Power for sensors - Sensors for power

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ABSTRACT

As sensors are increasingly deployed in locations removed from mains power and increasingly expected to operate for times that are long compared to battery lifetimes we look to means for "harvesting" or "scavenging" energy from the sensors' operating environments. Whereas many sensors are "parametric" - their interaction with the environment causes a change in one or more of their electrical parameters - many other are true transducers - they perform their sensing function by extracting energy from their environment. These kinds of sensors can thus serve - under suitable operating conditions - both as measuring devices and as power supplies. In this paper we review this background, review the fundamental restrictions on our ability to extract energy from the environment, enumerate and summarize sensing principles that are promising candidates to double as power supplies, and provide several examples that span the range from already off-the-shelf at low cost to in laboratory prototype stage to sufficiently speculative that there might be reasonable doubt regarding whether they can actually work even in principle. Possibilities examined across this spectrum include thermal noise, ambient RF scavenging (briefly), thermoelectricity, piezoelectricity, pyroelectricity, and electrochemistry, especially including electrochemistry facilitated by microorganisms.

Keywords: sensing, sensors, power, energy, transduction, harvesting, scavenging, noise, thermodynamics

1. INTRODUCTION

It is hardly surprising that power sources can be sensors and sensors can be power sources. Sometimes power sources being sensors is intentional, sometimes it is problematic, e.g., a solar photovoltaic panel, intended as a power source, is a sensor for the insolation. Less often a sensor is found to be an unintended power source, e.g., a spark from an unintentionally-struck piezoelectric sensor might damage nearby electronics, ignite an explosive atmosphere, etc. By way of a simple example of how a sensor might deliver useful power, Figure 1 shows on the left a primary school jar-and-diaphragm barometer demonstration[1] , and on the right an arrangement whereby the indicating arm's movement can be employed to do mechanical work[2], and thus with suitable transduction, to provide electrical power.

2. BACKGROUND

Fluctuations in pressure and temperature moving bellows connected to a spring-winding mechanism via a ratchet have been in use for a long time: clocks powered by atmospheric pressure and temperature variation were built in the 17th century, and the ATMOS clock[3], patented in the early 1930s is still being manufactured. Nor are new mechanisms based on atmospheric fluctuations not being sought: for example, a very recent Physical Review Letters article[4] raised the possibility of extracting power from the Brownian motion of a graphene sheet a single-atom-thick. The old and new are illustrated side-by-side in Figure 2.

In the business of sensing and sensors it is clear that one person's problem is another person's sensor, and often another person's power source: if you are in the business of making resistors you do everything you can to minimize the sensitivity of your resistors to temperature; having learned the formulation and manufacturing factors that make resistance depend on temperature, you know how to maximize your original vexation to make and sell resistive thermometer elements. Plagued by contact potentials? Use their measurement to identify unknown metals, or to make batteries. Suffering from spurious voltages because your probe contacts are at different temperatures? Measure temperature or even generate power via the Seebeck thermoelectric effect, or move heat via the Peltier thermoelectric effect. Your Teflon insulator generates a spurious voltage forever after you subjected it to a high voltage? Make electret

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microphones, or generate power via the piezoelectric and pyroelectric effects.

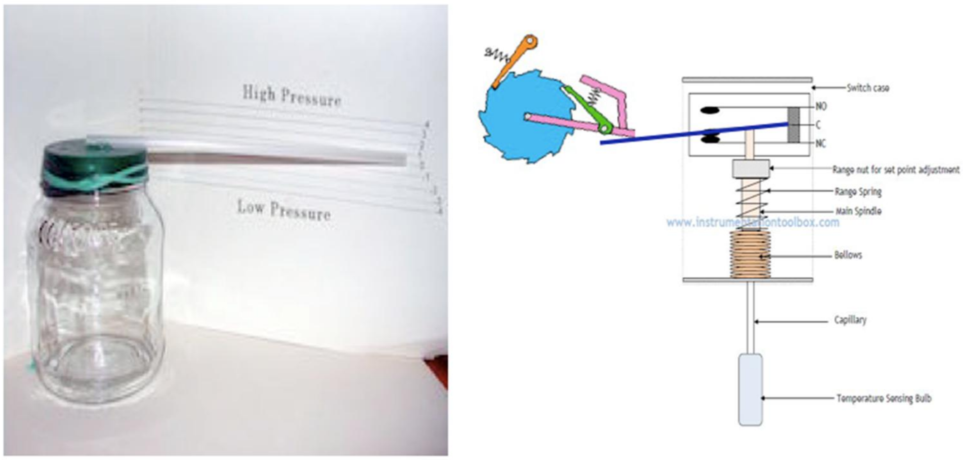

Figure 1: (left) A simple demonstration barometer made from a jar, a balloon diaphragm, and a drinking straw indicator [Ref. 1]. (right) Generating power from atmospheric pressure and temperature fluctuations: a gas or volatile-liquid filled bulb, a bellows that stretches and contracts in response to these fluctuation, a lever attached to the moving contact arm of the relay [Ref. 2], and a ratchet mechanism to create unidirectional motion from the bidirectional motion of the lever.

