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The origin and history of Landauer's principle is traced through the development of the thermodynamics of computation at IBM from 1959 to 1982. This development was characterized by multiple conceptual shifts: memory came to be seen not as information storage, but as delayed information transmission; information itself was seen not as a disembodied logical entity, but as participating in the physical world; and logical irreversibility was connected with physical, thermodynamic, irreversibility. These conceptual shifts were characterized by an ambivalence opposing strong metaphysical claims to practical considerations. Three sorts of practical considerations are discussed. First, these conceptual shifts engaged materials central to IBM's business practice. Second, arguments for metaphysical certainties were made with reference to the practical functioning of typical computers. Third, arguments for metaphysical certainties were made in the context of establishing the thermodynamics of information as a sub-discipline of physics.

1. Introduction

This paper charts conceptual shifts in the development of the thermodynamics of information as practiced at IBM from 1959 to 1982 (see Table 1). It begins with a careful examination of how disembodied formal concepts like information were merged with physical concepts like volume and entropy in 1959 at IBM in a discourse about the fundamental limits of computing. A logical operation called "RESTORE TO ONE" became "erasure" and was equivalent to the erasing of logical histories; these logical entities were taken to reside in physical objects or to be physical objects. Metaphorically twinned logical/physical systems moved toward forgetting information. This paper traces the genealogical origins of how computers came to forget. It elucidates a moment in the history of physics and computing when a disembodied,

theoretical concept became physical. And it displays a fundamental tension between the practical exigencies of computing and metaphysical claims. This began in the institutional context of IBM's research division from the late 1950s and 1960s. John Swanson made the transition from writing about the information stored *per symbol* in information theory to writing about information *per volume* of a computer memory device. He also shifted the concept of memory from a way of *storing* information to a delayed *transmission* of information. These two shifts allowed him to use the tools and concepts of Claude Shannon's information theory in his study of physical computer memory. Swanson's work prompted Rolf Landauer to formulate what became known as "Landauer's principle" that connected the erasure of information—a logical operation—to a thermodynamic process, dissipating heat.

These conceptual shifts were characterized by a pronounced ambivalence between strong metaphysical shifts and practical concerns. Three sorts of practical concerns can be seen to be operating in three phases throughout this conceptual development. In the first phase in 1959, there was Swanson's metaphysical assertion that information can be defined *per unit volume* rather than *per symbol* as in Shannon's information theory. This step is not singled out for special attention in his paper, but nevertheless marks a bold claim that disrupts the traditional division between abstract, logical entities and physical entities. This took place in the practical context of an analysis of ferrite core memory systems, a critical aspect of IBM's business practice. In the second phase in 1961, Landauer developed the equivalence of logical irreversibility with thermodynamic physical irreversibility. Crossing the same boundary Swanson trespassed, Landauer asserted that logical, informational "bits" could be in thermal equilibrium, and that their manipulation inevitably resulted in an increase in entropy of the computer system. The practical concern at work here lies in the fact that Landauer's discussion centered on the functioning of practical, standard computers. In the third phase from 1970 to 1982, the claimed philosophical implications of Landauer's principle were

Table 1. Three phases of the development of the thermodynamics of information at IBM.

Phase	Date	Metaphysical Claim	Practical Concern
I	1959	Information / volume	IBM's business
II	1961	Logical / physical irreversibility	Practical computation
III	1970–1982	Fundamental limits	Discipline building

strengthened and extended to all information handling in any physical system. The practical context during this phase was discipline building. Through rhetorical assertions of fundamentality and engagement with questions at the foundations of thermodynamic theory, Landauer and coworkers tried to carve out a space for their work as a sub-discipline of physics.

Landauer's principle's origin and context falls in the interstices of many areas of scholarship. It has a place in the history of information theory, the history of computing, and the history of physics. However, "interstices" is more appropriate than "intersection:" little attention has been paid to it. This is despite its central role in modern (quantum) information theory and an exponential growth of interest among physicists. A standard graduate text in quantum computing asks: What is the connection between energy consumption and irreversibility in computation? *Landauer's principle* provides the connection stating that, in order to erase information, it is necessary to dissipate energy (Nielsen and Chuang 2010, 153).

Citation analysis to Landauer's first paper on the subject shows an exponential curve, picking up speed in the 1990s (Fig. 1). This assertion of the physicality of information has been used to make grand metaphysical claims about the role of information processing in physics and even cosmology. Landauer claimed in 1967 that his work required limiting the laws of physics to quantities that computers could handle, even challenging the use of π (Landauer 1967). Charles Bennett claimed that Landauer's principle could save the Second Law of Thermodynamics from the challenge of Maxwell's demon (see below) (Bennett 1982). Tommaso Toffoli went so far as to use the physicality of information to imagine the universe as a computer. "In a sense, nature has been continually computing the 'next state' of the universe for billions of years; all we have to do—and, actually, all we can do—is 'hitch a ride' on this huge ongoing computation, and try to discover which parts of it happen to go near to where we want" (Toffoli 1982, p.165, Landauer citation, p. 171).

In the history of physics, this subject would fall under the history of solid-state physics.[1] However, the chronological range of recent work in this history has stopped just short of Landauer's work (Hoddeson 1992). In the history of computing, the foci of recent work have been on corporate, institutional, engineering, and military aspects of computing. The standard economic history of IBM mentions research little, if at all (Fisher et al. 1983). Kenneth Flamm briefly notes the turn toward research and development in the late 1950s and its importance from a business

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1. This categorization fits the intellectual content of Landauer's work—it was the field of his PhD and concerned the behavior of materials such as ferroelectrics—as well as its institutional context: Landauer was head of IBM's Solid-State Science Department.
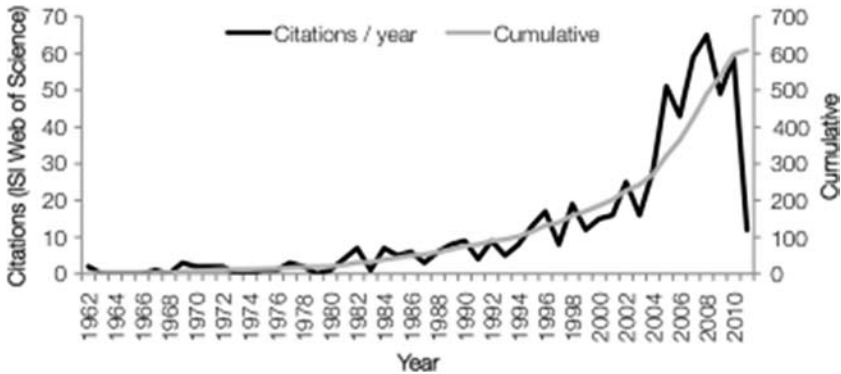
Figure 1. Citation statistics to Landauer (1961) from ISI Web of Knowledge (does not include books). Google Scholar finds 1053 total records. Analysis performed 26 April 2011.

perspective, but does not detail actual research work at the corporation (Flamm 1988, chap. 4). Where the focus has been on research it has been concentrated on the years up to the commercialization of computers in the 1950s (Ceruzzi 2003, Introduction, pp. 1–12). The history and philosophy of information theory offers more direct contact with the thermodynamics of computation. There is a literature on the history of cybernetics, addressing early military origins, its impact on twentieth-century social theory, and its practice as a science (Galison 1994; Pickering 2010; Geoghegan 2011). Perhaps most relevant to the current discussion is the work of Geoffrey Bowker, who has studied the concept of the archive in cybernetics (Bowker 1993). In Landauer and Swanson's work discussed below, the physicalization of information seems of a kind for these physicists and the cyberneticians: "something quintessentially abstract, of the mind (the ability to make hypotheses) became for the cyberneticians a physical fact of nature. Our modes of scientific practice were projected directly onto nature" (Bowker 2005, p. 82). The analogy is:

ability to make decisions : cyberneticians :: information : Landauer et al.

