Interdisciplinary Perspectives

What Is Information Theory a Theory Of?
Boundary Work among Information Theorists and Information Scientists in the United States and Britain during the Cold War

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Abstract

Information theory (as understood in the United States) was not created de novo from Claude Shannon's 1948 paper (1948a), as commentators often claim, but was the result of a decade of negotiations and debates among mathematicians, physical scientists, engineers, social scientists, and humanists over such issues as the meaning of information, the characteristics and rigor of the theory, and its proper or possible applications.

This paper tells one part of the story: the debates in the United States and Britain over the question, what is information theory a theory of? These disputes were at the center of "boundary work" done to carve out monopolistic fields, expand the boundaries of disciplines, expel transgressors, and protect fields from outside control—the four types of boundary work identified by sociologist Thomas Gieryn (1999). I discuss the reflexive debates of information theorists and a group who used their theories: librarians and information scientists.

The publication of *Cybernetics* by Norbert Wiener (1948a) and *The Mathematical Theory of Communication* by Claude Shannon and Warren Weaver (1949) stirred an enormous amount of interest in what was soon called "information theory."[1] Enthusiastic scientists, believing that the theory quantitatively described the fundamental phenomenon of communication, applied it to many fields in the 1950s (Dahling, 1962), including physics, physiology, experimental psychology, and linguistics (Cherry, 1957); artificial intelligence and cognitive psychology (Edwards, 1996); behavioral and molecular biology (Haraway, 1981–1982; Kay, 2000); economics (Mirowski, 2002); and library and information science (Shera, 1983). Ironically, communications engineers, the primary audience of Shannon and Wiener, were skeptical (Gilbert, 1966). It was not until the late 1960s that engineers successfully applied the abstract, esoteric theory to space and computer communications (Viterbi, 1973). Throughout the 1950s many aspects of information theory were highly contested. Mathematicians, physical scientists, life scientists, engineers, social scientists, and humanists disagreed about the meaning of the term *information,* the characteristics and mathematical rigor of the theory, and its proper applications. There was little agreement about the answer to the question of what information theory is a theory of until the late 1960s.

This essay tells part of that story by analyzing the interactions between information theorists and the nascent community of information scientists in the United States and Britain in the early cold war. But first I discuss the debates among engineers, mathematicians, and physicists over the meaning of information theory. Then I treat general issues involved in applying the theory. Finally, I explore its application by information scientists and responses by information theorists. As in other fields the theory was applied in an active rather than a passive manner. Information scientists adopted, adapted, modified, replaced, and rejected the theories of Shannon and Wiener. The many disputes in this story were at the center of "boundary work" done to carve out monopolistic fields, expand the boundaries of disciplines,

[1] For histories of information theory see F. W. Hagemeyer (1979), W. Aspray (1985), and J. Segal (1998).

expel transgressors, and protect fields from outside control (Gieryn, 1999).

Interpretations of Information Theory among Engineers, Mathematicians, and Physicists

The term *information theory,* like its referent *information,* referred to a variety of concepts in the postwar period (Machlup & Mansfield, 1983). Information theorists recognized several meanings. In 1953 Robert Fano, an electrical engineer at the Massachusetts Institute of Technology, thought four interpretations were common. Three of these were in the areas of Shannon's communications theory; the waveform analysis of Denis Gabor, a physicist at Imperial College in London; and classical statistics, based on the work of Ronald Fisher, a British geneticist and statistician. The fourth interpretation involved "miscellaneous philosophical speculations on broad communication problems." An admirer of Shannon, Fano used the first meaning of the term (Fano, 1953).

One of Fano's colleagues at MIT, Peter Elias, distinguished three meanings of information theory in 1959: Shannon's theory; "any analysis of communication problems," including Wiener's research on prediction and filtering; and a synonym for cybernetics. The second meaning prevailed in the Institute of Radio Engineers' Professional Group on Information Theory (PGIT), the predecessor of the current Information Theory Society of the Institute of Electrical and Electronics Engineers (IEEE). The third meaning was evident at two symposia on information theory held at MIT and three symposia held in London (Elias, 1959, p. 253). Early textbooks also popularized the second meaning (e.g., Goldman, 1953).

The British view was emphasized by electrical engineer Colin Cherry at Imperial College in 1957. He observed that the research of British and U.S. physicists on "scientific method, is referred to, at least in Britain, as *information theory,* a term which is unfortunately used elsewhere [i.e., in the United States] synonymously with [Shannon's] communication theory. Again, the French sometimes refer to communication theory as *cybernetics.* It is all very confusing!" (Cherry, 1957, p. 216). Shannon acknowledged the confusion in 1951 while discussing a paper presented by British information theorist Donald MacKay at one of the Macy conferences on cybernetics. "I think perhaps the word 'information' is causing more trouble in this connection than it is worth, except that it is difficult to find another that is anywhere near right" (Von Foerster, Mead, & Teuber, 1952, p. 219).[2]