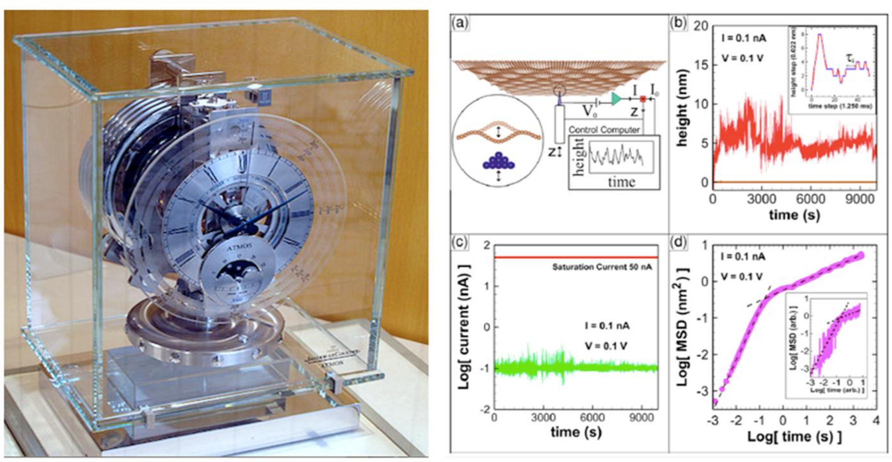

Figure 2: (left) ATMOS clock [Ref. 3]. (right) Extracting power from Brownian motion of a graphene film [Ref. 4].

3. UNDERLYING PRINCIPLES

What you *fundamentally* are allowed and not allowed to do in pursuit of power from your environment is certainly well known, but nevertheless bears repeating, especially in light of the ubiquitous availability of information - and misinformation - on the internet having possibly increased - versus decreased - advertisements for "freeing yourself from your power company's tyranny".

Nowadays nearly everyone knows that energy is conserved - they understand that fundamentally "there is no free lunch" - though it is nevertheless easy enough to meet schemes that are so complicated and intimidating that their violation of the fundamental principle - the First Law of Thermodynamics - is not immediately apparent, especially to the gullible who want to believe that it is possible to, e.g., get more energy out of than one puts into a microwave-powered discharge in water vapor. These are "perpetual motion machines of the first kind".

More subtle are the "perpetual motion machines of the second kind" - those that violate the Second Law of Thermodynamics - the principle that you cannot move heat from a colder reservoir to a hotter reservoir without putting some mechanical work into the process, and conversely you cannot extract energy from a hot reservoir and convert it to mechanical work without also transferring some "waste" heat energy to a cold reservoir.

Schemes to beat the Second Law have been around at least since Maxwell proposed a "demon" - an observer that would open a gate between two isothermal reservoirs to let through fast-moving "hot" molecules moving in one direction and slow-moving "cold" molecules moving in the opposite direction, thereby creating a hot reservoir on one side and a cold reservoir on the other side without doing any mechanical work. It is only in the last few decades that the fundamental underlying fallacy of Maxwell's Demons has been understood to lie in the cost of feeding the observer: the observer must have some sort of memory mechanism, memory is physically finite so it eventually fills up and has to be erased, and while computation is reversible, erasure is not reversible, i.e., it has an energy cost that at least balances the work potential generated by the demon's separation of heat and cold.

4. RATCHET MACHINES AND DIODE CIRCUITS

Putting this wisdom aside for the moment, we could naively believe that a "ratchet machine" or "diode circuit" might extract useful energy from an isothermal heat reservoir.

Feynman analyzed the hypothetical machine illustrated in the left part of Figure 3: a paddle wheel in one thermal reservoir is buffeted clockwise and counterclockwise with equal probability[5]. But a ratchet mechanism in a second thermal reservoir - to which the paddlewheel is connected by a common shaft - allows the shaft to rotate in only one direction. A string wrapped around the shaft between the two reservoirs can thus lift a weight, doing mechanical work. What's wrong? The picture fails to take into account the thermal "jiggling" of the pawl that prevents the ratchet from rotating in the "wrong" direction: if the two reservoirs are at the same temperature, and certainly if the reservoir containing the ratchet is at a higher temperature than the reservoir containing the paddlewheel, it won't work. However if the reservoir containing the paddlewheel is at higher temperature than the reservoir containing the ratchet it will work. But note that as the shaft turns some of the rotational energy generated by the paddlewheel is unavoidably converted heat by friction in the ratchet's reservoir, so for finite reservoirs the temperatures in the two reservoirs will eventually equilibrate and unidirectional rotation will cease.