Though Bowker's assertion is strong, the analogy is supported by the brute manner in which Landauer et al. often simply asserted—or left implicit— the physicality of information. That is, it was more of a direct projection than the result of explicit argument (see below).

The most sustained historical and philosophical attention to Landauer et al. has been motivated by an inquiry into the Second Law of thermodynamics and Maxwell's demon. The concern is whether and how "Landauer's principle"

might be used to save the Second Law from Maxwell's demon. Briefly, the Second Law states that there is a quantity called entropy that can be calculated for physical systems; if this system is closed—i.e., does not interact with its surroundings—entropy must either stay constant or increase (Uffink 2001). What exactly Maxwell's demon is or was is rather complicated. The idea is that it is a hypothetical microscopic creature capable of manipulating thermodynamic systems such that the Second Law would be broken: the demon lowers the entropy of closed systems. Economy does not allow the introduction of the historical or technical apparatus necessary to give more detail; see the excellent introduction by Leff and Rex (in a volume dedicated to Landauer) (Leff and Rex 2003). The historical question is: How has Landauer's principle been used to save the Second Law from the demon? The philosophical question is: Have any of these attempts worked, or is it even possible? Though the purpose of this paper is not to adjudicate the philosophical debate, sustained high-quality work by John Earman and John Norton seems to have settled on two negative answers. Even champions of Landauer's work have been (partially) convinced (Earman and Norton 1999; Norton 2005; Norton 2011). It is obvious from reading Landauer's original work that he did not intend his analysis to be used in this way, so Earman and Norton's work does not invalidate the work outside discussions of Maxwell's demon. That is, if one is willing to accept the Second Law (in some context) one may happily apply Landauer's principle. In this sense, the history of the thermodynamics of information is distinct from the history of cybernetics. Cybernetics has essentially died in the physical sciences, but the thermodynamics of information is growing rapidly.[2]

2. The Physics of "Forgetting"

In this section, I will trace a discourse on the fundamental limits of computation in research and polemical articles from 1959 to 1982. At its early stages, the conceptual progression joined physical limits in machines, from Brownian motion or "noise," with information theory through Brillouin and Shannon. This connection of the physical with the informational was developed and extended to the pair: irreversible logic and irreversible thermodynamic processes, and hence to entropy. This process established what would eventually be called Landauer's principle: erasing a bit of information

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2. This paper connects to the others in this special issue by showing how concepts of noise in one context (information theory) were brought into another (physics), and how other related concepts (information) changed in the process. Swanson's engagement with Shannon's noisy channel theorems set the course for a change in our fundamental concepts and for the development of a sub-discipline.

creates kT ln2 of entropy.[3] Through this process the concepts "information," "erasure," "memory," and "forgetting" were intertwined and pushed between the disembodied and the physical.

In 1961, Rolf Landauer (1927–1999) shifted between researcher in, and manager of, the Physics Division of the Solid-State Science Department at IBM's Thomas J. Watson Research Center under construction in Yorktown Heights, NY (see Fig. 8). He was trained as a theoretical solid-state physicist (Ph.D. Harvard, 1950). Since the appointment of E. R. Piore as IBM's director of research in 1955—promoted to vice president in 1960—the culture of the corporation had been changing. "Under Piore, the corporation moved away from a strict emphasis upon product development toward support for basic research …. The scientists under Piore's direction were given unusual latitude to pursue basic research" (McCuen 2003, Background Note). Landauer characterized the late-1950s at IBM as "exploratory days."[4] In this atmosphere, a small group of theorists—including Landauer, John Swanson, Robert Keyes, James Woo and later Charles Bennett—began exploring the fundamental limits of computation. The practical motivation, alongside intellectual exploration, for their work was the rapid development of miniaturization of computing circuits (Swanson 1960; Landauer [1961] 2000). Though I will not speak of an absolute beginning, the beginning of this research at IBM was a posthumous paper by Swanson, who prepared a "preliminary and relatively complete version" of a manuscript, which was then "brought into its present form by R. Landauer" in 1960 (Swanson 1960, p. 305).

2.1 Phase I: Swanson and the Context of IBM's Business

Swanson sought "what ultimate limitations the laws of physics impose on the progress" of miniaturization. These laws are manifested as "the increasingly important effects of quantum-mechanical tunneling and thermal agitation on the reliability of a memory, as the physical system *storing* an individual bit becomes very small" (Swanson 1960, p. 305; emphasis added). It is worth pausing here to note the conceptual state of play. The laws of physics of thermodynamics and quantum mechanics are settled, and they impose on technological progress. Bits are not physical systems, they are stored in physical systems. Before a decade passed, workers at IBM asserted fundamental changes to both of these conceptual arrangements.

3. Where k is Boltzmann's constant, T is temperature, and ln is the natural logarithm.
4. Interview of Dr. Rolf Landauer by Dr. Joan Bromberg on October 17, 1984. Niels Bohr Library & Archives, American Institute of Physics, College Park, MD, USA. http://www.aip.org/history/ohilist/4726.html (Accessed 28 September 2013)

Swanson considered miniaturized "binary symmetric storage elements"—
he used the example of a ferromagnetic block of metal that was clearly meant
to stand in for the magnetic core memory IBM used, for example, in the 705
Electronic Data Processing Machine introduced in 1955. We can get a sense
of the material culture and business context underlying Swanson's analysis in
a 1955 advertising photograph of the cores alongside a pencil and a circuit-
element (Fig. 2).

According to Swanson, quantum-mechanical and thermal effects may
cause such an element to undergo a "spurious transition from one of its
states to the other." These "may lead to error in the interpretation of what
information has been stored in memory" (Swanson 1960, p. 305). At some
point, the likelihood of a fluctuation is so high that it would not be stable
enough, on average, to hold information. Though Swanson's research into
the "ultimate limits" of computation may seem detached from the business
practices of IBM, the behavior of magnetic cores was of central concern.
The importance of the new arrays of cores can be seen in their placement
in the center of the 705 manual's wonderful mid-century cover, clearly the
focus of attention (Fig. 3). It floats in its own section above other memory
storage technologies: punch cards and magnetic tape. The claims in the
705 manual were somewhat divergent from Swanson's analysis. Under
the heading "Magnetic core memory" the manual effused that:

> Magnetic cores are tiny, doughnut-shaped objects that can
> "remember" information indefinitely …. A network of ferrite

