Communication Defined as Complementary Informative Processes*

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Abstract

Given a set of requirements for a definition of communication, we can define a communication as information that enters a process and eventually leaves its inverse process. For example, information is transmitted by speaking and received after processing by its inverse, hearing. This definition can be used to precisely describe and explain communication phenomena in an inclusive and exact manner. The nature of processes and their development is considered. Communication processes may support other processes, including non-communicative, evolutionarily adaptive processes supporting survival and reproduction. Communication is expected to develop in self-organizing systems, given certain assumptions. Receiving processes may be understood as information filters and their performance described, predicted, and understood. These precise definitions of communication and information can serve as the basis for a science of librarianship.

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1 Introduction

Communication occurs only when there are two associated information producing processes and the output from one process is the functional inverse of the other process's output. We can say that communication occurred and that information was transferred between the input to the first process and the output of the second. Note that *communication* and *information* are not synonymous terms. The formal incorporation of information and process into a definition of communication provides a model of communication that captures much of the common sense meaning of communication while allowing us to both accurately predict and precisely explain a great deal about communication systems. Dervin [Der93], in discussing the discipline of communication, notes that "It is process, however—the verbs of communicating—where we have something to offer that is, if not ultimately unique, at least for now ahead of the others."

How do we study "what happens in the elusive moments of human communicatings" [Der93], and what are "communicatings"? When communication is defined in terms of informative processes, one can study both the information that is conveyed and the processes that carry it. Definitions of communication often involve terms such as *knowledge, belief, meaning,* or *intention*. Moving beyond terminology about which many epistemologists and cognitive psychologists disagree to a definition that is often consistent with these abstract ideas but is based on more precise concepts enables us to use and build on the definition, as well as measure the output of communicating phenomena, both human and non-human. Human communication, a subset of all communication, plays a special role in the study of communication, but *human communication* is not equivalent to *communication*, and the former needs to studied as a subset of the latter. A precise but general definition of communication based on information requires a precise and discipline independent definition of information [Los97]. This will be provided below.

The study of communication phenomena may be divided into the experimental and the theoretical. Experimental studies of communication phenomena examine how informative processes work and precisely what information is provided by them. Statements are particular to a specific situation or domain and generalizability often becomes problematic. Theoretical studies of communication, on the other hand, address on a more abstract level the nature of processes and their outputs, as well as the inter-relationships between processes and their inputs and outputs. Mentioning inputs and outputs brings to mind introductory computer classes where this terminology is often introduced. Theoretical communication studies often use terminology similar to that used in computer science, with both disciplines borrowing terminology from the interdisciplinary theory developing in an area intersecting mathematics, computer science, communications, and engineering. *Process* and *information* are based on concepts in this intersection of disciplines.

Why should one be interested in a precise definition of communication? Having a useful definition or model of a phenomenon allows one to describe observations in a consistent way. In addition, such a model may allow us to accurately predict the characteristics of previously unseen communication systems. Most importantly, a successful definition and model helps us to explain how the system operates, leading one to an understanding of the nature of the system.

A satisfactory definition of communication should preserve some of the ideas in the common understanding of the term. Such a definition should be consistent and include only those items that need to be included, omiting mention of aspects that need not be included. At the same time, a definition should allows us to both better understand what communication is, defining clearly what phenomena are to be included and which are to be excluded from the domain of communicative phenomena, as well as to measure and evaluate communication systems both quantitatively and qualitatively. Qualitative studies emphasize understanding in a way that demands precision, and we believe that this definition brings to the discipline of communication a precision that is *necessary* and *sufficient* for both qualitative and quantitative studies. The increased understanding gained from a precise definition comes from statements of what is and what isn't communication, as well as how a communicative system functions. Being able to describe how communication takes place allows one to manipulate system components, improving the quantity or quality of communication taking place. A precise statement of the function of a system also leads to improved evaluative methods, with feedback from these leading to improved systems, and so forth. A clear statement of the domain of study allows one to focus on a phenomenon that is definitely part of communication, and thus worthy of study in depth, or one may address other phenomena with the understanding that they are clearly less central to the field.

