ART AND THERMODYNAMICS

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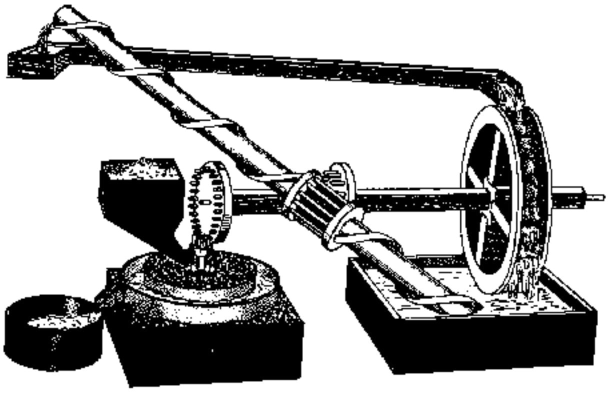

FIGURE 1. Robert Fludd's grist mill. A sophomore physics student should be able to see that his machine has no source of energy to do the work of grinding grain.

Twenty years ago I found myself with time on my hands. I lived in a place with nothing to do and no one around; and so, to keep my sanity, I plunged into study of, not art, but thermodynamics. Among the issues I vowed to resolve at this time was that of the relationship between all four laws of thermodynamics and the impossible constructions people know as perpetual motion machines. As it turned out, I could not find examples of two kinds of these machines within the engineering and science literature, and found examples only after searching through art.

1. The four laws of thermodynamics

Despite its success as a theory of physics, and its range of applicability, thermodynamics is rather simple to state. It's four laws are

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surprisingly easy to write down in plain English and very compact mathematically.[1]

(1) If two objects are separately in thermal equilibrium with a third, then they are in equilibrium with each other.
(2) Work and heat are different forms of energy. We can turn one into the other, but we can never get more of one than we have of the other.
(3) We can turn work into heat completely, but we can only turn a portion of heat into useful work.
(4) We can never reach absolute zero in any real process.

2. Searching for two kinds of machines

The study of perpetual motion machines helps to clarify thermodynamics. Examples of first kind machines, those that violate the first law of thermodynamics, are quite easy to find in the engineering and scientific literature. An example is the grist mill of Robert Fludd (Figure 1). Since these machines claim to perform work without a source of energy, there was always a financial motivation to invent them. People still invent them today. Drawings of these sometimes end up in by e-mail, along with a request for me to evaluate the invention.

Examples of machines of second kind are more difficult to find in the science and engineering literature, but pop up surprisingly often just the same. One of the best examples is the Gamgee Ammonia Motor, which was invented in the 1880s and sold to the U.S. Navy. However, a more recent example sent its inventor to prison for securities fraud. The machine combines a heat engine with a heat pump (see nearby figure).[2]

Is it important to study these machines? Some people would say "no", figuring that the epoch of these sorts of inventors is long past.[3]

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[1] The mathematical form of these laws:

$$If\, T_a = T_c\, and\, T_b = T_c\, then\, T_a = T_b \tag{1}$$

$$dU = \delta Q - \delta W \tag{2}$$

$$dS \geq 0\, or\, Q_h/Q_c \leq T_h/T_c \tag{3}$$

$$\lim_{T \to 0} (\partial U/\partial T)_P = 0 \tag{4}$$

The devil is in the details, as they say. Details in this case mean how to measure the state variables T, V, P, calculate the state functions U and S, and how to apply them to machines and processes.

[2] The would be inventor of the contraption in Figure 2 was convicted for securities violations. He sold millions of dollars of investment shares to unsophisticated people at a "free energy" fair.

[3] Ord-Hume, *Perpetual Motion, History of an Obsession*, for instance.

However, I say “yes”, for one reason that scam artists still try to sell investment in such schemes, but more fundamentally because studying each design helps illustrate the meaning of each law. We become better physicists and engineers through this study.