Figure 2. Magnetic core memory elements, 1955 IBM archives (VV2116) http://
www-03.ibm.com/ibm/history/exhibits/vintage/images/4506VV2116.jpg

magnetic cores is strung on screens of wire. When current is passed through a pair of wires it causes the core affected to store the data involved. Information is called out of memory by reversing the process ... (IBM 1955, p. 6)
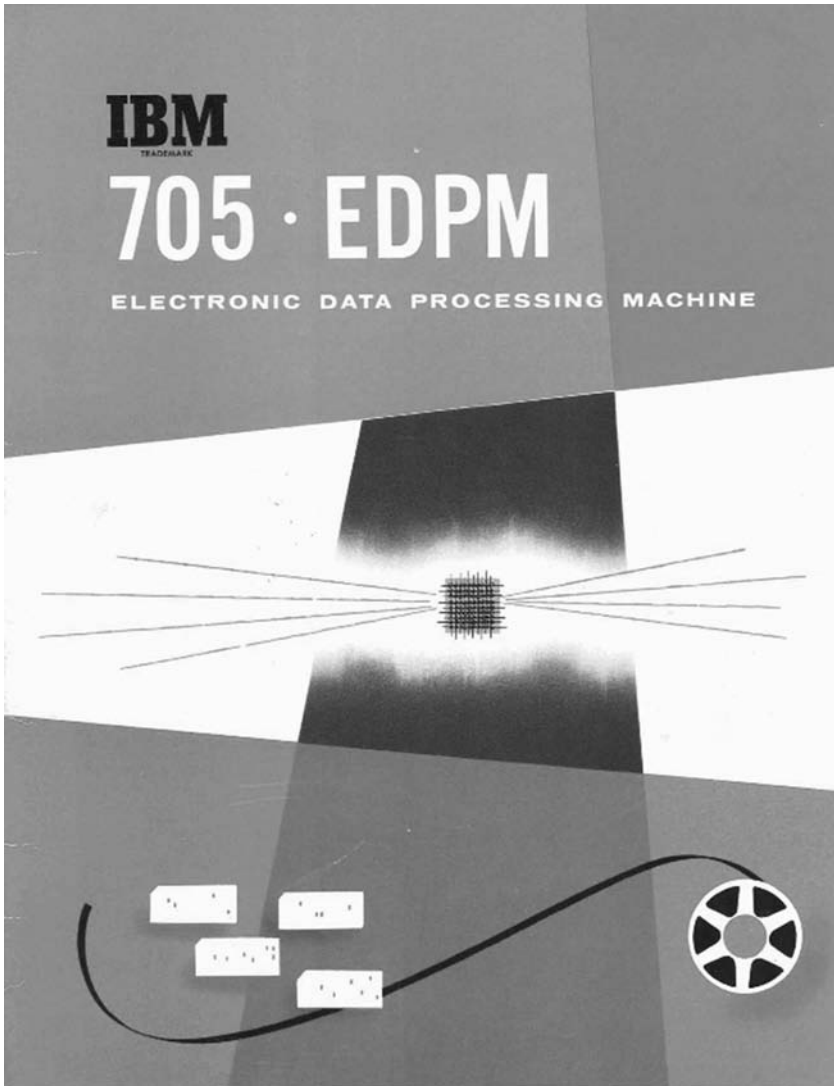

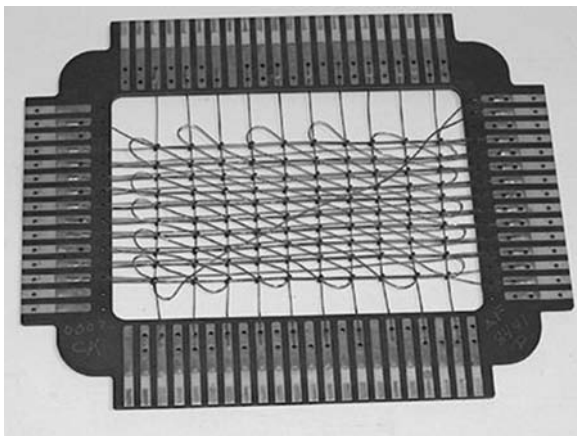**Figure 3.** IBM 705 Manual (1955), cover. Magnetic core array in center.

Figure 4. The cores are at the intersections of the wires in the center of the image (Image courtesy of Computer History Museum, Accession 102627814).

Unsurprisingly for marketing material, the manual hyperbolically represented magnetic core memory as capable of "indefinite" retention of information, a perfect artificial memory.

A ten-bit magnetic core memory plane from the IBM 702 is preserved in the collection of the Computer History Museum and is shown in Fig. 4. The grid-wiring allows information to be stored and read out of the cores in the center of the image. The looping wires allow the computer to identify which core in the array is which. Here is a simplified picture of how one bit of a ferrite-core memory functioned. Initially, the core is not magnetized. Then, a current is directed to a wire running through the center of the core causing it to be magnetized according to direction of the current. The core then has two magnetization states, up and down, according to whether the current came from the top or the bottom of the wire. By convention, one magnetization state is called 1 or ONE, the other 0 or ZERO. As long as the core retains its magnetization, the information is stored. To "read out" the information in the core, another current is passed through the wire. According to which magnetization state the core is in, the current will either be attenuated or amplified. This change in the current is interpreted by the computer as the information in the core. It is important to note that this "read out" current demagnetizes the core, *erasing* the information. The first thing the computer does after receiving the "read out" current with a ONE or ZERO signal is *re-write* the original memory core. Thus, it should be understood that information erasure was a necessary physical process in the functioning of magnetic core memory.

We move now from the material context of Swanson's work to the content of his paper "Physical versus Logical Coupling in Memory Systems"

(1960). Swanson first established the meaning of the term "physical coupling" between memory elements. Physical couplings were understood as, for example, chemical bonds between elements of the storage material. One could imagine trying to use a fleck of iron filing in place of the more-robust doughnut-shaped cores of the 705. Or the existing cores could be strung together so that they touched each other, creating a memory element twice as large. For each additional physical piece of storage unit there is a probability less than one that it will spontaneously transition from one memory state to another. As more memory states are added, therefore, the overall probability of the entire coupled system going through a transition decreases. Next, Swanson introduced a programmable, "logical coupling" between storage elements that would be mediated by computer coding. For example, a logical coupling could introduce a redundancy in the memory system such that for each memory element assigned to ZERO, say, three more surrounding elements were assigned to the same state. Again, for each additional redundant memory element, the chance of unwanted transitions decreases. A memory element and simple examples of physical and logical couplings are depicted in Fig. 5. Here a representation of a memory element "doughnut" is shown next to a string of physically connected elements along a wire which is next to a graphic indicating that the binary value of the topmost element is to be copied to three redundant elements in some way.

The connection between the physical and the logical began with Swanson's thesis that errors would be reduced by a "suitable *coupling* between the storage elements" and emerged when he defined both physical and logical coupling (Swanson 1960, p. 305). By defining these couplings, Swanson set the stage to connect the disembodied world of logic to the physical world of ferromagnets through information theory. A "[p]*hysical coupling* between *n* storage elements" was understood as "a connection such that a transition may occur if and only if all *n* elements make the same

one binary element   four logically coupled elements
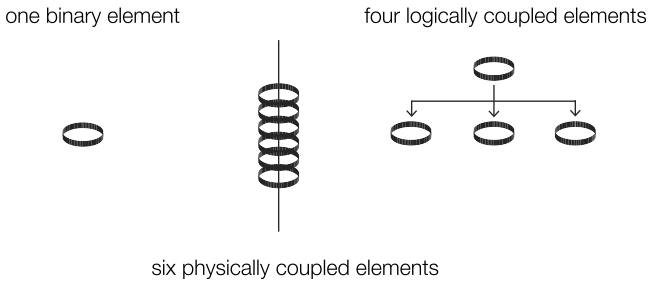
six physically coupled elements

Figure 5. Depiction of storage elements and physical and logical couplings.

transition simultaneously" (Swanson 1960, p. 305). This created new, more stable, storage elements. So, for an amount of ferromagnets to count as a storage element it must have only one domain—when some of the element switches spin orientation the rest follows.