2 Information

Information has historically been understood and measured in a wide variety of ways. Usually these models are discipline specific or limited in scope. For example, physicists speak of information in thermodynamic terms, while epistemologists describe information as something that occurs within the context of higher level human cognitive processes. We briefly present here a number of different ideas about information, concluding with a discipline independent definition of information that can be used to provide a basis for a general definition of communication.

The most widely understood notion of information for English speaking children may be seen in Cookie Monster's definition of information as "news or facts about something." Other definitions tend to be more explicitly human-centered, such as "information is knowledge." Similarly, Dretske [Dre81] views information as something that brings us to certainty, a definition that annoys those who use probability theory and assume that one can never be absolutely certain about anything. More formal than this is Bar Hillel's model of information as what is excluded by a statement [BHC53, BH55]. Bar Hillel's definition provides a bridge between formal and rigorous definitions of information and the idea of meaning. Based upon earlier thermodynamic models of entropy, Brillouin [Bri56] suggests that "information is a function of the ratio of the number of possible answers before and after...." and that anything that reduces the size of the set of answers provides information. Shannon's model of information and communication, with which we assume the reader is familiar, measures information as inversely proportional to the probability of a signal [Sha93b, Rit86, Rit91, Los90]. Most of the measures of information produce numbers similar to those produced by the familiar Shannon model, with the amount of information being inversely proportional to the probability of an event.

Several measures of complexity and information explicitly address processes. For example, several scholars, including Kolmogorov [Kol65], Solomonoff [Sol64a, Sol64b], and Chaitin [Cha77], have separately developed measures of the complexity or information inherent in a process as the smallest algorithm that produces the output produced by the process in question. The Minimal Description (MD) of the process, with all redundancy and extraneous material removed, captures the essential nature of the process. Slightly different than this is the Minimum Description Length (MDL), the length of the smallest description for a process, proposed by Wallace [WF87, WB68] and Rissannen [Ris89].

One measure of information, seemingly more popular in the U.K. than in North America, measures information as inversely related to the variance of a variable [Fis25, Mac69]. As we learn more about a variable or an event (e.g. the average height of communication scholars) the variance of our estimate decreases and the information increases.

There is a large gap between what is provided by a measure and what is provided by a definition, and many of the measures developed in the "hardest" of the sciences do not explicitly provide an associated definition. Information scientists, for example, may propose a model of an information related process and then measure a characteristic of the model without necessarily providing a clear definition of their terms. Definitions help clarify the essence of a phenomenon, while a measure may capture what is important in some respect about the phenomena. A measure without a definition is still useful, however a definition would improve the understanding of the context for most measures. We propose a definition of information, followed by a definition of communication, but one may also think of either more generally as a model allowing us to measure, describe, and predict characteristics and relationships.

Information and communication may be defined in relationship to the processes that move the information from the beginning, or entry of the information into the channel, to its exit from the channel. A process is an action-medium that moves an input presented to the process to the output, possibly assigning new values to one or more output variables. We use the term *process* because of Church's thesis, widely believed to be correct [KMA82], which suggests that processes, functions, and algorithms all describe the same phenomenon; all these models of computation for most purposes are equivalent and one may describe using one of these and at the same time satisfactorily also describe as effectively as if one were using one of the other models.

Information may be defined [Los97] as

> the values for all variables in the output of any process. This information is *about* either the process, or the inputs to the process (the context of the process), or both.

A process is a set of related components that produce or change something. When studying an information system, there may be one large process or several smaller processes. The scope of the process is not important to our definition of information, or later to our definition of communication. However, the choice of how to view a process will affect how one may study or understand the process. For example, the reader may view the entire process that takes the author's thoughts and results in the thoughts being understood by the reader as a communication process, or one may view numerous small steps in the writing, publishing, and reading processes as linked processes. Whether viewed as one large process or several smaller processes, the information presented at the end of the entire large process or at the end of the set of smaller processes is the same.