The research of Wiener and Shannon created the most excitement in the postwar period. Despite its abstruse mathematics the bold claims in *Cybernetics* about a new science that used the same methods to study machines and humans fascinated scientists, engineers, journalists, and the general public (Kay, 2000, chap. 3). The mathematics of Shannon's paper, published in the *Bell System Technical Journal* (1948a) in the same year as Wiener's *Cybernetics* was just as difficult to understand. But Warren Weaver, head of the natural sciences division at the Rockefeller Foundation, wrote a popularization of it for a book aimed at social scientists (Shannon & Weaver, 1949). Weaver emphasized the importance of the mathematical correspondence between Shannon's and Wiener's definition of information and the scientific concept of entropy (the degree of randomness in a thermodynamic system). It seemed to validate the claim that the "Shannon-Wiener" concept of information (Quastler, 1953, pp. 5, 17, 22), also called the "Wiener-Shannon" concept at the time (Cherry, 1957, pp. 214, 219, 226), formed the basis for a new science (Bello, 1953).

Although Shannon and Wiener independently developed similar measures of information, the different origins of their work led to dissimilar theories. While designing an anti-aircraft fire-control system at MIT during World War II, Wiener, a world-renowned mathematician, developed a statistical theory of communications to solve the problems of prediction and filtering (Masani, 1990, chap. 14; Galison, 1994). In *Cybernetics,* Wiener presented a "statistical theory of the amount of information." He equated information with negative entropy and related it to problems in prediction, filtering, and the rate of transmission of information (Wiener, 1948a, p. 18, chap. 3).

Shannon, who received his Ph.D. in mathematics from MIT in 1940, started his work where Bell Laboratories researcher Ralph Hartley had left off. Hartley (1928) proposed a simple logarithmic measure of information that did not consider noise or the statistics of messages. By 1945 Shannon had taken these matters into account in his theory of information, which he developed while working primarily on cryptography at Bell Labs. In fact, large chunks of the famous 1948 paper

[2] See Y. Bar-Hillel (1955) for an insightful analysis of the confusion in terminology. On the Macy conferences see S. J. Heims (1991).

came from a declassified cryptography report (Shannon, 1945). He went far beyond Hartley to consider comprehensively the statistical aspects of messages, noise, and coding problems. Shannon related amount of information to uncertainty and choice. The greater the uncertainty about which symbols a discrete source would select from a set, the more information the source produced. The meaning conveyed by the symbols was irrelevant to Shannon, just as it had been for Hartley. Expressing amount of information and channel capacity in terms of positive entropy, Shannon developed and proved a surprising theorem that said a code could be devised to transmit information with as small an error as desired over a noisy channel (Shannon, 1948a).

Despite claims to the contrary (see, e.g., Wellisch, 1972, p. 164; Machlup & Mansfield, 1983, p. 48), Shannon called his work "information theory" early on, especially in the titles of talks (e.g., Shannon, 1993, items 49 and 68). Wiener used the term more broadly (e.g., Wiener, 1956).

Although Shannon said he was influenced by Wiener's wartime work on the statistical aspects of communication (Shannon, 1948a, pp. 626–627, 652), he approached the problem from a different angle. Wiener filtered signals, representing messages (information), from noise. Shannon coded messages into signals in order to transmit information in the presence of noise. In 1948 Shannon wrote to Wiener about the difference in the sign of their entropy equations for information. "I do not believe this difference has any real significance but is due to our taking somewhat complementary views of information. I consider how much information is *produced* when a choice is made from a set—the larger the set the *more* information. You consider the larger uncertainty in the case of a larger set to mean less knowledge of the situation and hence *less* information" (Shannon, 1948b). Wiener agreed with Shannon's diagnosis (Wiener, 1948b), as did Peter Elias (1955, p. 21).

The other major theories of information diverged greatly. Before the war Ronald Fisher developed a definition of the "amount of information" to be expected, with respect to unknown statistical parameters (e.g., mean value), from a given number of observations. It was well known in science and statistics (Fisher, 1935a, ch. 11). He also noted a "strikingly similar" mathematical relationship between his measure of information and entropy (Fisher, 1935b, p. 47). In 1946 Denis Gabor defined a "quantum of information," which he called a "logon," in terms of the product of uncertainties of time and frequency of an electrical signal. Gabor used the concept to analyze waveforms in communication systems (Gabor, 1946, p. 435).

Gabor's colleague Donald MacKay, a physicist at King's College, London, attempted to reconcile these views at the first London Symposium on Information Theory, held in 1950. In his taxonomy MacKay defined the broad category of "information theory" as the "making of representations" in three areas: science, communication, and the arts (MacKay, 1953, p. 10). Believing that different concepts of information should be specified with appropriate adjectives, he coined several new terms. *Scientific information theory* was the realm of the physicist and the subject of an earlier paper by MacKay (1950). In it *metrical information* (derived from Fisher) was related to *structural information* (derived from Gabor) to give the total amount of information provided by an experiment. In the taxonomy communication theory was the realm of the engineer and was based on Shannon's and Wiener's definition of information, which MacKay termed *selective information.* While scientific information gave the precision and degrees of freedom of an experiment, selective information gauged the uncertainty of transmitted messages. MacKay wisely said that making representations in the arts was outside his purview.