Mathematically, Swanson's analysis of the switching of a single element proceeded by describing the transition probability as a Poisson process. A Poisson process has the characteristic that the probability P of a number of events $k=0,1,2,\ldots$, occurring in a time t is given by

$$P[k] = (\gamma t)\frac{ke^{-\gamma t}}{k!}$$

where γ is a constant. In the situation Swanson imagined, all the elements begin in one state.

$$P[k] = (\gamma t)\frac{0e^{-\gamma t}}{0!} = e^{-\gamma t}$$

The transition probability for a physical element to move from one state to another (if they are equally probable) such that for a number of elements all in one state n_0 the number of transitions to the other state is in a time, t, is:

$$n = \frac{n_0}{2}\left(1 - e^{-2\gamma t}\right)$$

where Swanson has inserted an extra factor of two in the exponent. Then the probability q of finding an element that started in one state to have transitioned to the other is

$$q = \frac{1}{2}\left(1 - e^{-2\gamma t}\right)$$

Because there are only two possible states, a double transition takes the particle back to its original position. Swanson takes the limit where γt is small to find $q=\gamma t$ and calls γ "the transition probability per unit time" (Swanson 1960, p. 306).

Swanson analyzed the "behavior of transition probabilities under physical coupling," from an "intuitive" and a "physical" viewpoint (Swanson 1960, pp. 306, 310). Here the physical viewpoint—an appendix to Swanson's paper—will be discussed, in which "one assumes a memory element to be equivalent to a particle in a potential with two minima" depicted in Fig. 6. The figure "shows the energy (or perhaps free energy) of the switching system as a function of the coordinate x being switched. A and B are the two
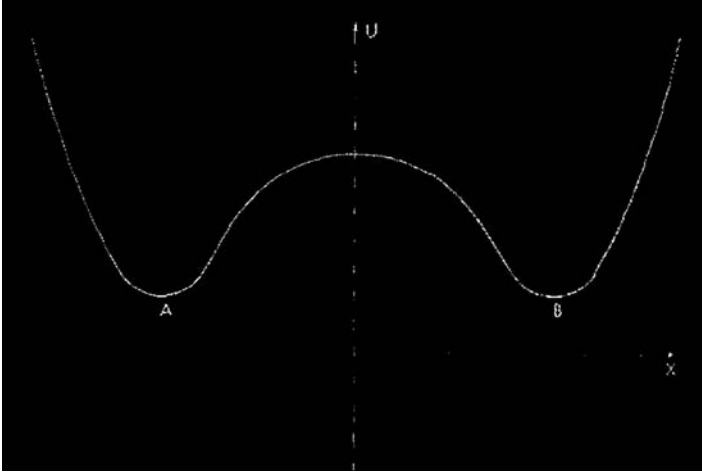
Figure 6. Swanson's figure of a double potential well (Swanson 1960, p. 310).

possible stable states denoting '0' and '1' respectively" (Swanson 1960, p. 310). Under these assumptions, Swanson argued that "the transition probability due to thermal agitation or quantum-mechanical tunneling of n physically coupled elements is proportional to the exponential of a negative constant times n" (Swanson 1960, p. 306). That is, if each memory element depicted in Fig. 5 has a characteristic constant determining the probability of random switching U, than the probability of n elements switching will have characteristic nU. His first example is of transfer by thermal agitation. "The probability for transfer from A to B by thermal agitation is then of the form $v \exp(-U/kT)$," where v is a frequency factor (typical of the well A), U is the height of the potential barrier, and kT is Boltzmann's constant multiplied by the temperature (Swanson 1960, p. 310).[5]

Swanson's more intuitive argument does not rely on the assumption of a system characterized by a one-dimensional potential graph, Fig. 6, but picks up the assumptions of the Poisson process analyzed earlier of a system characterized by a transition probability per unit time, γ. Swanson sought to find γ_n, the probability per unit time of a physically coupled system on n identical elements. Acting under the assumption that there is some

5. Swanson also wrote down the probability for quantum mechanical tunneling, but argued that if there is enough thermal scattering in the transfer that quantum coherence would be destroyed. "That is, the system after arriving in B [would] go through a considerable history before it arrive[d] once more at the portion of the barrier which permits maximum tunneling. In this period it [would] have an opportunity to interact sufficiently with other systems to lose its quantum-mechanical phase memory" (Swanson 1960, p. 310).

characteristic time τ governed the switching, Swanson asserted that the probability for switching to occur was $(\gamma\tau)^n$, making the probability per time τ

By performing the common trick of writing a quantity as its logarithm raised to an exponential,

$$\gamma_n = \tau^{-1}(\gamma\tau)^n$$

Swanson re-arranged this into

$$\gamma_n = ve^{\mu n}$$

where $v=\tau^{-1}$ and $\mu\equiv-\log_e\gamma\tau$. This is the same form as the expression for thermal tunneling above. Though Swanson leaves this obscure, in order to proceed to a general expression for the probability for switching in some general time t, one must begin again with the Poisson analysis. Swanson simply notes that he assumed $q_n = vte^{\mu n}$, $\gamma_n t \ll 1$ and wrote, skipping the assertion that the physically coupled elements must also behave as a Poisson process, just as the individual elements do.

Swanson's connection to information theory came in his discussion of logical couplings. A *logical coupling* among n elements was

> the introduction of a redundancy such that only $k(k<n)$ of the group of n elements can be adjusted in a logically independent fashion. The remaining *(n-k)* elements have their states uniquely determined [...] by a definite function of k arguments, chosen so as to make "error correction" possible. (Swanson 1960, pp. 305–6)

This was called an *(n,k)* coupling (Fig. 7). Swanson was aware that these logical couplings would have to be realized physically with machine
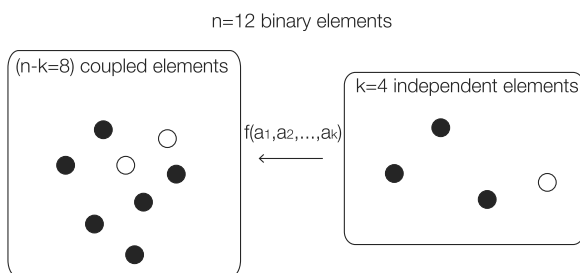
n=12 binary elements

Figure 7. An n-k coupling with $n=12$ binary (white or black) storage elements and $k=4$ independent elements. A function of k arguments determines the relationship between the k independent elements and the n-k coupled elements.

components and programmed, but he excluded these considerations from his analysis. Here, he wanted to establish the smallest n such that the probability of a transition caused by thermal agitation or tunneling is small over a length of time the memory element might be used for. By establishing a logical coupling as something that selects k states out of a possible n states, Swanson set up his analogy to Shannon's *Mathematical Theory of Communication*. Recall that Shannon introduced his theory in 1949 by stating that:

> [t]he fundamental problem of communication is that of reproducing at one point [...] a message selected at another point. Frequently the messages have *meaning*; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem. The significant aspect is that the actual message is one *selected from a set* of possible messages (Shannon and Weaver [1949] 1998, p. 31).