The amount of information produced by a process may be measured, as with Shannon's model, as the logarithm [Har28] of the inverse of the probability of the state of nature found at the output of the process. This may be used for the values of both discrete and continuous output variables. An output variable with a value having associated probability of $1/4$ may be computed as having $\log_2 4 = 2$ bits of information, for example.

We refer to a process that produces output from a context (defined as the set of values presented to the input of a process) as an *information channel*. The channel is that set of components that implements the functionality inherent in the process. A channel might be implemented by a computer and its program, or it might be a mechanical device such as a pantograph that reproduces an input movement at the output with a pre-specified degree of magnification.

Processes may consistently produce the same result when given the same input and context. These *deterministic processes* are what most people mean when they refer to *a process* in an unqualified manner. Given the same input, two identical *probabilistic processes* may produce different results. The output of a probabilistic process may be described by a probabilistic distribution or density function. Observers of such a process may understand the randomness as coming from two sources: inherently random processes and error-producing noise.

The process based definition of information differs in several respects from Shannon's model of information, to the extent that Shannon's ideas about information may be separated from those he had about communication. Shannon views communication systems primarily as transmitting symbols between a source and a destination. This is very different from the process model proposed above which produces output from input, with *no* explicit attempt being made to encode or represent something symbolically, or to be message based. Shannon notes that his theory is "quite different from classical communication engineering theory which deals with the devices employed but not with that which is communicated" [Sha93a, p. 212]. Shannon's focus clearly was on the message.

Unlike Shannon's model, the process model describes information as the outcome of any process, not just an encoding process in a symbol based communication system. The process model of information, for example, can be used to describe an *addition* process that accepts two inputs and produces the sum (information) at the output. This output is informative about the additive process and the inputs. This notion of aboutness is similar to Devlin's notion of a constraint [Dev91]. While the addition process could be interpreted as encoding the input, that is certainly not a very natural interpretation and is certainly not a required interpretation if we wish to understand arithmetic sums. Similarly, the process model of information measures the information at the output as proportional to the number of possible states and their relative frequency in the output.

Each process accepts inputs or environmental characteristics and produces something (or nothing), given these input values. The function $f(x)$ denotes the processing (or encoding) of x by function $f()$. A function $f()$, when combined with its functional inverse $f^{-1}()$, accepts a variable x and produces as output x, which was presented to the processes at the input; i.e. $f\left(f^{-1}(x)\right) = x$. For example, the square and the square-root functions are well known functions with each being the inverse of the other for positive numbers. Thus, $\sqrt{3^2} = 3$ and $\left(\sqrt{3}\right)^2 = 3$.

Consider again the *addition* function and its inverse. An addition function that accepts two inputs and produces an output, the sum, discards information that was present at the input (the output of other processes). One cannot work backwards from only the sum to the original two numbers (the reader is encouraged to consider what the original pair of numbers might have been if the sum is 3.)

Consider a function which produces both the sum of two presented numbers and the difference between the two numbers. This function hasn't discarded any information in producing the sum and the difference, in that one can work backward to produce the original numbers. Consider a sum of 3 and a difference of 1; one can solve $x + y = 3$ and $x - y = 1$ to produce $y = 1$ and $x = 2$. Given a *lossless* process, in which no information is lost during processing, there is always an inverse process that can recreate the input to the first process.

Is this precise model of information too narrow to be of much practical use by scholars? Saracevic and Kantor [SK97] suggest that such normative approaches, including "formal and rigorous models involving uncertainty...." (p. 532) take "the narrowest view of information." We disagree, believing that the above rigorous and general model represents a very broad view of information, with other models of information being capable of being shown to be special cases of this model. Below, we present what we similarly consider to be a general, yet rigorous, definition of communication.