Other researchers, primarily mathematicians, explored the mathematical relationships between the information theories of Fisher, Shannon, and Wiener (e.g., Barnard, 1951). They also led the movement to rewrite the proofs of Shannon's theorems in a more rigorous mathematical form (Slepian, 1973).

MacKay's novel attempt to combine different views of information into a unified theory was an expansive type of boundary work.[3] An even greater expansion of the field was manifest at the London symposia on information theory. Cherry, one of the organizers, presented "A History of the Theory of Information" (1953) at the first meeting in 1950 that described the work of all the researchers I have mentioned thus far, plus many others. Willis Jackson, another organizer, claimed that a "new branch of science is emerging which reveals and clarifies connexions between previously unrelated fields of research" (Jackson, 1951, p. 20). The 1955 meeting covered communication theory, physics, linguistics, hearing, physiology, psychology, automata, and the mechanical translation of languages (Cherry, 1956). Information

[3] For a later statement, see MacKay (1983, p. 488).

theorist David Slepian was amazed at the variety of papers at the meeting. He reported to his colleagues at Bell Labs that the "best definition I was able to get as to what constituted 'The Information Theory' was 'the sort of material on this program'!" (Slepian, 1955, p. 1).

Physicists often performed expansive forms of boundary work. Leon Brillouin, a French quantum physicist who emigrated to the United States in 1941, argued that information theory could explain physical phenomena and that physics could explain information theory. Brillouin coined the term *negentropy* and equated it with information in order to resolve a paradoxical nineteenth-century thought experiment in thermodynamics known as "Maxwell's demon." In 1951 he adjudicated the difference between Wiener's and Shannon's entropic definitions of information. Brillouin could not agree with Wiener's reversal in sign. "Shannon's formula is all right, only the interpretation of the formula is more involved" (Brillouin, 1951, p. 342).

Much of the boundary work done by leading information theorists in the United States at this time was monopolistic (see below). Robert Fano, for example, disliked the variety of meanings given to information theory at the 1952 London symposium. In the letter cited earlier, he told Cherry that "confusion of these four broad areas of work because of ambiguous terminology is responsible in my view for many of the misunderstandings between the two sides of the Atlantic" (Fano, 1953). Fano continued to limit the phrase *information theory* to Shannon's work, while acknowledging the broader British meaning of the term (Fano, 1961, p. 2).

The boundary work done by engineers, mathematicians, and physicists helped to create a version of what sociologists of science call *closure* of a scientific controversy (Collins, 1985). But in this case there were several closures, each corresponding to a different meaning of information theory. Gabor's measure was confined to circuit theory, Fisher's to statistics. By the 1960s the research of Shannon and Wiener had been divided into two streams within electrical engineering. Wiener's formed the river of "statistical communication theory" (e.g., Lee, 1960) and Shannon's that of "information theory" (e.g., Fano, 1961, pp. 1–2). The PGIT and its successors in the IEEE increasingly accepted the latter designation. MacKay's taxonomy and other forms of boundary work enabled researchers to stake out separate fields and not worry about competing interpretations. These disputes were settled or dropped by drawing boundaries around different meanings rather than by agreeing on a universal answer to the scientific question, what is information?

Issues in Applying Information Theory

Those who applied information theory outside of engineering and physics drew other boundaries that helped to construct its meaning. Here I focus on the application of Shannon's research, rather than the work of Wiener, Fisher, Gabor, Brillouin, and MacKay. I do note a few references to Wiener's popular writings. The wide appeal of *Cybernetics* and Weaver's popularization of information theory created great interest in Shannon's work. In 1953 science writer Francis Bello told readers of *Fortune* magazine that "attempts are being made to use information theory [whose origins he attributed jointly to Shannon and Wiener] in a dozen fields from psychology to sociology. In a few fields, notably psychology, neurophysiology, and linguistics, the theory has already been applied with considerable success" (Bello, 1953, p. 137).

But there were many difficulties as well. Henry Quastler, a radiologist at the University of Illinois who attempted to apply information theory to biology (Kay, 2000, pp. 115–126), admitted that "there is something frustrating and elusive about information theory. At first glance, it seems to be the answer to one's problems, whatever these problems may be. At second glance it turns out that it doesn't work out as smoothly or as easily as anticipated. . . . So nowadays one is not safe in using information theory without loudly proclaiming that he knows what he is doing and that he is quite aware that this method is not going to alleviate all worries. Even then, he is bound to get his quota of stern warnings against unfounded assumptions he has allegedly made" (Quastler, 1955, p. 2).