Thus, for Swanson "[a]n *(n,k)* coupling reduce[ed] the number of messages written upon a group of n storage elements from 2^n to 2^k." But spurious transitions re-opened the possible states to 2^n. Then "the decoding scheme consists in associating 2^{n-k} configurations with each message." Swanson then described the information state of the elements to be determined by the "specification of the message to which a given configuration belongs." Then, in analogy with physical states transitioning, Swanson defined an "error" to be a change in information state due to spurious transitions. But these cannot be logically-spurious transitions—caused, say, by errors of programming—because these do not follow probabilistic laws. Once the notion of probabilistic information state errors was in place, Swanson cited Shannon's theorem "regarding the capacity of a noisy channel" to put bounds on the "probability of an error in the information state" being introduced (Swanson 1960, p. 307). Memory became noisy.

Once the notion of probabilistic information state errors was in place, Swanson wrote $q_{n,k}$ for the probability of an error in an information state and appealed to Shannon's theorems for the capacity of noisy channels, asserting that:

$$\lim\ q_{n,k} = 0$$

as n→∞ and k varies such that, with δ a constant,

$$\frac{k}{n} \leq C - \delta$$

with

$$C \equiv 1 + q \log_2 q + (1 - q) \log_2(1 - q)$$

being the channel capacity (Swanson 1960, p. 307). Though Swanson did not provide the details of his derivation, some can be reconstructed. It is important here to distinguish the physical entropy Swanson invoked from the information entropy used by Shannon. Swanson never directly invokes Shannon's information entropy—defined per second or per symbol—however, it is implicit in the use of the channel capacity, C, above. For the case of a discrete noisy channel, Shannon defined the channel capacity as the maximum of the entropy of the source of information minus the entropy of the receiver (conditional on knowing the source).

$$C = log_2 m + \sum q_i \log_2 q_i$$

For Swanson's binary system, C can be written in terms of the number of symbols m:

$$C = Max\big(H(x) - H_y(x)\big)$$

where q_i are the transition probabilities (Shannon [1949] 1998, p. 70). Since this is a binary system, $m=2$, therefore the first term above is $\log_2 2 = 1$. And since there are only two possible states and probability is conserved the sum can be expanded as

$$\sum q_i \log_2 q_i = q \log_2 q + (1 - q) \log_2(1 - q)$$

recovering Swanson's result, the definition of C. However, I have been unable to reconstruct other aspects of Swanson's analysis. Nowhere did he specify the quantity $q_{n,k}$ or how he arrived at his inequality involving k/n.

That Swanson's noisy memory was physical—rather than some disembodied, formal, logical concept—was cemented in Swanson's discussion of "The optimum [volume of a] cell" (Swanson 1960, p. 307).

> If information is stored at time $t=0$ and read out at a later time t, we may regard the entire process as a (delayed) transmission of information, and may define a channel capacity in the sense of Shannon. However we define a capacity per *unit volume* rather than per symbol. (Swanson 1960, p. 307)

By interchanging the informational concept "symbol" with the physical concept "volume" without other comment Swanson asserted their interchangeability.

He continues, "It follows from information theory that the *information I* stored in N elements cut from a volume V [...] is

$$I = N(1 + q\log_2 q + (1 - q)\log_2(1 - q)).$$

The information per unit volume is

$$\frac{I}{V} = \frac{i}{v}(1 + q\log_2 q + (1 - q(\log_2)(1 - q))$$

with v as the optimal volume. He continued to maximize this function while varying v (Swanson 1960, p. 307). Swanson estimated that the size of his minimum element is "exceedingly small" for an information-storage time of between "a second and [...] 1000 years:" of the order of 100 elements (say, Fe atoms) (Swanson 1960, p. 309).

Swanson established the physicality of information, forming a key conceptual link between information theory and the physical quantities of thermodynamics. He established the view of computer memory as a delayed transmission of information, which could be understood in Shannon's sense as a "noisy channel." And he asserted that information could take up volume in real space, not the ethereal space of symbols of information theory. These conceptual developments set the stage of Landauer's analysis, discussed below.

2.2. Phase II: Landauer and the Context of Practical Computers

If Swanson's contribution to the connection of the logical and the physical was at the level of logical error and physical fluctuation and of information density with physical density, Landauer's 1961 "Irreversibility and Heat Generation in the Computing Process" (2000) attempted to connect logical irreversibility with physical irreversibility through information theory and thermodynamic entropy.[6] His project was notably more modest than Bennett's later reconstruction in terms of Maxwell's demon and the second law of thermodynamics. Unfortunately, Landauer's notebooks have not been preserved at the IBM corporate archives, however, there is much to be gained from a close reading of the published sources. Landauer asserted only that "we can show, or at least very strongly suggest, that information processing is inevitably accompanied by a certain minimum amount of heat generation [...] independent of the rate of the process" (Landauer

6. In thermodynamics a process is considered reversible if there is no net entropy exchange with the environment (Δ S=0).

Scanned at the American
Institute of Physics

Figure 8. Photograph of Rolf Landauer (September 1969), Niels Bohr Library and Archive, American Institute of Physics.

[1961] 2000, p. 261). However, his goal was not to demonstrate inevitable waste, instead, "the [heat] dissipation has a real function and is not just an unnecessary nuisance" (Landauer [1961] 2000, p. 261). It existed to erase information.

   Landauer's analysis centered on similar objects to Swanson's binary symmetric storage elements: "data processing equipment" with two symmetric states, like ferromagnets (Landauer [1961] 2000, p. 262). These were abstracted to consist of degrees of freedom with two possible states represented by a "bistable potential well," illustrated in Fig. 9. This visual continuity of this figure with Swanson's emphasizes their conceptual closeness. Imagining a particle in this well, Landauer considered implementing the function "RESTORE TO ONE, which leaves the particle in the ONE state, regardless of its initial location," i.e., the function does nothing if the particle is already at ONE, and applies a force to bring the particle to ONE if it begins at ZERO. RESTORE TO ONE was equivalent to erasure of information (Landauer [1961] 2000, p. 264). Landauer first considered the case where the computer can choose between two programs (exert force or not) depending on the initial position of the particle and found that with a symmetrical application of a force and a restoring force RESTORE TO ONE could be executed without energy cost. For this he imagined a dissipationless-subharmonic oscillator. As long as the computer retained a "history" of its initial conditions, logically irreversible actions—AND, say—could be performed by reversible computers. However this was "not how a computer operates. In most instances a computer pushes information around in a manner that is independent of the exact data which
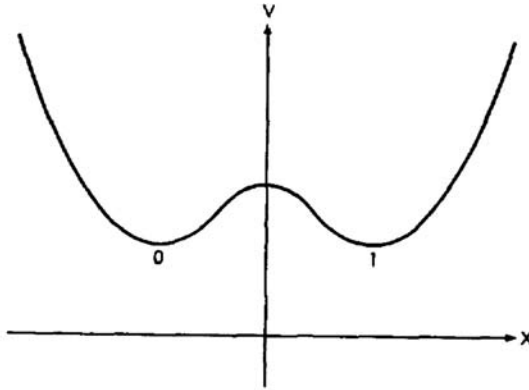
Figure 1   **Bistable potential well.**
x is a generalized coordinate representing
quantity which is switched.