3 Defining Communication

Hundreds of explicit and implicit definitions of communication have been published in the communication and related literatures for use by scholars and practitioners trying to describe, predict, and understand communicative phenomena. These definitions vary around the common language definitions, with variations depending on individual scholarly interests and general scholarly trends. The diverse definitions of communication offered by Hauser [Hau96, p. 7] serve as a representative, albeit small, sample of ideas about communication from a wide range of disciplines. Of seven definitions provided by Hauser, three definitions of communication place communication in the context of humans or organisms, while a majority mention the effect of a message on its recipient.

Edward Wilson notes that "the ongoing fragmentation of knowledge and resulting chaos in philosophy are not reflections of the real world but artifacts of scholarship" [Wil98, p. 8]. The definition of communication developed below is both rigorous and general in capturing all and only the communication phenomena in the "real world." We are not trying to build on traditional definitions of communication and our definition isn't "an artifact of scholarship"; instead, we build a model of communications on both a precise definition of information and on a list of required characteristics for a definition of communication. Thus, there is no explicit preference for which side should win in long-running intra-disciplinary debates, such as whether there is intrapersonal communication, for example. We assume that communication has the following characteristics (derived in part from questions posed by Motley [Mot90]):

1. communication is characterized by information transfer,
2. processing takes place in communication systems,
3. both the sender and the receiver are actively involved in a communication system, and
4. the quality of communications varies.

Communication should be defined without regard to possibly false assumptions made about portions of the communication system. Put differently, we will assume that numbers 1 through 4 above need be the *only* characteristics used in developing a definition of communication. We thus begin developing our model of communication from observable phenomena and the desirable characteristics of a definition describing the phenomena, not from traditional definitions.

We choose not to place an emphasis on communication as symbolic in nature. Motley [Mot90] emphasizes this symbolic nature, mentioning that "Cronkhite (1986) presents a very compelling case for symbolic behavior as the common denominator of all communication study." However, as Hauser [Hau96, p. 507] notes, the symbolic approach may not be the best in all situations, although it is certainly a reasonable assumption for some models of communication. We also choose not to focus on intentionality, motivation, or the behavior of the sender or receiver. Instead, we adopt an approach that, with the precise model of information developed above, provides us with a more physical, observable, and precise set of requirements for a definition of communication.

We may define communication in a precise and information-based manner using the characteristics above, allowing us to understand the mechanisms underlying communication.

> *Communication* occurs if, and only if, information moves from the input to one process to the output from a second process, the latter process being the inverse of the first process.

We refer to the information at the output of this inverse, receiving, process, as *a communication.* Communication is more complex than information; communication processes are composed of multiple complementary informative processes.

Here we have two informative processes, the second of which "undoes" what the first process "does." Viewed loosely, hearing, for example, undoes what speaking does. Telephones provide communication circuits, providing an input device at one end of a connection and an inverse, decoding process at the other end. Similarly, the language component of a person talking on the telephone may be said to communicate with the (inverse) language component of the listener. The knowledge components of the two are in communication.

Using this model of communication, we may define a communication *receiver* as the implementation of a function $f^{-1}()$ where $f()$ is referred to as the communication *transmitter.*

If the first process merely copies the input to the output, and the inverse process copies its input to its output, communication is taking place under our model. This "straight wire" system clearly neither encodes nor decodes, showing an obvious difference between this model and other models based on *encoding* and *decoding* of *messages*. None of these three concepts is essential to our model of communication. We use the communication jargon "encoding" and "decoding" to