The most common warning was not to interpret Shannon's theory as a theory of meaning. Weaver had encouraged this interpretation in 1949 by describing three levels of communication. Shannon restricted his theory to level A, the "technical problem" ("how accurately can the symbols of communication be transmitted?"), and did not deal with level B, "semantics" ("how precisely do the transmitted symbols convey the desired meaning?"), nor level C, what semioticians called "pragmatics" ("how effectively does the received meaning affect conduct in the desired way?"). Weaver thought the levels overlapped. "Thus the theory of Level A is, at least to a significant degree, also a theory of Levels B and C" (Weaver, 1949, pp. 96, 98). Many researchers who semantically applied Shannon's theory drew on this passage to support their work.

Wiener also encouraged a semantic interpretation of information theory. In *On the Human Use of Human Beings,* a popularization of cybernetics, Wiener (1950) gave a nonsemantic definition of information as negative entropy, similar to that in *Cybernetics.* But he then equated amount of information with the "amount of meaning" of a message to support his semantic use of "information" throughout the book. Such statements as "it is quite clear that a haphazard sequence of symbols or a pattern which is purely haphazard can convey no information" show his distance from Shannon, who said the meaning conveyed by symbols was irrelevant to his theory (Wiener, 1950, pp. 6, 8).[4] It appears that in viewing information as a measure of order rather than disorder as Shannon did, Wiener was inclined to use the term in a more everyday, semantic way to mean knowledge.

Yet some philosophers and psychologists (e.g., Bar-Hillel & Carnap, 1953; Bar-Hillel, 1955; Miller, 1953) warned against the semantic interpretation of Shannon's and Wiener's entropic measure of information. So did information theorists and information scientists.

A second issue was the mathematical equivalence between entropy and information. While physicists extensively debated the physical aspects of this relationship (e.g., Brillouin, 1956), many social scientists interpreted it more broadly (Shaw & Davis, 1983). This drew the ire of Colin Cherry. He had "heard of 'entropies' of languages, social systems, and economic systems and of its use in various method-starved studies. It is the kind of sweeping generality which people will clutch like a straw." Although Cherry thought some of the interpretations were valid, entropy "is essentially a mathematical concept and the rules of its application are clearly laid down" (1957, p. 214).

Information Theory and Information Science

The case of information science in the United States illustrates the debates over these issues and the boundary work done by those outside the information-theory community. Called bibliography, documentation, and scientific information during the first five decades of the twentieth century, the field became known as information science in the early 1960s. In a reflection of this movement the American Documentation Institute (ADI), which was established in 1937 and reorganized as a professional society in 1952, changed its name to the American Society for Information Science (ASIS) in 1968. The field was one of those "method-starved" disciplines alluded to by Cherry. At least that was how many insiders viewed it. Much debate ensued within the documentation–information science community about the definition of *information science,* its relationship with librarianship, and what served or should serve as the theoretical foundation for the field in order to make it a "true science." Information theory seemed a logical choice because it quantified the field's subject of study, but problems of interpreting the theory semantically plagued the profession (Cuadra, 1966; Wellisch, 1972; Shera & Cleveland, 1977; Machlup & Mansfield, 1983; Rayward, 1983; Shera, 1983; Schrader, 1984; Farkas-Conn, 1990; Buckland, 1996).

The journal of ADI and ASIS, from its founding in 1950 to the early 1970s, and contemporary publications reveal the status of information theory within this community during a formative period.[5] The dozen or so librarians and information scientists I studied assumed that a major goal of the profession was essentially a problem in communications: how to improve the flow of information from library (source) to patron (receiver). Two issues predominated: could Shannon's theory, which did not deal with semantics, help solve the technological problem of storing and retrieving meaningful information; and could it provide the theoretical basis for the new discipline of "information science." As in other fields proponents and critics alike actively engaged with information theory rather than passively applying it. In addition to using the theory nonsemantically, as Shannon intended, they semantically adapted it to their needs, supplemented it, and replaced it with their own theories. I thus present a more complex picture than that of eager information scientists misinterpreting and over-extending Shannon's theory in an ill-fated, "intellectual get-rich-quick scheme" (Shera & Cleveland, 1977, p. 261).

Designing Information Systems

Many information scientists thought the nonsemantic aspects of Shannon's theory limited it to the design of information systems, especially to coding problems.

[4] For a similar criticism see Bar-Hillel (1955, pp. 97–98).
[5] For a recent review of topics covered by the journal since its founding, see Bates (1999).

James Perry, of the Center for Documentation and Communication Research in the School of Library Science at Western Reserve University and an MIT chemist who became a leader in the computerization of literature searching (Wright, 1985; Aspray 1999, p. 7), stated this position at a conference on documentation held at the university in 1956. Perry drew a sharp boundary around the scope of information theory in order to protect the field of documentation. Because information theory dealt primarily with the accurate transmission of symbols, he limited it to improving indexing and classification by appropriate coding. "Thus, the role of information theory . . . is seen to be in the insuring of efficiency of documentation operations rather than in defining the purposes to be served or in formulating basic principles of documentation methods" (Perry, 1956, p. 95).[6] The same year Perry and two colleagues also predicted that extensions of the "Shannon-Weaver information theory" could evaluate the effectiveness of information systems (Perry, Kent, & Berry, 1956, pp. 124, 129).