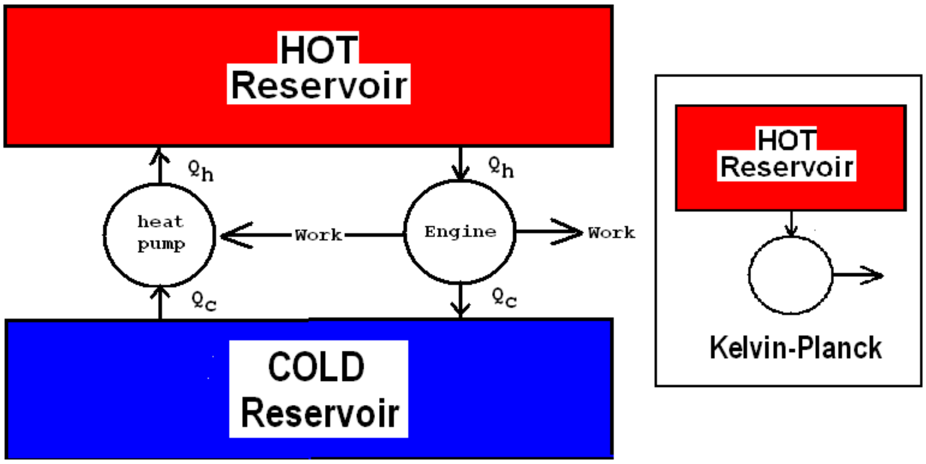

Figure 2. The perpetual motion machine combines a heat engine with a “highly efficient” heat pump (the object of development of the inventor selling shares.). On the right side of the figure is the Kelvin-Planck form of the second law which this machine violates. Kelvin-Planck states that no machine is possible that only extracts heat from a reservoir and converts it completely to work.

While I could find examples of first and second kind machines in the scientific literature, I could not find zero and third kind machines. After a few fruitless years in this search I decided to look into art. Maybe, I thought to myself, people imagined, but never tried to sell or build, these sorts of machines? In order to recognize these things, though one needs to imagine how they might look.

What would a zero law machine look like? It violates the zero law. Let’s do a thought experiment. We imagine a zeroth kind machine. A machine that does this behaves as follows. Two systems put in contact with a reservoir and allowed to reach thermal equilibrium end up not in equilibrium with one another. In other words, if they are now put into contact with one another heat will flow from one to the other. What does this mean? It means we could put a tiny heat engine between them and obtain some work. Then we could put the two into contact with the reservoir once more, restore the state of each component, and run the cycle again. I think you can see that this allows us to obtain work forever; and we do this by chasing heat around in circles.

What would a third kind machine look like? This one is really difficult to imagine.[4] It would be a machine or process in which the heat capacity failed to go to zero at very low temperature; or, more simply, a machine or process that required a temperature of absolute zero to work.

3. Examples from art

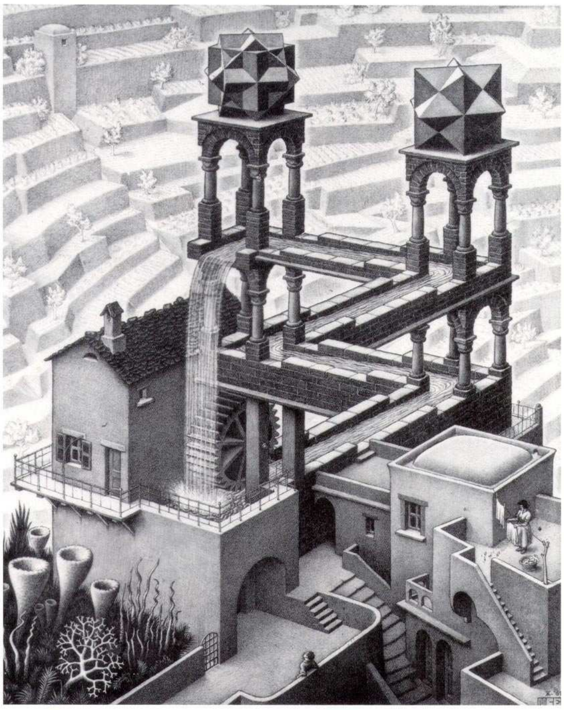

Figure 3. A perpetual motion machine of zeroth kind in an M.C. Escher woodcut. Water just goes around in circles.

3.1. A Zero Kind Machine.

If one is looking for an example of art crossing with mathematics or physics, then M.C. Escher is the artist to start with. I was not disappointed in my search. Almost immediately I came upon one of Escher's ambiguous drawings–the sort for which Escher became famous. This particular one has a waterwheel in it.

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[4] Zemansky's excellent book on Heat and Thermodynamics states that a third law machine is one free of friction or other irreversibilities. But this is not so interesting, and fails to get at some interesting speculations about third kind machines.

Unlike a real waterwheel, the water that passes over this one wanders around to somehow fill the upper reservoir again. Water flow, here, plays a role that heat does in a zeroth kind machine. It goes around in circles; flows up and down gradient for no apparent reason.