Similarly the arrangement of resistor and diode illustrated in the right part of Figure 3, originally described and analyzed by Brillouin[6], purports to rectify - the rectifier being the electronic equivalent of the mechanical ratchet - the Nyquist-Johnson thermal noise of a resistor to deliver DC power to a load. Analogously to the case of Feynman's paddlewheel-and-ratchet, the naive analysis omits the thermal noise present in the diode: it works only if the diode is colder than the resistor, and then only until the resistor's thermal reservoir and the diode's thermal reservoir equilibrate.

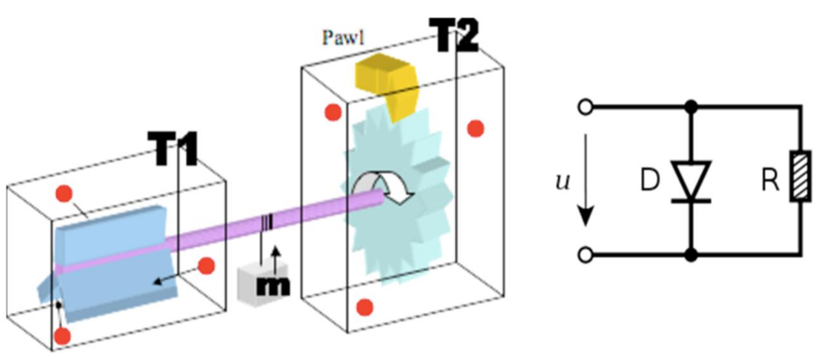

Figure 3: (left) Feynman's Ratchet-and-Pawl [Ref. 5]. (right) Brillouin's Resistor-and-Diode [Ref. 6].

5. SENSORS THAT CAN POWER SENSORS

Most readers know, but likely have not explicitly articulated, that the world of electronic sensors divides into two generally distinct hemispheres: parametric sensors - in which the sensed environmental parameter changes an electrical parameter, e.g., resistance, capacitance, or inductance - and transduction sensors - in which the signal is a voltage or a current extracted from (or sometimes delivered to) the environment along with some power over some time, i.e., energy. Parametric sensors are clearly not going to be useful as power sources, whereas transduction sensors may be, depending on the details of their operation.

Although we will not discuss them at length, to be concrete we identify some exemplary parametric sensors: thermistors - semiconductor resistors with large (positive or negative) dependence of resistance on temperature, capacitive humidity sensors - where a hygroscopic dielectric material produces the dependence of capacitance on humidity, and inductive proximity sensors and eddy-current sensors, where nearby conductors affect the inductance of a coil whose magnetic field extends beyond the physical extent of the coil. All these are generally monitored either by forcing a voltage and measuring a current or by forcing a current and measuring a voltage, or both, e.g., when an inductive or a capacitive sensor is an element in an oscillator circuit and what is actually measured is the oscillator frequency, Q-factor, etc. Parametric sensors are clearly power consumers, not power sources.

Transduction sensors extract energy from the environment - or sometimes deliver energy to the environment. If the former then at least in principle they can be exploited as power sources, e.g., to operate other sensors. We can characterize them as primarily voltage sources, perhaps but not necessarily with little ability to deliver current, current sources, perhaps but not necessarily with little ability to deliver voltage, or actual power sources from which voltage and current can be flexibly transformed. Examples include thermocouples, which produce a voltage characteristic of the temperature difference between two junctions of dissimilar conductors or semi-conductors, but which can deliver significant power, especially when multiple junctions are combined in arrays; photocells and semiconductor photovoltaics, in which incoming photon flux translates directly into electron current, providing a measure thereof, but with sufficient energy-per-electron, i.e., voltage, to deliver substantial power, as from a solar electric panel; and devices like antennas at radio frequencies, lenses at optical frequencies, suitably shaped mirrors at almost any frequency, etc, from which fundamentally power is collected and easily transformed between voltage and current (and optical analogs). Transduction sensors provide opportunities for application as power sources.