Coding was the hallmark practice of Perry's rival, Calvin Mooers, an early computer expert. In 1945 he worked on John Atanasoff's electronic computer project at the Naval Ordnance Laboratory and was included in the famous Moore School lectures on computing after the war (Williams, 2001). The founder of the Zator Company in Boston in 1947, Mooers received his master's degree in mathematics the next year from MIT (Mooers, 1948), a hotbed of information theorists. Straddling the disciplinary divide between information science and information theory, Mooers claimed to have coined the term *information retrieval* in 1950 (Mooers, 1957). His patented system, known as Zatocoding, consisted of machines that sorted edge-notched cards (tallies) containing coded descriptors to identify relevant documents. The superimposed numerical codes were chosen randomly, according to parallels and analogies drawn from coding messages in information theory, in order to make them optimal and efficient (Mooers, 1951). Mooers drew from Shannon for the concepts of probability and choice in coding (Shannon, 1948a) and for random codes (Shannon, 1949).

Although Zatocodes were not semantic, Mooers did not shy away from semantic issues. He told the 1954 symposium of the Institute of Radio Engineers' PGIT that "unlike the situation in communication theory, the semantic problem cannot be dodged in information retrieval." While Shannon's entropy function was abstracted from meaningful information, information retrieval systems "must deal with very real problems in semantic information" in regard to documents and descriptors. Yet Mooers did not interpret Shannon's theory semantically. Instead he used analogs to Shannon's entropy equation to calculate the optimal number of bits per tally and the probability of retrieving the wrong document per tally (Mooers, 1954, pp. 112, 113, 116).

As the field of documentation was being transformed into information science in the mid-1960s, academic researchers applied the mathematics of information theory as heavily as Mooers had done. In 1967 Pranas Zunde and Vladimir Slamecka, at the Georgia Institute of Technology's School of Information Science, considered the index to be a noiseless channel linking the information store to the receiver (user). Index descriptors and postings (e.g., documentation number) coded the documents. They used Shannon's entropy equations to calculate an optimal frequency distribution of descriptors by the number of postings that maximized the use of the index. The problem was analogous to finding an optimal code in information theory. In one example 1,000 documents were indexed by 22 descriptors on average, with each descriptor having an average of 11 postings. The optimal frequency distribution turned out to be 182 descriptors with 1 posting, 165 descriptors with 2 postings, 146 descriptors with 3 postings, and so on. They used the nonsemantic approach to evaluate existing retrieval systems, such as the one at the Defense Documentation Center (Zunde & Slamecka, 1967).

Other researchers reinterpreted Shannon's theory semantically to design information systems. In 1970 Bertrand Landry and James Rush, at the Department of Computer and Information Science at Ohio State University, adapted Shannon's approach to create a theory of indexing. Using a semantic definition of information proposed by Marshall Yovits (see below), they situated the index of an information-retrieval system in the noisy channel of Shannon's communication model and added search and feedback functions to the receiver (Landry & Rush, 1970). By claiming that indexing decreased the entropy of the system, they followed more in the path of Wiener's semantic interpretation of information

[6] Perry's boss at Western Reserve, Jesse Shera, dean of the School of Library Science, made a similar demarcation twenty years later (Shera, 1983, p. 383), despite the tensions between him and Perry over the relationship between librarianship and information science (Wright, 1985).

(Wiener, 1950) than Shannon's original work. In 1974 Jack Belzer of the University of Pittsburgh, where the first Ph.D. program had been established in information science (Aspray, 1999), maintained that differences in documents could provide "measures of semantic information content." In an experiment he calculated probabilities of prediction and relevance, provided by seventy users, of retrieved documents based on citations, abstracts, first paragraphs, last paragraphs, and first and last paragraphs. He plugged the probabilities into entropy equations to calculate the information content of these finding aids. Abstracts were not as informative as paragraphs, indicating that lower-paid clerks could replace higher-paid abstractors. Belzer concluded with an even broader, and more dubious, claim that his method actually measured the "amount of meaningful information" of the full document (Belzer, 1973, pp. 300, 303). This was a semantic evaluation of cataloging that did not heed Weaver's injunction (1949, p. 100) that Shannon's concept of information measured the freedom to choose from a set of possible messages, not the content of individual messages.

One bold designer of information systems replaced Shannon altogether. In 1962 Clifford Maloney, at the Biomathematics Division of the U.S. Army's Chemical Corps Biological Laboratories, dismissed the attempts to apply Shannon's theory as "sterile" (Maloney, 1962, p. 276). Maloney developed a theory of "semantic information" from the mathematics of n-dimensional Euclidean geometry, which Shannon (1949) had also used. Maloney's semantic codes consisted of three parts: context, the concept itself, and the order of concepts.