My description of this machine makes it sound almost like a Kelvin-Planck device, but the Escher drawing suggests it is like a first law machine, even though Escher's depiction shows no work output to a grist mill. When I first made my thought experiment of a zeroth kind machine I thought it seemed to violate the second law; possibly the zeroth law isn't needed, and covered by the second law. Escher's woodcut, however, made me reconsider this idea, and I now think the zeroth law might be a combination of the first and second laws.

3.2. **A Third Kind Machine.** The example of a third kind machine took many years for me to find. I can't even recall how I made the connection, in fact. I had a long plane ride to endure in spring of 1996. To keep me entertained along the way a friend had given me Carl Sagan's novel *Contact* to read. I'm not keen on Sagan, but I read the book. It wasn't so bad. The plot hinges on some advanced civilization that has received old TV broadcasts from Earth, and has retransmitted them back to us packaged with a subchannel carrying lots of information about how to make contact with them.

At some point I recognized that this cannot work without a machine of third kind–or at least without a background reservoir at zero Kelvin. The story hinges on an impossibility. In 1948, Claude Shannon, an electrical engineer and mathematician, working for Bell Labs, proved one of the most important theorems in communications theory.[5] This theorem stated that as long as the information content of a signal does not exceed capacity of the channel carrying the signal, then there is a means to encode the information to provide communications with error rates made as small as one wishes. The converse is also true; that exceeding the channel capacity leads to error rates that grow without bound. Shannon's formula for channel capacity is:

$$C = \int_{f_1}^{f_2} Log_2(1 + SNR)df \tag{5}$$

$$= BLog_2(1 + SNR)\ B = bandwidth\,(Hz) \tag{6}$$

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[5] Shannon's M.Sc. thesis, which showed an equivalence between Boolean logic and electrical circuits, is called the most important graduate thesis of the [20^{th}] Century.

where the integral is needed for communications channels where the signal to noise ratio (SNR) varies with frequency, and the second form is appropriate to a bandlimited channel with constant SNR.

Note that if the noise level is zero, then any channel has unlimited capacity. However, as a real signal, embedded in interference, expands outward from an antenna of any size (r_c), the SNR must decline as $(\frac{r_c}{r})^2$. At some distance the SNR approaches zero nearly and channel capacity approaches zero with it. But the TV signal has a fixed information rate which does not decrease with channel capacity. The TV channels of VHF broadcast, which the story involves, had a fixed bandwidth of $5\,MHz$, and although the actual information rate could be less than this value, it is still fixed at the time of transmission. At some distance this information rate must exceed channel capacity; and, beyond this distance the error rate of the receiver grows without limit. This distance is surely not so far away as the nearest star–it probably is inside our own solar system. This is why deep space probes have very low data transmission rates.

An interesting alternative explanation about SNR involves temperature. Antenna temperature is a way of expressing how bright the antenna looks to a receiver, it is not the actual temperature of an antenna. However, it does onvolve the actual temperature of the environment and background. Any receiver no matter where it is located looks at a background temperature no lower than $3 - 4\,K$–the cosmic background microwave radiation (CBM). As the signal from the transmitter antenna expands in space its intensity declines. Eventually its intensity falls below that of the pervasive CBM, and from there on error-free reception is not possible. Channel capacity would always be pertinent to this situation unless the CMB had a temperature of $0\,K$; or another way to state this is that the receiver would have to have a temperature of zero for one to not care about data rate. No matter how we look at this situation, the plot of *Contact* requires a third kind machine.

I find incomprehensible that Sagan failed to see the pertinence of Shannon's theorem to his novel, especially as Sagan had a long association with SETI–the search for extra-terrestrial intelligence; and even more so considering alternative plot vehicles available to avoid this issue. Credibility, I suppose, is really not an issue in fiction.

4. Thermodynamics as inspiration for art

A little known woodcut of Escher is among the more interesting depictions of the second law. Little reptiles come to life on the east side of the board of tesselated figures, and march from there over a book, a ramp, and a dodecahedron to the west side of the board where they reenter the tesselated pattern. The scene seems isothermal, apparently, apart from the possible gasp of steam, air, or smoke from the reptile atop the docecahedron.