Practical examples of common devices that can do double-duty as both sensors and power sources include photovoltaic solar panels[7], whose open-circuit voltage measures incident light intensity, that can deliver current, hence power, to an electrical load at a voltage reduced by the voltage drop across its internal resistance (also see Figure 4); wind and water turbines, whose free-wheeling rotational velocity measures fluid mass flow, that can generate mechanical work or electric power at rotational velocity reduced by the torque of the mechanical load or the back EMF of the generator; radio frequency sources, intended primarily as information carries, that can be "harvested" or "scavenged" for usable power, or used in self-powered arrangements like the crystal radios popular during the early 20th century; various ways of exploiting spatial and temporal temperature gradients, some of which are mentioned briefly above and will be discussed in more detail below; and biological transducers between dietary caloric intake and mechanical output, e.g., beasts of burden, humans pedal-powering electric power generators, light from jars filled with fireflies, power from electric eels, decaying compost heaps, or the temperature gradient between clothing-covered human skin and the cold environment outside the clothing, and electric power from bacterial respiration (illustrated and discussed in more detail below).

Besides the obviously-well-developed photovoltaic panel discussed above and via Figure 4, two more that are already well developed are radio frequency (RF) harvesting[8], illustrated in Figure 5 and not further discussed here because it is already an off-the-shelf technology, albeit one less well known than photovoltaics, and vibrational energy harvesting, illustrated in Figure 9 in the section on piezoelectricity and discussed in detail there.

6. THERMAL NOISE IN RESISTORS

Thermal noise in a resistor - known as Nyquist, Johnson, or Nyquist-Johnson noise - originates in random temperature-driven spatial fluctuations of electron density, analogous to the random density fluctuations that occur in a gas volume. These charge density fluctuations generate internal electric fields, of random direction and magnitude, that are externally observed as random voltages across the resistor. The mean value of these voltages is zero, but their RMS value is not, so a correspondingly fluctuating current - the voltage divided by the resistance - in phase with the fluctuating voltage is externally available, hence power may be drawn from the resistor. Of course the RMS voltage increases (as illustrated and quantified in Figure 6) with increasing temperature[9], so net electrical power flows from the hotter resistor to the colder resistor - so if the resistors are embedded in finite hot and cold reservoirs the reservoirs will eventually equilibrate by purely electrical means - no heat conductivity is required. A typical value is about 1 mV RMS for a temperature of 600 K, a resistance to 10 MΩ, and a bandwidth of 200 kHz.

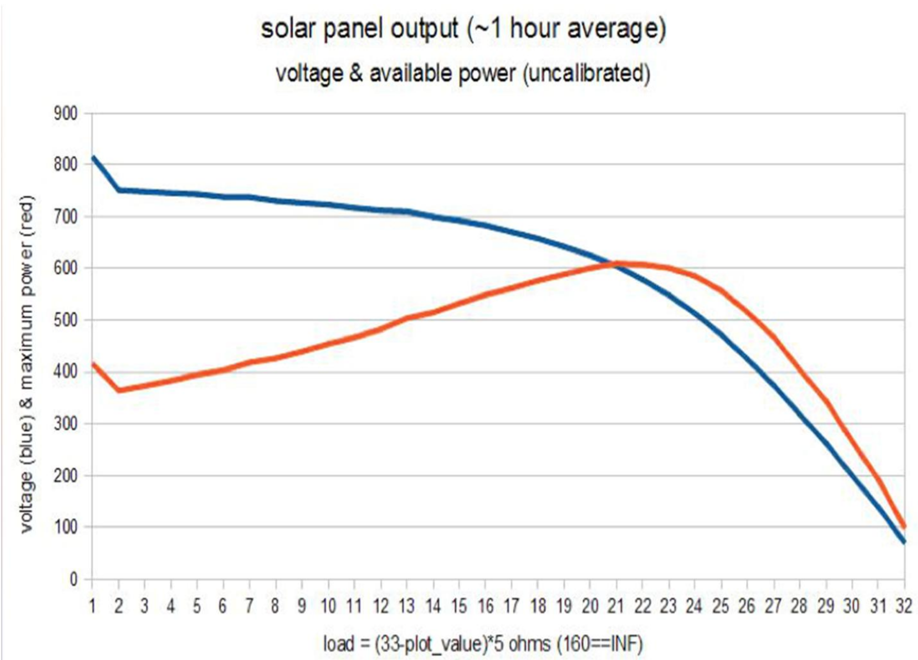

Figure 4: Solar panel voltage (blue, arbitrary units) and power (red, arbitrary units) as a function of load ("1" = open circuit, "2" - "32" = (33-"n")*5 ohm). Open circuit voltage is a measure ("sensing") of incoming solar power; peak of red curve at around 50 ohm load indicates that maximum power output occurs when voltage is about 2/3 of the maximum value measured when the panel is unloaded [Ref. 7].