Theoretical Basis for Information Science

The second type of application of information theory was to view it as a foundation for information science. A typical approach was to use the theory's concepts metaphorically. This was evident in the writings of Laurence Heilprin, staff physicist of the Council on Library Resources in Washington, D.C., who was president of ADI in 1964–1965. In 1960 Heilprin discussed the future of information science from Wiener's viewpoint that "civilization is held together by messages." Other terms from communication theory, such as signals, decoding, and channel capacity, peppered his talk. Citing Brillouin (1956), Heilprin claimed that the "advance of knowledge and the process of education are equivalent to the local production of negative entropy" (Heilprin, 1961, pp. 1, 3), a view that Wiener stated in his popular writings (e.g., Wiener, 1950). In a later paper Heilprin acknowledged that meaning was irrelevant to Shannon's theory. But he still stated (incorrectly, from Shannon's viewpoint) that the amount of information necessarily depended on the number of words in a message (Heilprin & Goodman, 1965, p. 164). Heilprin corrected himself in 1968 by saying that the unique selection of words was what made copyrighted works valuable (Heilprin, 1968).

Several researchers saw information theory as one of the contributory fields of information science. Irving Klempner (1969), at the School of Library Science at the State University of New York, Albany, thought Shannon's theory supplied the basis for the storage-transmission segment of information science. In a more expansive view Glynn Harmon at the University of Texas stated that "by 1955 information theory had diffused through a large number of disciplines, including several of the contributory disciplines of information science" (Harmon, 1971, p. 236), which included communications and linguistics. Anthony Debons at the Department of Information Science, University of Dayton, and Klaus Otten, of the National Cash Register Company, held that information theory was one of the fundamental theories underpinning the new metascience of "informatology," their neologism for "information science" (Otten & Debons, 1970). They followed MacKay's usage by saying "selective information" needed to be supplemented with a semantic theory of information, which was not yet forthcoming. Jack Belzer (1970, p. 270) maintained that Shannon "made some important contributions to the field of information science" by providing a unit of measure, which is "necessary to every field of science." As we have seen, Belzer also tried to extend Shannon's theory semantically to solve problems in information retrieval.

Educational programs in information science often taught some version of information theory. Graduate programs at the University of California, Los Angeles, Georgia Institute of Technology, Lehigh University, and the University of Dayton required a course in information theory in the 1960s (Taylor, 1966, p. 23; Debons & Otten, 1969). Yet a survey of 185 courses in 45 university programs in library and information science, conducted by the curriculum committee of ASIS in 1969, did not list information theory as a major topic of study. This oversight was rectified by the committee, headed by Belzer, during a workshop held at the University of Pittsburgh in early 1971. Then the committee added

"Information & Communication Theory" to the top ten "analytical factors" in the field (Belzer, Isaac, Finkelstein, & Williams, 1971, p. 202).

The pioneering information scientist Robert Fairthorne attempted to supplement Shannon's theory in order to provide a basis for the discipline. Fairthorne, a mathematician at the Royal Aircraft Establishment Library in England (Schultz & Schultz, 1971), introduced the topic of information theory to librarians in the early 1950s (Fairthorne, 1953). He told ADI that information theory could calculate the cost-efficiency of retrieval operations in a library and thought it would be extended semantically (Fairthorne, 1956). Fairthorne attempted to do this himself in 1967. He criticized the "purely rhetorical extrapolation of Shannon's strictly delimited Information Theory beyond its valid scope." The "Shannon model is necessary, though not sufficient" because it omits to specify "who signals to whom about what." Consequently, he supplemented the primary items Shannon considered—code, message, and channel—with the discursive triad of source, destination, and designation (e.g., descriptor). Fairthorne argued that entropy equations were only valid for Shannon's triad. However, coding in information retrieval was "not an aspect of Signalling, but of Subject Classification," an implied criticism of Mooers (Fairthorne, 1967, pp. 711, 712, 716). Susan Artandi (1973) at Rutgers took a similar middle-ground position, saying that information theory supplemented by semiotics could provide a useful theoretical framework for information science.

Bolder researchers replaced Shannon's theory with their own models. In the late 1950s Thomas Minder, a librarian at the Curtiss-Wright Corporation, stated that Shannon's "theory is not adequate" because communication was "not synonymous" with information storage and retrieval. He based his mathematical theory of bibliographic organization on a definition of information as a "countable subset" of Whitehead's concept of "nature" (Minder, 1957; Minder, 1960, pp. 2, 6). In 1969 Marshall Yovits, of the Department of Computer and Information Science at Ohio State, described a model of a "generalized information system" based on the definition of information as data of value in decision making, which he and R. L. Ernst had developed in 1967. He thought it could serve as the basis for making information science a "true scientific discipline" (Yovits, 1969). In 1973 Yovits and Bruce Whittemore expanded this into a general, quantitative theory of "pragmatic information" based on the reduction of uncertainties in decision making (Whittemore & Yovits, 1973).