Figure 9. Landauer's bistable potential well ([1961] 2000, p. 262). The v-axis is potential energy.

are being handled" (Landauer [1961] 2000, p. 262). Landauer then argued that "it is not possible to invent a single [force] which causes the particle to arrive at ONE regardless of its initial state" unless there is dissipation (Landauer [1961] 2000, p. 262). We find again the emphasis of form over content, like in Swanson and Shannon, but also ambivalence about the fundamentality of the discussion. Was this about the fundamental limits of computation, or about the limits of how standard computers operate?

Landauer provided three arguments "on three distinct levels" for the necessity of logical irreversibility that again exhibit this ambivalence between strong metaphysical claims and practical considerations. "The first level argument consist[ed] simply in the assertion that present machines do depend largely on logically irreversible steps," so that any similar machine will as well (Landauer 2000, p. 264). This was the level on which most of the paper proceeded: assuming the necessity of logical irreversibility and doing work to connect this to physical irreversibility. However, two more arguments were briefly presented (the last of which Bennett later challenged). The second argument imagined a computer that only used logical functions of one or two variables. If this machine were logically reversible, its possible truth functions would not form a complete set. Though Landauer did not use these terms, this reversible device would

thus not be Turing-complete, and should not count as a useful computer.[7] Rather, he cited Hilbert and Ackerman's *Principles of Mathematical Logic* ([1950] 1999). The third level of analysis considers more general computers that were reversible in the sense that their input could be deduced from their output. The most obvious way to do this would be to save the input of each step as part of the output, and save the bias of each operation.[8] "We will, therefore, in a long program clutter up our machine bit positions with unnecessary information about intermediate results" (Landauer [1961] 2000, p. 264). For Landauer, this was a larger problem than it may seem. He "contend[ed] that this larger machine, while it is reversible, is not a useful computing machine in the normally accepted sense of the word" (Landauer [1961] 2000, p. 265). Here Landauer made two points. First he noted that "in order to provide space for the extra inputs and outputs" setting up the reversible computer "requir[ed] knowledge of the number of times each of the operations of the original (irreversible) machine will be required." That is, each operation of the reversible computer must be thought of in advance. However, this nullified the usefulness of the machine, because a computer was "more than just a table look-up device; it can do many programs which were not anticipated in full detail by the designer" (Landauer [1961] 2000, p. 265). Landauer concluded with a second point: that in a reversible computer, bias must be set when a program is loaded, for example by "restoring a long row of bits to say ZERO," and this was

> just the type of irreversible operations [he was] trying to avoid. Our unwieldy machine has therefore avoided the irreversible operations during the running of the program, only at the expense of added comparable irreversibility during the loading of the program. (Landauer [1961] 2000, p. 265)

As demonstrated here, Landauer's claims of necessity were based on assertion and practicality, seemingly at odds with strong metaphysical claims.

Landauer used RESTORE TO ONE as an exemplar of logical irreversibility, because if you were to "run" RESTORE TO ONE backwards in time you would be unable to determine the initial condition (ZERO or ONE). He "call[ed] a device *logically irreversible* if the output of a device does not uniquely define the inputs" (Landauer [1961] 2000, p. 264). Here is the briefest statement

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7. Meaning that the computer Landauer envisioned here would not be able to simulate a Turing tape machine—it would not be a general purpose computer.

8. Bias is the initial state of the computing element—i.e., zero or one.

of Landauer's argument that connects the logically irreversible information erasure program and entropy:

> Consider a statistical ensemble of bits in thermal equilibrium. If these are all reset to ONE, the number of states covered in the ensemble has been cut in half. The entropy therefore has been reduced by $k \log_e 2 = 0.6931k$ per bit. The entropy of a closed system, e.g., a computer with its own batteries, cannot decrease; hence this entropy must appear elsewhere as a heating effect, supplying $0.6931\ kT$ per restored bit to the surroundings. (Landauer [1961] 2000, p. 265)

Before unpacking this further, it is important to note that this argument assumes the validity of a version of the Second Law of thermodynamics. The connection between the logical and the physical is in the first sentence. As for Swanson, logical/informational bits could be in physical thermal equilibrium. However, there is a puzzle in reading this as a straight application of information theory. Landauer wrote "that [his] argument here does not necessarily depend upon connections, frequently made in other writings, between entropy and information" (Landauer [1961] 2000, p. 265). If this is read strongly, I believe it is simply false; a more accurate reading is to assume that he is referring to Brillouin's connection between each act of information acquisition (measurement) and entropy. Brillouin's work on information theory was published in English in 1956 (Brillouin 1956). Brillouin was a staff member at IBM in the mid-1950s. As a pioneer of both solid state physics and information theory, Landauer would have been familiar with his work. As discussed above, Landauer argued that information can be acquired (but not erased) without entropy cost. Instead "[w]e simply think of each bit being located in a physical system, with perhaps a great many degrees of freedom, in addition to the relevant one" (Landauer [1961] 2000, p. 265).

In the crucial association of bits of information with thermal processes, the metaphor of forgetting first appears. Landauer imagines an assembly of bits that is "somewhat equivalent to an assembly of spins […]. In thermal equilibrium the bits (or spins) have two equally favored positions" (Landauer [1961] 2000, p. 265). If spins in a ferromagnetic lattice are all magnetically aligned and placed next to some material, when you remove the magnetic field the spins will become disordered, taking entropy from the material and cooling it ("magnetic cooling"). "An assembly of ordered bits would act similarly. As the assembly *thermalizes and forgets* its initial state the environment would be cooled off [emphasis added]" (Landauer [1961] 2000, p. 265). Once the assembly of bits—information—is thought to be "simply" in a physical system, erasure becomes thermalization and

forgetting. This forgetting actively cools a system. In this framework, "[i]n carrying out the RESTORE TO ONE operation we are doing the opposite of the thermalization" (Landauer [1961] 2000, p. 265), creating heat rather than absorbing it. Disembodied concepts of logic and information are pushed onto nature, and nature gained the human capacity to forget.[9]

And what does nature forget? A peculiar notion of information. The maximum possible entropy shift comes when RESTORE TO ONE is fed a random sequence of ONEs and ZEROs; these carry the "maximum possible information," and therefore the largest entropy exchange. (Of course, a person may find random static over a phone line to carry less information than some tightly correlated string of words.) In contrast, there is no entropy change if RESTORE TO ONE is fed only ONEs or only ZEROs, for these "carry no information" (Landauer [1961] 2000, p. 265). I think of the opening scenes of Tom Stoppard's *Rosencrantz and Guildenstern are Dead* where the titular characters begin tossing coins, and always finding heads—it is not interpreted as nothing. From the 1990 film version that Stoppard directed:

> It must be indicative of something, besides the redistribution of wealth.
> Heads.
> A weaker man might be moved to re-examine his faith, for nothing else at least in the law of probability.
> Heads.
> Consider. One, probability is a factor which operates within natural forces. Two, probability is not operating as a factor. Three, we are now held within sub- or super-natural forces. Discuss!