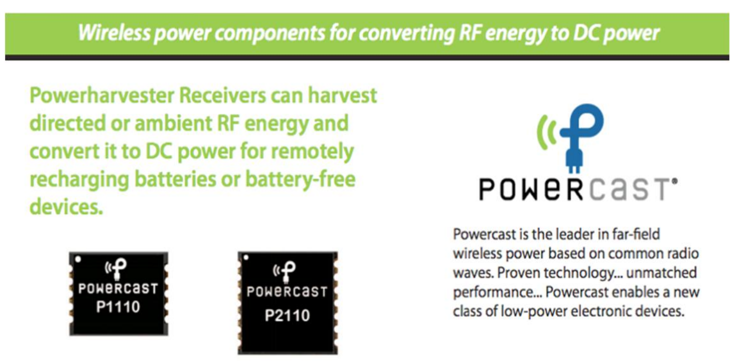

Figure 5: Off-the-shelf wireless power collection and conversion chips [Ref. 8].

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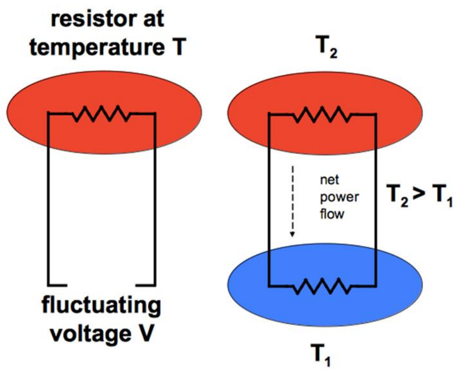

Figure 6: (left) Resistor as thermometer: thermally-induced fluctuations in charge density generate externally-detectable voltages. (right) Greater RMS voltage generated by hotter resistor result in net energy transfer from hot to cold resistor.

The RMS noise voltage is given, via thermodynamic considerations (kT/2 energy/degree-of-freedom) by

$V_{RMS} = \langle V^2_{noise} \rangle^{½} = (4\ kT\ R\ B)^{½}$

where <> denotes averaging, kT is Boltzmann's Constant times absolute temperature, and B is the bandwidth of the connection or the instrument. [Ref. 9]

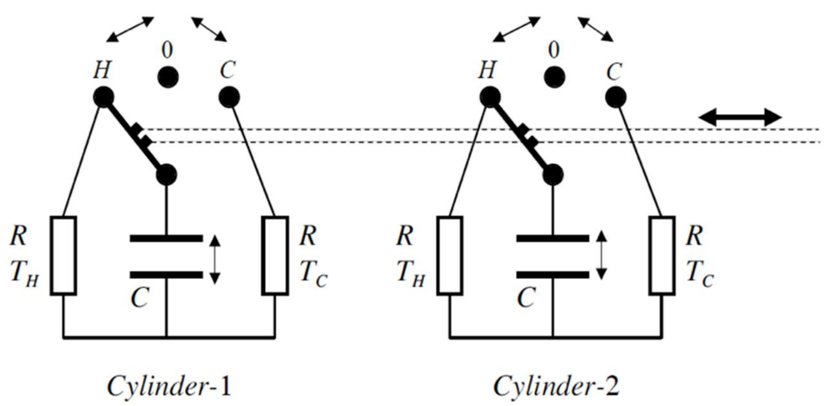

Figure 7: Scheme for extracting power from a synchronized array of capacitors charged by hot resistors and discharged into cold resistors [Ref. 10]. Because force between capacitor plates is independent of sign of charge, mechanical motions are synchronized, and can be used to generate more mechanical work than is needed to operate the synchronizing mechanism.

7. THERMOELECTRICITY, PYROELECTRICITY, AND PIEZOELECTRICITY

Three effects that connect electrical power, thermal power, and mechanical power are discussed in this section. The thermoelectric effect - the voltage that accompanies a temperature difference between two parts (usually ends of a wire) of a conductor or a semiconductor, and its inverse - the heat transfer that accompanies a current - are universal; the pyroelectric effect and the piezoelectric effect occur only in materials whose crystal or polymer units are composed of molecules with permanent electric dipole moments. In the pyroelectric effect a temporal gradient in temperature dynamically reorients the microscopic dipoles, generating a macroscopic voltage; in the inverse effect the application of a macroscopic electric field reorients the microscopic dipoles, releasing or absorbing heat. In the more familiar piezoelectric effect a macroscopic mechanical distortion of the microscopically polarized crystal or polymer generates a macroscopic voltage, and in the inverse effect application of a macroscopic voltage causes a macroscopic mechanical distortion.

The principle of thermoelectric effect is illustrated[11] in Figure 8, the principle of the piezoelectric effect is illustrated[12] in Figure 9 and an off-the-shelf piezoelectric harvester of vibration energy is illustrated[13,14,15] in Figure 10, and a MEMS implementation of a pyroelectric energy harvester is illustrated[17] in Figure 11. The thermoelectric effect is, of course, well known both in sensors and in electronic heat-pump power sources.