What was the fate of these applications and revisions of information theory? Mooers sold information-retrieval systems based on the theory, and more successful rivals such as Mortimer Taube melded Mooers's ideas into their own systems (Williams, 2001, p. 22). A method of using information theory to compress data, proposed in the 1970s (Lynch, 1977), became the basis for some forms of data compression used in personal computers two decades later (Lynch, 2004). But most applications of Shannon's theory seem to have been fallow from 1948 to 1970. Zunde admitted as much in 1981. "The claims of enthusiastic proponents of Information Theory, who sought to apply it indiscriminately to any kind of information process have so far not been justified. In particular, Information Theory has made little impact on information science, which ought to be its main and natural domain of application." He attributed the failure to semantic applications of the theory (Zunde, 1981, p. 346).[7] Four years later a review of theories of information science noted that "information theory has not had the impact on information science, as least as yet, that some theoretical works have had in other disciplines" (Boyce & Kraft, 1985, p. 157).

These comments would have pleased Emmett McGeever, a research librarian at the John Crear Library in Chicago. In 1958 McGeever gave a luncheon address to ADI in which he satirized the enthusiasm for information theory. In this protective form of boundary work he feigned appreciation for the work of Shannon and Weaver. He then presented a nonsense version of Shannon's entropy equation and an equally nonsensical longer equation, which a mathematician had supposedly derived for library practice. McGeever probably deadpanned the next line: "from which the application to everyday problems of finding the article the boss wants is immediately obvious" (McGeever, 1958, p. 76).

Yet McGeever would have shaken his head at Zunde's conclusion in 1981. "On the other hand, the tendency to underestimate the significance of Information Theory for information science may prove to be premature and in the final result wrong." He pinned his hopes on structural linguistics to augment the theory (Zunde, 1981, p. 346). Not surprisingly, the quest to make Shannon the basis for information science continued into the

7 For a similar statement see P. Zunde and J. Gehl (1979, p. 69).

1990s (e.g., Cole, 1993), as has the criticism of the semantic interpretation of information theory (e.g., Buckland, 1991, pp. 119–120).

Response by Information Theorists

How did information theorists in the United States respond to these applications? I will consider relationships between the two communities and a few direct reactions from information theorists, and then relate these to how leaders of PGIT tried to control similar applications of Shannon's theory outside of communications engineering.

There were some contextual links between information theorists and information scientists. Shannon's mentor for his M.S. and Ph.D. training was Vannevar Bush, well-known in information-retrieval circles for proposing the futuristic hypertext Memex in 1945. While a graduate student at MIT in 1938, Shannon worked on a predecessor device, Bush's ill-fated Rapid Selector, an early microfilm-based information-retrieval machine (Burke, 1994, p. 185). Weaver popularized Shannon at the same time he initiated the project on machine translation of scientific documents from one language to another (Bar-Hillel, 1951). Louis Ridenour (1951), a physicist at the University of Illinois and a proponent of mechanical aids for information retrieval, helped arrange the publication of the volume by Shannon and Weaver (Dahling, 1962). The military funded much research and its dissemination in information theory (Edwards, 1996) and information science (Aspray, 1999; Debons & Horne, 1997), the latter because of the tremendous growth in the volume of scientific reports and papers published after the war (Bowles, 2000).

These sorts of connections did not immunize information scientists from criticism. Mooers, who had a foot in both communities, had an uncertain status among information theorists. Both PGIT and the third London symposium published his conference papers on the use of information theory. Yet Weaver, at the Rockefeller Foundation, indicated in his diary that some U.S. researchers did not welcome the prospect of Mooers attending the 1955 London meeting. Jerome Wiesner, a colleague of Wiener's at MIT who was handling the U.S. end of the arrangements, asked Weaver for travel grants for "two cases that cannot be handled by military transport: *Margaret Mead* (since she is a woman), and *Calvin Mooers.*" No reason was given for Mooers. Wiesner had said that Mooers, an individualistic inventor-entrepreneur, "is doubtless something of a nut, but the British have asked for him" (Weaver, 1955 [unpaginated]).

Yehoshua Bar-Hillel was one of the chief critics of Mooers and his rivals. Trained in logic, mathematics, and philosophy in Israel, Bar-Hillel worked under Wiesner at MIT's Research Laboratory of Electronics on the cold war–funded machine translation problem in the early 1950s. He and positivist philosopher Rudolf Carnap developed a mathematical theory of "semantic information" in the same period (Bar-Hillel & Carnap, 1953). Bar-Hillel was a self-described "devil's advocate," who criticized the basic concepts of machine translation and the misuse of information theory (Bar-Hillel, 1962, p. 15). In 1957 he took on the designers of information-retrieval systems on their home turf, the journal of ADI. Bar-Hillel criticized the top designers—Mooers, Perry, and Taube—for serious lapses in symbolic logic. They had impatiently rushed into this and other fashionable fields when "not a first-rate logician, linguist, or information-theoretician has so far been sufficiently attracted to the problem of information search to want to spend much of his time on it" (Bar-Hillel, 1957, p. 104).