What is going on here, thermodynamically? The tesselated pattern of reptiles suggests the order of a crystalline material, which we know occurs in a solid when it has shed enough internal energy to settle into a regular pattern. In other words the tesselation suggests low temperature. At least it does on the west side of the graph. On the east side however, the reptiles emerge from this low entropy state. If heat animates the reptiles, here, then it is high temperature heat because that has low entropy. Escher's prints contain more than geometric ambiguity–it has temperature ambiguity.

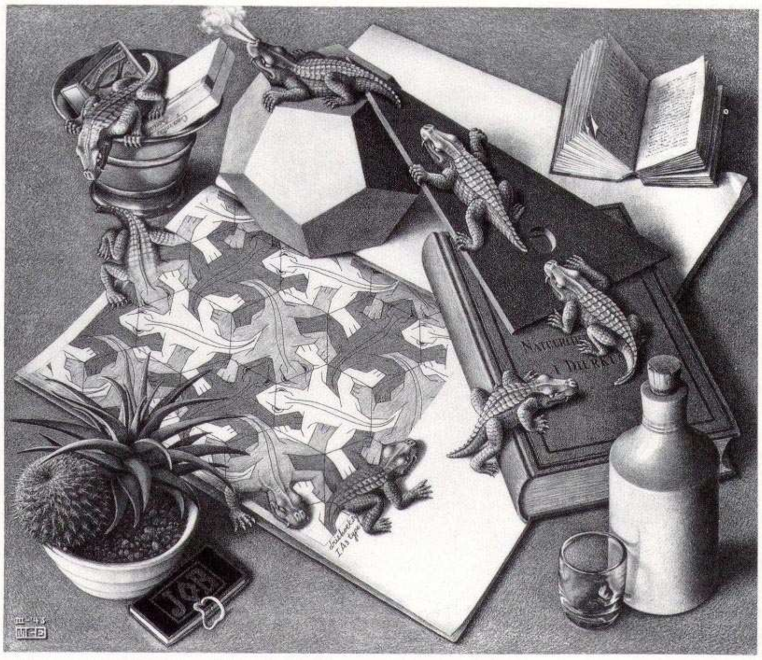

Figure 4. M.C. Escher woodcut.

A person can point to all sorts of perpetual motion machines that creep into the motion picture arts or fiction. The least interesting of these are the first kind machines. Harry Potter's broom stick for instance does all sorts of work without any obvious source of energy–as do baseballs that fly impossibly far in *The Natural.* None of these allusions are very interesting though. Violating the first law simply requires a magical element. One suspends disbelief and accepts that the magic works.

The second law provides more interesting allusions. Perhaps this is so because the second law is difficult to understand and therefore difficult to parody. Or is it because we appreciate life's limitations, most of which the second law imposses? Oscar Wilde's novel, *The Picture of Dorian Gray*, suggests a violation whereby Dorian's portrait accumulates increasing disorder in his stead without an explanation of how this could happen. I'd call it an allegorical tale of a refrigerator.

Figure 5. A portion of Winslow Homer's, The Fox Hunt, 1893. Oil, 96.5 x 174 cm (38 x 68 /2 in.). Pennsylvania Academy of the Fine Arts, Philadelphia, Joseph E. Temple Fund .

One of my favorite depictions of the second law comes from the movie *The Sand Pebbles*. In the clip I have embedded in the accompanying Power Point presentation for this talk, engineer Jake Holman (Steve McQueen) teaches coolie Po-han (Mako Iwamatsu) about the second law of thermodynamics as it applies to the ship's steam engine. Could any professor of engineering come up with a more pertinent or charming example?

In the late 19th century thermodynamics became a societal interest, strangely enough. It became so in much the way that black-holes, and strange notions of time and space became a societal interest in the

FIGURE 6. Winslow Homer, Snap the Whip, 1872. Oil, 55.9 x 91.4 cm (22 x 36 in.). The Butler Institute of American Art, Youngstown, Ohio.

1980s and after.[6] As happens often today, did this societal interest translate into a genre of painting and literature?

If so, the second law, once again seems responsible. The literature of Stephen Crane, Jack London, or William Hope Hodgson,[7] with their economy of writing, and plots involving the brutal inevitability of events brings to mind the brutal inevitability of the second law.