A scientific example: if an epidemiologist had an array of binary systems, say disease cultures that either show infection or do not, and found thousands of "not infected" results in a row it would not be "no information," it would indicate a disease-free population; a triumph. Just as we have technical reasons to object to the merging of thermodynamics and information theory, we easily find that this logical information is not human information.[10]

Landauer returned to the "question whether the entropy is really reduced by the logically irreversible operation" (Landauer [1961] 2000,

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9. C.f. "something quintessentially abstract, of the mind (the ability to make hypotheses) became for the cyberneticians a physical fact of nature. Our modes of scientific practice were projected directly onto nature" (Bowker 2005, p. 82).

10. For example, you cannot form a *canonical* statistical ensemble over microstates with discrete probability distributions, as in $\rho = 1/2$ ONE$+1/2$ ZERO, and so cannot define an "information" entropy that matches thermodynamics entropy (Norton 2005).

p. 266). Perhaps even after RESTORE TO ONE there is some difference between states that were once ONE or ZERO that the computer could use to find each initial state? Landauer claimed that keeping these histories over repeated machine cycles would make the computer useless as more and more resources were devoted to them. Or, the differences would be so great as they propagated through the system that they would overwhelm the original signals, and ONE and ZERO could not be told apart. "[W]e cannot tolerate a cumulative process, in which differences between possible ONE states become larger according to their detailed past histories" (Landauer [1961] 2000, p. 266). These histories must be forgotten. Landauer concludes with a caveat about the realism or applicability of his analysis that reinforces the purpose of heat dissipation/erasure. He has sought the "absolute minimum" dissipation required for computation, but "[a]ctual devices which are far from minimal in size and operate at high speeds will be likely to require much larger energy dissipation to serve the purpose of erasing the details of the computer's past history" (Landauer [1961] 2000, p. 268).

2.3. Phase III: Landauer, Keyes, Woo, Bennett and the Context of Discipline Building

Almost a decade later, Landauer (with Robert Keyes) defended his earlier paper against critical comments from M. S. Neyman, and proposed a new physical model of coupled particles in potential wells to analyze "Minimal Energy Dissipation in Logic" (Keyes and Landauer 1970). This delay may have been due to the intensification of Landauer's managerial work in the intervening years. In 1962 he was promoted to IBM's Director, Physics and Chemistry and in 1966 to Assistant Director of Research at Yorktown Heights. However in 1969 Landauer was made an IBM Fellow, allowing him more latitude to direct his activities.[11] Landauer and Keyes maintained Landauer's earlier focus on information transmission and information theoretic "noise." Computers still necessarily had energy dissipation sources, thus they had internal noise sources. "A very basic and important question then becomes, Is computing to an arbitrary reliability specification possible, or is there an irreducible error probability?" (Keyes and Landauer 1970, p. 152). Keyes and Landauer argued from "general statistical mechanics considerations" that there were "no obvious reliability limitations to the computing process" (1970, p. 152). Landauer and Keyes saw their work as contributing to a growing sub-discipline, focusing on

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11. "Background for Rolf W. Landauer Interview," [n.d., post-1976] IBM Corporate Archives LS-119, Central Services Building. Route 100 Somers, NY 10589 USA (hereafter IBMCA), THP/MF/People/Landauer/B109/F24.

the physical limitations of computation and with philosophical scope. "Studies of the ultimate physical limitations of information handling, even though they are still in a very rudimentary state, constitute the beginning of a genuine physical science of epistemology" (Keyes and Landauer 1970, p. 152).

Landauer (now working with James Woo) returned to this topic again in 1971, though not in his regular venue. His previous technical work on energy dissipation has been published in house in the *IBM Journal of Research and Development*. While he certainly published in other places on different topics, his 1971 paper in the American Institute of Physics' *Journal of Applied Physics* was his first foray with this material in a broader physics-publishing context.[12] The paper introduced a hypothetical computing device consisting of particles in potential wells coupled through springs. Landauer and Woo investigated this system to establish the minimal dissipation of energy and the maximal error used in computation. Though the technical details of this paper are not relevant to this discussion, it provides a window into how Landauer thought of his field and how he is seen today (i.e., by Bennett) as the foremost person responsible for making his sort of analysis acceptable in physics. Landauer and Woo began the paper with strong rhetorical assertions of the importance of this work:

> Information processing *inevitably* requires the use of physical degrees of freedom to represent information. This leads to *fundamental* limitations on the handling of information (Landauer and Woo 1971, p. 2301; emphasis added).

They continued, noting some review papers Landauer presented at conferences.[13] However in the same initial paragraph we are pointed to some friction with a referee. "As a result of a specific request by the referee, however, we will repeat some key points" (Landauer and Woo 1971, p. 2301). They proceeded to lay out their "field," which studies these fundamental limitations.

> The limits, however, that we have begun to understand are a great many powers of ten away from current technology, and therefore relatively useless as a guide for the technologist.[14] What we are doing

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12. This is confirmed up to 1968 in Landauer's IBM Fellow citation. "Citation" [n.d., 1969?] IBMCA IBM Fellows/Landauer, R., [8]–[10].

13. These do not appear to have been actually published, and are not preserved in Landauer's archive.

14. "Technologist" should not be taken as disparaging; Landauer considered himself, at least in aspects of his work, a computer technologist.

in this field, instead, is to understand the ultimate limitations on information handling, whether carried out in a computer, in biological systems, or in any other system. Thus we are asking about the physical restrictions on operations which the mathematician and logician normally (and in our opinion quite incorrectly) assume do not necessarily require a physical embodiment. (Landauer and Woo 1971, p. 2301)

Not only did Landauer and Woo's work deal with the inevitable and fundamental limitations on information processing, they are the "ultimate limitations"; in scope, they could not be more general, encompassing all systems. They argued against the incorrect assumptions of their detractors. As the paper was evidently accepted for publication, we may assume that this rhetorical strategy contributed to assuaging the reviewer's (and/or editor's) concerns.

Landauer and Woo depicted their field as divided among two parts. The first is focused on "memory, i.e., the portion of a computer whose sole function is to retain information in undeteriorated form" (Landauer and Woo 1971, p. 2301). Though he is not cited, it is safe to assume the Swanson's work was being implied here. However, in their paper Landauer and Woo were "concerned more explicitly with the elementary logical operations carried out in a computer, i.e., with the interaction of information streams" (Landauer and Woo 1971, p. 2302). And while they do not explicitly invoke "forgetting," they do reaffirm Landauer's connection between logical and physical irreversibility and vividly invoke the necessity of erasing information. "Computers require the ability to discard information; otherwise they will choke on their intermediate results. This logical irreversibility can be linked to physical irreversibility and heat generation" (Landauer and Woo 1971, p. 2302).

Charles H. Bennett is and was also a researcher at the IBM Watson Research Center. He received his Ph.D. from Harvard in the computer simulation of molecular motion in 1971, and joined IBM in 1972. He has been one of the most active scientists working in Swanson and Landauer's footsteps. In an obituary for Landauer he is quoted as saying "Rolf Landauer did more than anyone else to establish the physics of information processing as a serious subject for scientific inquiry" (Johnson 1999). He was active in developing conceptual computers that were *reversible*, and advanced an information-theoretic view of biological processes, particularly those involving DNA. In an influential review article in 1982 he connected Landauer's principle to the second law of thermodynamics explicitly. In 1973 he published a paper in the *IBM Journal of Research and Development* on the logical reversibility of computation (Bennett 1973). Though this may seem counter to Landauer's work, Bennett does

not challenge Landauer's conclusions, considering the systems that his co-worker analyzed. Rather, Bennett imagined a novel computer that would record its history as it calculated.