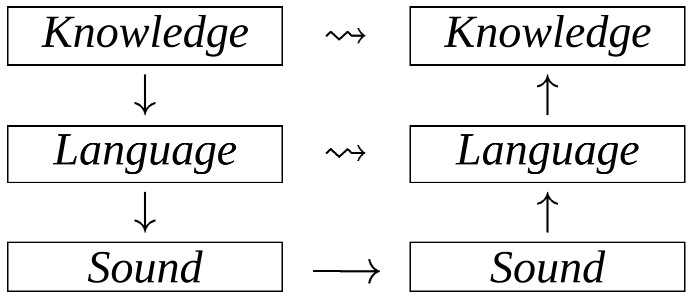


Figure 1: A hierarchical model of human communications representing the passage of something being transmitted, being transformed or encoded (left) and decoded (right). The straight right arrow represents a physical connection between the processes, while the squigly right arrows for the higher levels represent channels provided by the lower level processes.

represent $f()$ and $f^{-1}()$ but note that in cases such as the "straight wire" system it becomes clear that this terminology captures the essence of this copying operation only weakly, if at all.

Not all information transmitted represents communication. Given communication defined in terms of inverse processes, the page you are reading isn't communicating with you. You are receiving the information that is on the page because of visual processes. The author *is* communicating with you through processes that first took ideas resulting in written text, and an inverse process within the reader is taking written text and transforming it back into thoughts. Similarly, if one person is talking to another and is nervous, the nervousness may be communicated to anyone who can translate observed perspiring or a quivering voice or shaking hands into an understanding that the first person is nervous.

Figure 1 shows a hierarchy of processes used for information transfer and communication. Consider each hierarchy representing an individual. One communicates her or his knowledge in language, which is further transformed or encoded as sounds. These are decoded on the right hand side, producing language from the sounds using an inverse function, and the language is converted back into knowledge, again through the function inverse to the function that initially transformed the information. The decoding takes place on the right hand side, with ascending function $f^{-1}(x)$ representing the inverse of the $f(x)$ function; the functions on the right hand side of Figure 1 "undo" what the earlier processes on the left "did."

In addition to different physical phenomena being modeled by specific layers of a hierarchy, psychological and epistemological phenomena may be represented by layers in a communication hierarchy [Los97]. For example, a perception function may have as output a belief instilled in the individual, and a belief function in turn may produce knowledge.

Note that the choice of a hierarchy as a structure is arbitrary and that a set of communication processes may be also understood as placed in a straight line, with one set of processes producing information which is then presented to the inputs to the inverse processes. Using the notion of a hierarchy facilitates an understanding of the relationship between related individual information processes and the larger communication processes. We also do not mean to imply that encoding or decoding as Shannon viewed these operations are essential to this model of communication. While the hierarchical model emphasizes transformations which may be interpreted as the traditional encoding and decoding found in more traditional Shannesque models, remember that a straight wire may allow one end to communicate with the other end, with little processing present to suggest the encoding and decoding metaphor.

This model of communication differs from many more traditional approaches to communication. At the core of the difference is that the model used here is not human-centered. It doesn't have being human, or even organic, as a prerequisite for being an endpoint in a communication system. This expands communication systems to include processors such as computers, as well as less sophisticated reproducing devices such as photocopiers. By not arbitrarily limiting the system to humans, little is lost and much is gained, both by describing phenomena outside humans that seem very similar to what is traditionally referred to as *communication* and by greatly simplifying the definition and making it precise. Because the definition is not explicitly biological in nature, it is also not explicitly intentional in nature. Intentional characteristics can be incorporated into processes; modeling communication as complementary processes can be consistent with intentional processes and human communication, allowing models of communication such as that described by Sperber and Wilson [SW95] to be seen as describing communications that are special cases of this more general model of communication. Unlike many models of communication, however, our communication processes are *not limited to* intentional or human phenomena. Similarly, communication does not have to transmit *meaning* or be intrinsically symbolic, although these phenomena can be incorporated. This differs from Shannon's model of communication, which begins with a source which ”produces a message or sequence of messages to be communicated to the receiving terminal” [Sha93b, p. 6]. Similarly, when Shannon says that we can ”roughly classify communication systems,” the categories are described as having a message component [Sha93b, p. 7–8].