The transformation of previously optimistic writers and artists, though, is even more revealing. I have always been stuck by the transformation of Mark Twain from the humorous correspondent writing *The Celebrated Jumping Frog of Calaveras County* to author of the dark, brooding *The Mysterious Stranger* and absolute pessimist in *Letters from the Earth*. Paul Staiti[8] makes this same case about Winslow Homer in a puzzling thesis which is the source of the Winslow art here. Homer evolved from the creator of sweet, innocent, optimistic scenes such as *Snap the Whip* in 1872, to darker, pessimistic works such as *Hunter in the Adirondaks* in 1892, with its gloomy depiction of forest decay, *The Fox Hunt* in 1893, with its coldness of scene and apparent despiration, or *The Gulf Stream* in 1906, with its hopelessness, menace and impending doom.

Need thermodynamics have made our artists so gloomy, here? Without doubt the second law says that closed systems will evolve toward minimum availability and eventual ruin. This is, as Staiti says,

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[6] Stephen Hawking's book *A Brief History of Time.* is an example of a societal interest in space and time. In another vein all the truly awful books about global warming, some of which are written by politicians, is another example of science as societal interest.

[7] *The Ghost Pirates*, 1909.

[8] Winslow Homer and the Drama of Thermodynamics, American Art, Vol. 15, No. 1 (Spring, 2001), pp. 11-33, Published by: The University of Chicago Press on behalf of the Smithsonian American Art Museum Stable URL: http://www.jstor.org/stable/3109370 Accessed: 21/12/2009 16:09

> a characteristic that led the nonscientific community to believe in the inevitable movement of all systems, whether mechanical, chemical, and biological, or social, cultural, and human, toward fatigue, exhaustion, and entropy.

Closed systems aren't interesting to the scientist or engineer, though. Open systems, which have sufficient input of energy to continually renew themselves, maintain their vitality. Buck up everyone, there's hope.

Did the second law really inform Winslow Homer's art? Homer, himself, never said a word about it, as Staiti admits, but it could be that general horror about the second law, driven by misunderstanding about open versus closed systems, led to general pessimism among our more sensitive cohort. Yet, it isn't Homer that moves Staiti's thesis forward, but rather Henry Adams, an American novelist.

> Henry Adams was the preeminent voice of social thermodynamics. His collected essays in The Education of Henry Adams on "The Dynamo and the Virgin" (1900), "The Grammar of Science" (1903), and "A Dynamic Theory of History" (1904) were exemplary. In the 1904 essay he concluded, with thermodynamic fatalism, that "man created nothing." In "The Dynamo and the Virgin," he was famously awestruck in the Gallery of Machines at the Great Exposition in Paris, in 1900, by a steam engine producing heat from coal. His epiphany that day was the realization that the heat was not being created but merely exchanged from, as he put it, "the heat latent in a few tons of poor coal."

The novelist and social theorist has misunderstood the engineer, here. The point is not to make heat, which is so easy a cave man, literally, can do it, but to use heat to produce work, or at least the possibility of work; and, to do so efficiently. Do Homer's paintings depict thermodynamics in any way? Only a little. *The Fox Hunt* and *Hunter in the Adirondaks* both look like closed systems, but *The Gulf Stream* looks so expansive that one can only conclude it is open. There is little else to say. If Homer meant to depict hopelessness, it does not necessarily follow that thermodynamics was his inspiration. Perhaps

FIGURE 7. Winslow Homer, Hunter in the Adirondacks, 1892. Watercolor over graphite, 35.3 x 50.7 cm (13 7/ x 20 in.). Fogg Art Museum, Harvard University Art Museums.

his choice of a black man as victim suggests political and social forces, not thermodynamic ones.[9]

One final example is that of zombies which have captured the literary and cinematic imagination lately. One might consider zombies as first kind machines as they have no obvious source of energy, yet manage to work. I have no idea how zombies might gain energy, so it isn't obvious to me they are first kind machines at all. Yet, it is quite obvious that zombies are part of the dead state, and we all know, or ought to know, the second law states prohibits raising work out of the dead state. Zombies are second kind machines.

5. Conclusions

Oscar Wilde once observed that "Life imitates art far more than art imitates life." Certainly thermodynamics is too fundamental and deep to be a mere imitator of anything. However some inspiration goes both ways. Perhaps inspiration is a reversible process.

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[9] Staiti by the end of his article undoes his original thesis, by drifting off into political and social issues probably more germane to understanding Homer's state of mind.

Figure 8. Winslow Homer, The Gulf Stream, 1899. Oil, 71.4 x 124.8 cm (28 /8 x 49 /8 in.). The Metropolitan Museum of Art, New York, Catharine Lorillard Wolfe Collection, Wolfe Fund, 1906