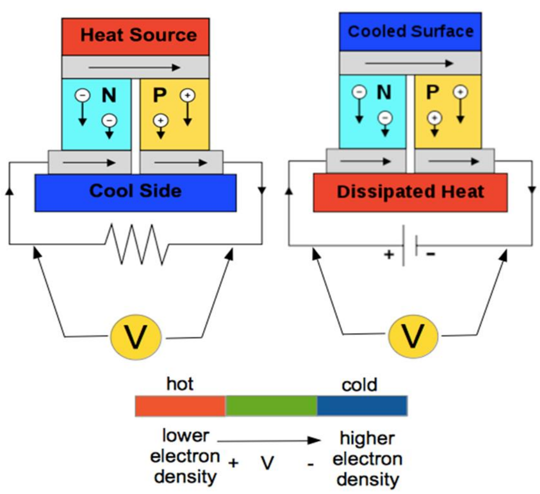

Figure 8: Two aspects of the thermoelectric effect, here illustrated in semiconductors vs. metals, but there is no essential difference [Ref. 11]. (left) The Seebeck Effect: junctions between dissimilar electrical conductors) in hot and cold reservoirs result in net voltage that measures the temperature difference and can deliver power to an external load. (right) The Peltier Effect: an applied voltage forces current through the circuit, the current carries heat from a cold reservoir ("refrigerator") to a hot reservoir ("heater"). (below) The hotter end of the conductor has a lower electron density than the colder end, generating the voltage difference between the ends.

As sensors, thermocouples are constructed of two junctions of two different different metal wires, one junction held at a reference temperature, the other at the temperature to be measured. A high-input-impedance voltmeter is inserted at a break in one of the wires at a convenient location, typically at "room temperature". Junctions of two different metals are needed because with a single metal only a brief transient current would flow before the resulting electric field opposed further current flow. Modern thermocouple-monitoring ICs incorporate phantom reference junctions, so in practice only a single junction, at the monitored temperature, is needed for proper function.

Arrays of thermocouple junctions can provide useful power at the price of cooling the hot reservoir and warming the cold reservoir. Replacing the load on such "thermopile" with a voltage source capable of delivering power, it becomes a heat pump: with the junctions in two reservoirs initially at the same temperature, one junction becomes warmer and the other becomes colder, moving heat from a colder reservoir to a hotter reservoir legally because the because the source provides the work demanded by the Second Law.

Although piezoelectricity was noticed long ago in natural crystalline materials, most piezoelectric devices today are made of polymers that incorporate molecular units with permanent dipole moments, for example polyvinylidene difluoride (PVDF). Figure 10 illustrates an IC for harvesting (among other possible source of a somewhat fluctuating voltage) vibrational energy from operating machinery, a breakout board for implementing the IC, an example of a small piezoelectric generator - the specimen is well-known in as the "tap sensor" included in kits sold for student projects with microcontrollers, but apparently it is manufactured primarily for this energy harvesting market.

Pyroelectricity is in a sense more common than piezoelectricity - 20 of the 32 three-dimensional crystal classes are pyroelectric and 10 of these are also pyroelectric - but apparently less well known. It is in some sense the temporal counterpart to the thermoelectric effect: the thermoelectric effect is a voltage developed in response to a spatial gradient of temperature, the pyroelectric effect is a voltage developed in response to a temporal gradient of temperature. However the analogy is weakened by the fact that the thermoelectric effect is universal but the pyroelectric effect is found only in crystals or polymers whose molecules have permanent dipole moments.

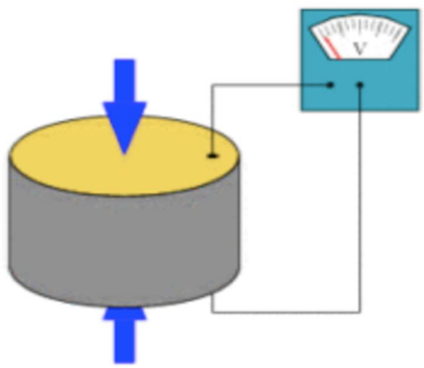

Figure 9: The piezoelectric effect [Ref. 12]: Mechanical deformation of a piezoelectric crystal or polymer rotates molecules with a permanent dipole moment, generating a voltage on the capacitance between metalizations on opposite faces of the macroscopic device; in the inverse effect, a voltage applied to the macroscopic metalization rotates the microscopic polar molecules, generating a complementary mechanical deformation of the crystal or polymer.