Scholars such as Oliphant [Oli97] have accepted that many of the popular existing definitions of information are inadequate for their work and have developed their own definitions for the purposes of their research. We believe that the proposed definition of communication is a universal, domain independent definition that allows for many of the concerns motivating other definitions of information. We thus feel that this definition serves as a common definition of communication for the field, providing a common language. Additional constraints may be added to this, but they are not part of the fundamental nature of communication; they are additional constraints that may or may not be worthy of discussion based on their own merits.

As we defined an information channel, we may define a *communication channel* as the set of components in the universe that implement the functionality *needed* for the communication process to take place. Because communication requires two or more information processes, *a communication channel always consists of two or more information channels in series*. By using the word *needed*, we refer only to those components that directly and obviously contribute to the operation of the channel, ignoring the fact that a butterfly moving on the other side of the world does affect the performance of a communication system on the reader's side of the world.

Using this model of communication, we may measure both the amount of information that is present at different points in the model. For example, we may measure the amount of information entering the system as well as capture and describe the information at the output of the first and second processes and at intermediate points in a communication hierarchy.

4 Basis for a Hierarchy

For a system to be a communication system, it must be composed of two complementary informative processes. If we are to study a communication system as composed of more than one function, that is, we choose to treat it as something other than an indivisible whole, it is necessary to break the larger process into smaller processes. Central to breaking a process into parts is determining which descriptions of processes are most natural and best help us describe, predict, and understand the communication system. In some decompositions, the resulting sub-processes may appear to be natural, having a reasonable explanation, while in other cases, the division into sub-processes will appear very arbitrary in nature with unnatural sub-processes. Obviously, a decomposition that produces reasonable explanations is superior to one where the boundaries between processes are arbitrarily chosen.

Communication processes may be delimited so that they represent an entire receiver or an entire sender, or processes may be viewed as being much smaller, so that many of these smaller processes together constitute the processing capability of an individual. If the most natural form of a hierarchy is with a large number of small processes, it may be easiest for an organism to learn the details of each smaller function instead of learning the nature of a single, large function. On the other hand, in some cases it may be beneficial to define a process larger than a single individual, with, for example, a group of people producing a document, or an individual reading a document, including the document and its production, in a single large process.

There are a number of processes that occur frequently in higher level species, including a number of components to natural language processing, such as the movement of vocal cords, the reception of sound and its translation into neural signals, syntactic processing, and phonological processing. Hockett has suggested that there are at least 13 different features (and thus functions) in human communication [Hau96, p. 47]. No other species has all 13 features, although many species have several. These may serve as a basis for an understanding of the human processes in natural language communication hierarchies.

Those processes that exist and are observable are more likely to have contributed to the survival of the greater systems within which the process exists than are less adaptable processes that did not contribute as much. A process may contribute to its own survival, or it may contribute to the survival of similar or identical processes in other systems, when contributing to the survival of others increases the chance for similar processes to appear in future systems. For example, someone who can communicate the nature of a vaccine for a childhood disease that can save the lives of millions of children may not increase their own chance of survival but will increase the number of communicative humans with intellectual abilities similar in some respects to those of the vaccine's developer.

We refer to systems that take on increasingly sophisticated and non-random structures as they evolve as *self-organizing* systems. Functions may be learned or may evolve through self-organization over time. This often occurs because increased organization or structure itself leads to increased adaptability and survival, although we should not make the mistake of assuming that increased complexity necessarily implies increased survivability [Gou97]. Through learning processes, a function may infer the characteristics and parameters of a function of interest through supervised learning, where labeled cases are learned when inferring a generalizing principle. The effect of learning also may be produced through evolution, with randomly generated variations either surviving with increased or decreased frequency over time. This has the effect of learning adaptive characteristics.

Learning communicative functions through evolutionary processes requires the presence of a higher level layer that both produces and receives information. In the case of bees said to be communicating through *dancing*, there is a process above the dancing process (which has evolved) that allows the dancing process to be be evolutionarily supported by increasing the survival rate of bees with dancing (or understanding) skills.