> An irreversible computer can always be made reversible by having it save all the information it would otherwise throw away. For example, the machine might be given an extra tape (initially blank) on which it could record each operation as it was being performed […]. However, as Landauer pointed out, this would merely postpone the problem of throwing away unwanted information […]. (Bennett 1973, p. 525)

How is it possible to avoid erasing the tape? By exploiting a "subtle redundancy" between the machine and its history tape.

> Now, a tape full of random data cannot be erased except by an irreversible process: however, the history tape is not random—there exists a subtle redundancy between it and the machine that produced it, which may be exploited to erase it reversibly. (Bennett 1973, p. 526)

Bennet proposed that the machine simply be run backwards, using the "history tape." "Since the forward computation was deterministic and reversible, the backward stage would be also" (Bennett 1973, p. 526). But there is a problem here. "Unfortunately, the backward stage would transform the output back into the original input, rendering the overall computation completely useless" (Bennett 1973, p. 526). Fortunately, Bennett saw a solution: midway between the forward and backward stages, print out another tape with the result of the forward calculation. Then there would be three tapes: input, history, and output. And reversible computation was possible at the price of some extra tape and time for extra computing steps.

Bennett continued his paper with a formal logical proof that his machine could emulate the activities of any Turing complete computer, the details of which are irrelevant here. He did include a brief discussion of physical as opposed to logical reversibility later in the paper. This laid the ground for his later review paper which included thermal computers and biological examples.

> An obvious approach to the minimizing of energy dissipation is to design the computer so that it can operate near physical equilibrium. […] At first sight this may seem impossible […]. However, nature provides a beautiful example of a thermally activated 'computer' in the biochemical apparatus responsible for the replication, transcription and translation of the genetic code. (Bennett 1973, p. 531)

In 1982 Bennett published "The Thermodynamics of Computation—a Review" which discussed developments in reversible logic (in terms of branching); reversible computation such as "Ballistic" and "Brownian" computers (including DNA-as-computer, and a "Brownian Turing Machine"); "algorithmic entropy and thermodynamics;" and "reversible measurement and Maxwell's demon." I posit that the writing of a review article itself was an act of disciplinary-building. It was an attempt to consolidate disparate individual articles into a unified whole, under the rubric of the "thermodynamics of computation." Bennett began the review with an assertion of the connection between logic and mathematics and computation: "The digital computer may be thought of as an engine that dissipates energy in order to perform mathematical work" (Bennett 1982, p. 906). Bennett claimed heroes of physics as predecessors—von Neumann, Brillouin, Szilard—while establishing the naturalness of studying the fundamentals of these systems. "Early workers naturally wondered whether there might be a fundamental thermodynamic limit to the efficiency of such engines" but of course these early workers, impressive though they may be, were wrong. Their "conjectures have a certain plausibility […] [h]owever, it is now known [… etc.]" (Bennett 1982, p. 906). The greats of the past are wrong in the present, and Bennett would show why.

Discussions of Maxwell's demon are notoriously unclear and difficult to navigate. Let alone the demon's entropic machinations, there is not yet a consensus on what the Second Law of thermodynamics is! (Uffink 2001). Earman and Norton provide an excellent technical discussion of this history (Earman and Norton 1998, 1999). They note that the demon was originally invoked as a thought experiment about containers of an ideal gas to establish the limits of applicability of Boltzmann's Second Law, but that the debate quickly became about how to find a mechanism to show that the Second Law is universally applicable. The demon need not be anthropomorphic (e.g., Smoluchowski's trap door), but information theoretic analyses first conjure a demon with a mind and then replace that mind with a computing device. Until Bennett the debate was focused on entropy generated by the demon acquiring information about gas molecules. He redirected this to focus on the demon's forgetting this information. For Bennett it was forgetting that "saved" the Second Law.[15]

This paper has not been focused on the technical dimensions of this work, and so only Bennett's descriptive, introductory paragraphs will be quoted. His demon was "an organism or apparatus that, by opening a door between

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15. The present state of the debate appears to acknowledge that Landauer's principle of entropy generation by "forgetting" follows from the Second Law, and cannot "save" it (Bennett 2003; Norton 2005; Ladyman et al. 2007).

two equal gas cylinders whenever a molecule approached from the right, and closing it whenever a molecule approached from the left, would effortlessly concentrate all the gas on the left, thereby reducing the gas's entropy by Nk ln2" (Bennett 1982, p. 927). "The second law forbids" this unless there is "a corresponding entropy increase elsewhere in the universe."

> It is often supposed that […] the measurement the demon must make to determine [if the molecule is coming from the left or right] is an unavoidably irreversible act, requiring an entropy generation of at least k ln2 per bit of information obtained, and that this is what prevents the demon from violating the second law. In fact [these measurements] can be made reversibly, provided the measuring apparatus (e.g., the demon's internal mechanism) […] does not overwrite information previously stored [on a history tape]. Under these conditions, the essential irreversible act, which prevents the demon from violating the second law, is not the measurement itself but rather the subsequent restoration of the measuring apparatus to a standard state in preparation for the next measurement. This forgetting of a previous logical state […] entails a many-to-one mapping of the demon's physical state, which cannot be accomplished without a corresponding entropy increase elsewhere. (Bennett 1982, p. 927)

This is certainly a different relationship to the Second Law than was found in Landauer's original paper, which assumed its validity. However, like Landauer, Bennett locates the essential irreversible physical act in "forgetting."

From 1960 to 1982 research on the fundamental limits of computation drew information theory and thermodynamics together. Arguing against earlier information-theoretic approaches focused on observation and measurement, entropy generation was attached to erasure of information. Nature was anthropomorphized as information erasure became natural systems forgetting. In an effort to attach this movement to a paradigmatic fundamental law of physics, not just nature but demons were made to forget. This entropic forgetting was at the same time a limit on computation, and an active, positive, necessary part of computation.

3. Conclusion

This paper has traced a thread in the history of what came to be known as the "thermodynamics of information": the application of physical ideas from thermodynamics to information theory and computing. At IBM, it began with Swanson's 1959 assertion that information density can be defined per volume rather than per symbol as Shannon's information theory would have it. Landauer followed upon this work by connecting

physical irreversibility to logical irreversibility, and locating in information erasure or forgetting the creation of heat. At a cost of time and tape, Bennett proved that, in fact, computers could be built reversibly, and propounded a computer-biological process equivalence. He later introduced "Landauer's principle" in the context of Maxwell's demon and the Second Law of thermodynamics (apparently erroneously) placing the physics of information at the heart of physics.

There is some irony, then, in the history of the thermodynamics of information. After Bennett, "Landauer's principle" was used to try to save the second law of thermodynamics. However, attention to the text reveals the modesty of Landauer's specific claims for his principle, and that he assumed the second law in deriving it. Forgetting saves. It seems, though, that there has been too much forgetting here (Ricoeur 2004, chap. 2). Citations to Landauer's paper have increased in recent years (Fig. 1), some of which assume that Landauer's principle is the savior of the Second Law. Landauer himself noted "the tendency of authors to copy historical citations from earlier papers, without careful thought, or inspection of those early papers."[16] Alongside technical discussions by philosophers such as John Norton and John Earman, I hope this historical account will contribute to the restoration of memory of the context and content of Landauer's work.

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