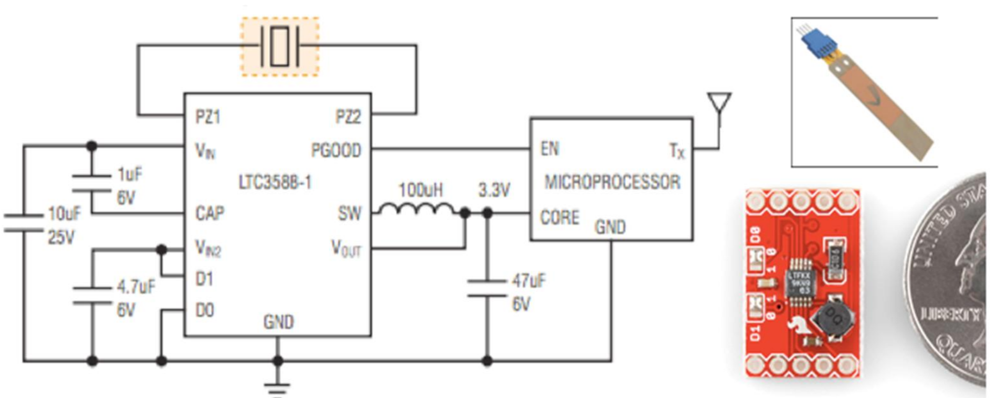

Figure 10: Low-cost IC for harvesting energy from fluctuating voltage sources [Ref. 13], IC breakout board [Ref. 14], and piezoelectric "tap sensor" [Ref. 15]. (left) Circuit diagram showing IC, external components, and piezoelectric input at top. (upper right). Piezoelectric generator, length ~2 cm long. (lower right) Breakout board with US quarter dollar for scale.

Pyroelectric sensors are often seen - but probably rarely recognized as such - in moving-warm-body-detecting switches, e.g., lighting controls for public toilets, shared meeting rooms, and back yards. These sensors are usually configured as shown[16] in Figure 11: two adjacent pyroelectric devices in electrical opposition, and an infrared lens that casts a rough image of the scene on the pair. A substantial signal is developed only when a warm object moves through the scene, producing a differential heating effect on the elements of the pair. Once the room is empty - or the graduate students are all asleep - a timer turns the lights off.

Although pyroelectric power sources are nowhere nearly as highly developed as either thermoelectric or piezoelectric sources, theoretical analyses suggest that in suitable arrangements - where a time-varying temperature difference exists naturally or can be created from static hot and cold reservoirs - their efficiencies can be high. An example of an early prototype is shown[17] in Figure 12. In this MEMS device a bimorph oscillates between a warm reservoir - for example, the effluent from a conventional power plant - and a cold reservoir. The cyclic heating and cooling of a pyroelectric capacitor integrated with the bimorph generates potentially useful electric power. Large arrays of these small devices could in principle recover much low-grade energy that is currently dumped into the environment. The referenced paper reports a mixture of experiment and modeling: prototypes were built and demonstrated mechanical oscillation between hot and cold reservoirs, but pyroelectric power generation was only modeled based on the observed thermo-mechanical performance.

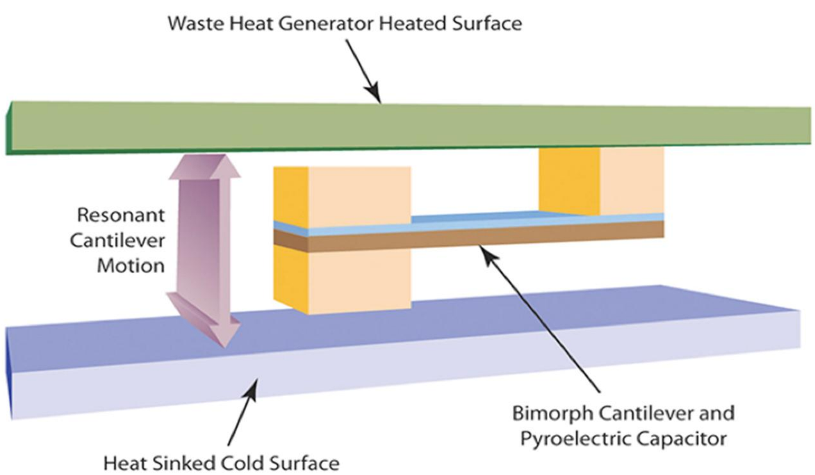

Figure 11: Oak Ridge National Laboratories MEMS device for pyroelectric extraction of electric power from waste heat source and cold reservoir [Ref. 17]. When heated the bimorph bends into contact with the cold reservoir, when cooled it bends into contact with the hot reservoir, thereby mechanically oscillating between the two reservoirs. The structure is of a mass and stiffness such that its oscillation frequency is in the AC mains power range.The consequent rapid temperature cycling of the pyroelectric capacitor generates useful electric power.