Any process located above another process may be a *goal* process that rewards, allowing the function before it to evolve. We refer to a function that maximizes a goal function as *maximally useful*. For an informative function to be learned genetically, it must support a goal which is relatively constant in the species, with evolution leading toward it becoming maximally useful. Goal processes often contribute toward reproductive behavior or are survival related. Communication processes produce results with the systems in which they occur such that similar processes are as likely or more likely to survive and reproduce than they were before. This is because introducing communicative capabilities essentially makes a system larger, which can lead to increased self-organization, than would be the case with individual, smaller, non-communicative systems.

Given our model of communication, communication systems are likely to develop in self-organizing systems because of their support for what are conceptually larger systems, leading to more self-organization and increased adaptability. We assume that it is almost as likely that if one process evolves then its inverse will also evolve. We also assume that information about another system may be beneficial to the system in question under many circumstances and thus communication systems are evolutionarily adaptive.

5 The Performance of Processes

All receiving informative processes within a communication system may be viewed as filtering processes, selectively providing information to a process immediately succeeding (above) it in the right half of the hierarchy. Some processes pass no information to succeeding neighboring processes, some processes selectively pass information, while others pass all input information to their neighbor.

A neighbor process whose output is input to a second process is referred to as a *context* for the second process. When *all* input to a particular process comes from the output of another process, the latter process is the *full* or *complete context* for the former process. The context may be viewed as providing a query or statement of information need for a filtering process.

A filtering process accepts information from the process below and, based upon the context and the interests and needs it represents, will transmit or not transmit information to the level above it, depending on the incoming information and the context provided from its predecessor and other processes. Information that is passed to a higher level process may modify the context itself and may thus affect future filtering actions. The filtering process may thus be recursive.

Consider a message with one binary characteristic which would occur in a noiseless informative process transmitting a single bit. The characteristic occurs with probability (and average frequency) p in messages to be passed (referred to as relevant messages) and probability (and average frequency) t in all messages [Los98]. If a filter attempts to pass only those messages at or above the average position of relevant messages in a list of messages ordered by decreasing relevance, the percent of all messages that will be passed is $1-(1-p+t)/2$. Smaller values represent better filtering performance. Clearly, other filtering performance measures will be needed with more complex term relationships and probabilistic distributions, but this indicates the kind of result that may be obtained, increasing our understanding of communication systems.

6 Imperfect Communication

Defining communication as the output of two complementary informative processes describes communication in an ideal noiseless environment where the second function is a perfect inverse of the other. Here, the second function perfectly "undoes" what the first function "does" and there is no noise introduced into the system.

In the real world, however, there is almost always noise present and communication is imperfect, except in the presence of error correcting codes that allow the recipient of a message other than the message that was sent to recover the original message [Ham86, Los90].

We refer to the output of a noisy communication channel as *noise modified communication.* Communications received that have been noise modified but can be understood accurately or used by a human, even given the noise induced changes in it, are *acceptable noisy communications*. These errors or noise may be induced by external processes and events, causing the informative processes to function differently than they would without the error producing process. Noise or errors in the information may be viewed as additive if the operations of each process are independent of the operations of the other processes and these processes are in series.

In many cases, the inversion provided by a process f or f^{-1} is imperfect, that is, for some $x,$ it will be the case that $f\left(f^{-1}(x)\right) \neq x.$ For example, consider the case where the author who grew up in the northern United States refers to *snow* when talking with his daughter, who has spent her life in the southern half of the country. The author's hierarchy encodes a certain set of meanings as *snow* while his daughter decodes the term *snow* as a rather different phenomenon. Here the daughter's receiving function isn't the exact inverse of her father's encoding function.