Perry and Mooers answered the editor's call to reply. Both questioned Bar-Hillel's knowledge of the field. Mooers (1957) stated that *information retrieval* had an established meaning different from Bar-Hillel's. Perry used satire to defend expansive boundaries. He detected in Bar-Hillel's paper an "undertone of resentment that research workers in such a field should invade his own specialty for the purpose of borrowing, and perhaps adapting, certain ideas and techniques." Bar-Hillel should not worry. A "borrower takes nothing away from the lender. The theoretician still has his entire equipment of concepts and established relationships for his own use and enjoyment" (Center for Documentation and Communication Research, 1957, p. 122). Bar-Hillel was not "particularly impressed by the rebuttals" (Bar-Hillel, 1962, p. 14).

Neither Perry nor Mooers responded to the issue of how to apply information theory. Bar-Hillel was skeptical. He even criticized an unnamed "colleague of mine, a well-known expert on information theory," who had proposed using statistics about the documents requested by users to prepare bibliographies (Bar-Hillel, 1957, p. 111). The colleague was none other than Robert Fano, who made the suggestion at the documentation conference held at Western Reserve University in 1956. Fano was quick to "dispel the idea that the presence of the word 'information' in 'information theory' implies that this theory is necessarily pertinent to the 'retrieval of recorded information.' " But it could suggest new viewpoints for library science. Fano praised the work of

Mooers, a former student at MIT, as "a good illustration of one way in which information theory can lead to new practical developments" (Fano, 1956, p. 240).[8]

Fano's comments were not atypical for him or his colleagues. He told Cherry in 1953 that he was "leading a private fight" against the unjustified use of Shannon's theory (Fano, 1953, p. 2). Other leading information theorists also performed monopolistic boundary work. Like Fano, they were skeptical of general applications and approved mathematically sound ones. Often they admonished members of the PGIT, whom they feared would stray too far afield. In a 1956 editorial Shannon said applications were "not a trivial matter of translating words [like information, entropy, and redundancy] to a new domain" (p. 3). He recommended that information theorists stick to their research rather than engage in exposition. Peter Elias used the disciplinary technique of satire in a 1958 editorial titled "Two Famous Papers." The first type produced results in prediction and filtering that Wiener had given a decade earlier. The second sort of paper had the generic title, "Information Theory, Photosynthesis and Religion." Its author, usually an engineer or a physicist, discussed the "surprisingly close relationship between the vocabulary and conceptual framework of information theory and that of psychology (or genetics, or linguistics, or psychiatry, or business organization)." Elias suggested "that we stop writing them" and work on more fruitful areas (p. 99).

These editorials helped tighten boundaries around the information-theory community at the time (Slepian, 1973, p. 146). Boundary work aimed more at outsiders was evident in one of the histories commissioned by the IEEE Information Theory Society in 1973 to mark the twenty-fifth anniversary of the publication of Shannon's paper. John Pierce, an avowed "Shannon worshiper" at Bell Labs (Pierce, 1961, p. ix), thought applications in physiology and physics did not get at the heart of the theory. Even Shannon's own research in automata was "foreign to information theory in the sense Shannon formulated it. So is much else that was inspired by information theory." Pierce then expelled Wiener from that field, saying most of *Cybernetics* was irrelevant to Shannon's theory and that Wiener never really bothered to understand it (Pierce, 1973, pp. 6, 7).

Conclusion

The interactions among information theorists, librarians, and information scientists show the central role of boundary work in the history of their disciplines. Many disciplinary techniques were used to carve out new fields, expand boundaries, protect others, and expel transgressors.

Information theorists in the United States carved out their discipline in relation to outsiders and insiders. They acknowledged the technical criticisms of physicists, mathematicians, and competing information theories, gradually cutting Wiener out of the picture. They responded to enthusiastic applications by disciplining insiders with admonitions and satires in editorials, as well as with private battles, histories, and anniversary celebrations. I have thus far found little evidence about efforts to influence librarians and information scientists, except Fano's remarks at the 1956 documentation conference. (Bar-Hillel was the only researcher based in the United States who commented on papers on information retrieval at the London symposia.)

Enthusiastic librarians and information scientists generally attempted to expand the boundaries of their field to include information theory. As a mathematical discipline it held the promise of raising the status of information science. They saw possibilities for information theory as a scientific foundation for their field, a metaphor to analyze broad topics, and a mathematical tool to design information-retrieval systems. When most of these attempts failed, except the application of coding theory to retrieval systems, some leaders drew tight boundaries around the application of Shannon's theory to protect outsiders from controlling information science. Skeptics relied on the traditional tools of satire and history (e.g., Shera & Cleveland, 1977; Shera, 1983) to keep the intruders at bay.

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[8] The praise did not prevent Mooers from criticizing Fano's proposal a few years later. See Mooers (1960).

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