8. ELECTROCHEMICAL AND MICROBIOLOGICAL POWER SOURCES

Batteries are, of course, electrochemical sensors: their open-circuit voltage is a signature of their chemistry, from about 1.34 V for Zn/HgO batteries (now banned in most countries because of concerns about mercury toxicity) to 3.8 V for Li/CrO_2, and typically for commonly used cells around 1.5 V. In cells the anode and cathode materials are the primary determinant of the cell voltage with the electrolyte (or electrolytes) being present primarily to complete the electrical and chemical circuits. In intentional electrochemical sensors, e.g., pH and pIon probes, it is mainly the chemistry of the electrolyte that is of analytical interest. The measurement is made with a voltmeter with as high as possible an input impedance so as to draw as little current as possible, thus avoiding error due to the voltage drop across the cell's internal impedance. Nevertheless, at least in principle these sensors are potentially power sources, and it is not difficult to imagine scenarios in which small amounts of power might be drawn from them.

As noted, in most of the batteries that we use in our everyday lives the interesting chemistry goes on at the electrodes, at least one of which is consumed - reversibly in a rechargeable battery - as the battery is discharged; the electrolyte is mostly there to complete the circuits. However there are in use and in ongoing development industrial-scale flow-through batteries in which the electrodes are mostly passive and the chemical energy from which electricity is generated resides in a pair of flowing electrolytes; these power sources are sometimes thought of as crosses between fuel cells and rechargeable batteries.

There are many energy-rich chemicals in the environment that are not directly suitable for generation of electricity, but whose energy is accessible to microorganisms. Furthermore there are schemes whereby some of the charge that passes between the microorganisms and their nutrient-rich liquid environment during their respiration can be directed through a external circuit to power a load. This kind of microbial battery, via which power might be extracted by a biological intermediary from energy reservoirs - like sewage or sludge - that are otherwise inaccessible to us. One such experimental bio-battery[18] is shown in Figure 13. A key feature is the separated liquid inlets to a laminar flow channel, which allows adjacent flows without mixing - and without a membrane - of the passive electrolyte flowing over the cathode and the energy-rich electrolyte flowing over the anode. The respiration of a bacterial colony adhered to the anode, oxidizing the nutrient, provides the charge that moves as current through the external circuit, driven by the contact potential difference between the cathode and anode materials.

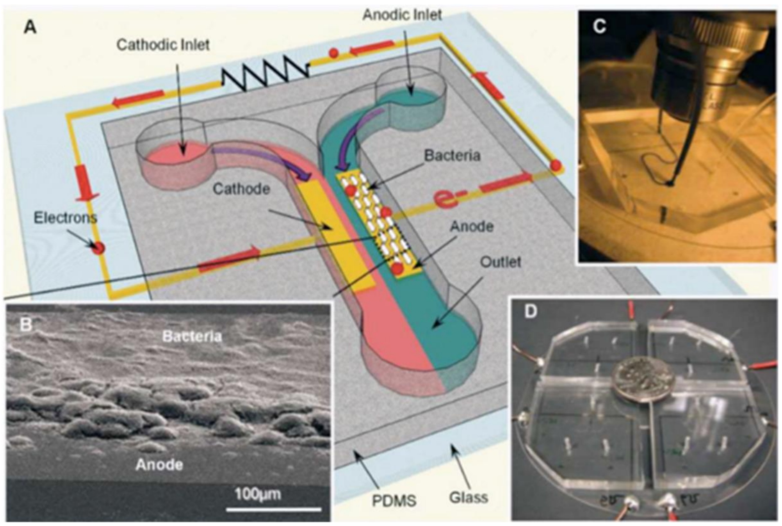

Figure 12: Micro-fabricated flow-through electric power source based on microbial respiration. (A) Laminar flow cell supporting bacterial growth and respiration on anode. (B) SEM image showing bacteria on anode.(C) Dye experiment under microscope confirming laminar flow. (D) Multi-cell array of flow-through power-generating units.[Ref. 18]

9. LESSONS

A "conclusions" section isn't the obviously appropriate way to end a survey paper like this one, but it seems rather appropriate to wrap up with a few hopefully useful "lessons" that might stay with and prove useful to the reader:

There is no free lunch: Energy is conserved, the First Law of Thermodynamics is obeyed.

There is no perpetual motion: Entropy only increases, the Second Law of Thermodynamics is obeyed.

Ratchets and diodes work: Given spatial and/or temporal temperature gradients, we can (within limits set by the Second Law) extract "harvest" or "scavenge" useful power.

Befriend a materials scientist: phenomena like thermoelectricity, piezoelectricity, and pyroelectricity occur, or occur strongly, in materials - often engineered materials - that are built out of complex molecules or complex hybrid structures of atoms or simple molecules.

Befriend a biologist: life needs energetic molecules that we can parasitize.

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