and was even more surprised. The memorandum originated from no less a bulwark of national security than the Naval Undersea Warfare Center (NUWC) of the United States Navy. ‘Eureka’, I thought, ‘The US Navy plans to power its nuclear submarines with vortex tubes!’ I ran my eyes rapidly down the page to see the details of this exciting (and thoroughly unworkable) undertaking, and from the haunting familiarity of the text realised immediately that my speculation was conceived too hastily. There, on the screen before me, was the text of *my own book*, five laser-printed pages full of material from Chapter 6, complete with diagrams!

Apart from the thought, natural to an author, that the dissemination of his book over the internet without permission must constitute some sort of copyright infringement, I stared in amazement at the screen, wondering why the U.S. Navy was citing my discussion of the *Wirbelrohr*. In answer to my silent query, I read further<sup>21</sup>: ‘The following may be relevant to the Potapov device. It contains excerpts from “And yet it moves...strange systems & subtle questions in physics,” by Mark P. Silverman, ...’

I never heard of ‘the Potapov device’, but it did not take more than a few mouse clicks to learn all that I needed to know about it. According to one source<sup>22</sup>, it was a water-heating device developed in Moldavia by Dr. Yu. S. Potapov ‘reported to produce a heat output up to 3 times greater than the energy required to drive it.’ But why stop at a mere 300% efficiency? Another more exuberant source<sup>23</sup> proclaimed that ‘Potapov’s devices input several kilowatts of electricity into a centrifugal water pump...and gets [*sic*] out reportedly 400% to 1,000% excess power in hot water!’ Moreover, the device is available commercially and ‘hundreds upon hundreds of satisfied customers have ratified the technology in the marketplace!’ I presume that meant that a lot of Moldavians bought the device, but there is no mention of what they thought after trying it. Based on experiments reported in the first source, however, I can readily guess. ‘The Potapov device’, the experimenters reported ruefully, ‘did not show any evidence of over-unity performance in our tests. We can find no explanation for the failure of this Potapov device to perform as reported (300% over-unity).’

I can suggest an explanation: The device doesn’t work, has never worked, and will never work, and the report of ‘over-unity performance’—pseudoscience jargon for getting out more energy than one puts in—is either a deliberate fabrication or inept self-delusion. No device (like an engine or a pump) operating cyclically—i.e. returning to its original state after an operating cycle—produces more energy than it receives; to do so would violate the First Law of Thermodynamics. Moreover, the Second Law is even more restrictive; it prescribes what fraction of input energy can at best for given circumstances be converted into useful work—and this fraction is always less than 1. The only way a device could release more energy than it receives would be by tapping into the chemical or nuclear potential energy of its working material (a noncyclic process), which, in the case of the Potapov device is water.

Water (H<sub>2</sub>O) contains hydrogen atoms, and the fusion of hydrogen atoms into helium (the process that powers the Sun) releases an enormous quantity of energy. For example, the fusion of deuterium <sup>2</sup>H and tritium <sup>3</sup>H, two isotopic forms of hydrogen, to form helium <sup>4</sup>He generates a neutron and 17.6 MeV (million electron volts) of energy. One electron volt, or eV, is the energy acquired by an electron accelerated through a potential difference of 1 volt. An energy on the order of 10 eV is required to ionise

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<sup>21</sup>From: bernecky@starbase.nl.nuwc.navy.mil (W. Robert Bernecky), 1 July 1995.

<sup>22</sup><http://www.eden.com/-little/yusmar/potapov.txt>

<sup>23</sup><http://www.planetarymysteries.com/energy/ie.html>

a hydrogen atom; this is roughly the energy scale at which chemical and biological processes occur. It is indeed wonderful to contemplate the production of vast quantities of energy by hydrogen fusion, except that the Potapov device, operating (as I understood it) off room temperature water, could never do this. For hydrogen atoms to get close enough to fuse, they must overcome the repulsive electrical force or Coulomb barrier between them, and this requires a mean kinetic energy per particle of about 10 keV (1 keV = 1000 electron volts)—or a temperature of about one hundred million degrees Centigrade.

There are many out there in cyberspace, I have found, who do not like the laws of thermodynamics, or other physical laws for that matter. They regard them, not as limitations imposed by an indifferent Nature, but as barriers constructed by an arrogant scientific priesthood for the purpose of thwarting their wishes. Their diversity embraces all kinds of irrational beliefs—the denial of biological evolution, the denial of an ancient Earth, or the espousal of countless invalid schemes for generating energy out of nothing. Among the latter is a large subculture devoted to the exploitation of ‘cold fusion’, the generation of nuclear fusion at temperatures close to room temperature, usually (although not exclusively) by various kinds of electrochemical reactions. All attempts to date by credible laboratories to reproduce such claims have, to my knowledge, failed.

There is a certain irony to the ending of this essay. I began, in effect, with my father-in-law’s search through his science fiction collection for an article he once read concerning the vortex tube, and, as a consequence of my own internet search for the vortex tube, I have found the NUWC message with extensive excerpts from this essay embedded in web sites touting ‘new energy’, ‘new science’, etc. The only difference between science fiction and ‘new science’ is that the authors of the former *knew* they were writing fantasy. The authors of the latter, I suspect, do not want to know. As one such site proclaimed proudly<sup>24</sup>, it was ‘a big nasty nest of “true believers” ...and skeptics may as well leave in disgust.’

Driving away sceptics, however, will not change the reality of the physical world. Neither the Potapov device nor any other room-temperature water pump is going to generate more energy than it receives, or perform work with an efficiency greater than that permitted by the Second Law. If you don’t believe me, just ask one of those 38,000 Achnoid mutants without brain stems ... or was it one of those encephalographic carbon aliens without adenoids ... or ... whatever.

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<sup>24</sup><http://www.eskimo.com/~billb/weird/wvort.html>.