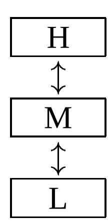
The acceptability of noise-modified or imperfectly inverted communication may be best viewed as either binary or continuous. The exact nature of the acceptability function is an empirical question to be determined for any given communication channel. Binary acceptability occurs when a message is either acceptable or not acceptable. Acceptability may thus occur when the message is similar to at least a certain degree to an expected message. Acceptability may also be continuously valued, that is, the acceptability itself can take any of a range of values from, for example, 0 to 1, depending on how close the acceptability is to the best-case acceptability and the worst-case acceptability.

7 Branching Communication Hierarchies

The proposed definition of communication systems as complementary informative processes enables one to accurately model and understand a range of communication phenomena. With this model, we can describe and predict the characteristics of previously unstudied systems. While the linear hierarchy presented above captures simple communication environments, the usefulness of the model may be improved significantly if we allow a single process to have multiple processes beneath it (which we refer to as multiple *feet*) and multiple processes above a single process (which we refer to as multiple *heads*). Doing this allows claims to be made about multiple heads and feet that more closely reflect the complexity of real world settings. In addition, graph theoretic communication models may be applied to complex structures, providing a wider range of both quantitative and qualitative models of communication.

Consider that the author might be able to communicate with you through this publication, or through email, hand-written correspondence, or by telephone. Each different medium can be represented by a different foot. The author's language component can be understood as having below it several feet, each consisting of one or more communication processes connecting the author and the reader.

Modeling social communication systems may be facilitated by using multiple "feet" in the model. A group of people having a particular relationship is referred to as a social network, which may be studied qualitatively [Cha92] or quantitatively [WF94]. The study of social networks can be viewed as the study of which processing feet exist for each individual and what other feet in what other hierarchies individuals use for communication. For example, assume that each individual has a hierarchy and that there are three levels on each hierarchy: high (H), medium (M), and low(L):



Consider where a particular social network is implemented by all the L levels for the individuals in the network being connected because all the L levels are the identical outputs of a single larger process which accepts as input information provided by any of the individuals in the group. When each individual in a set of individuals is connected and there is perfect communication, then we may refer to this set of people as constituting a social network. Each person in this group

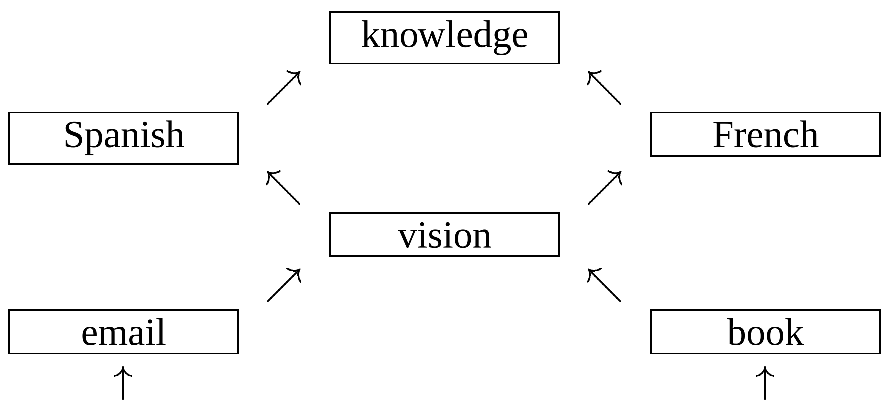


Figure 2: The hierarchies for incoming information from two different written sources and in two different languages.

receives information at the L level that individuals outside the network don't necessarily receive.

The diffusion of information or of an innovation is the transmission of information to some or all of the members of a domain of individuals, with the communication channels going from one individual to one or more others, with the recipient in turn possibly transmitting to one or more others, with time delays often occurring between transmissions [MP85, Rog83]. The diffusing information may spread from one person to another through any of a number of communication media and at varying rates [Cha86, Jen82, LB75, MP85, Rog83].

Person to person diffusion is modeled by each person having a foot connected to several other people's feet, each connection representing a possible point of contact between this individual and another. Diffusion through an individual thus depends on the individual receiving the information and the decision being made to pass along the information.

Multiple heads may occur within the processing of information by an individual human. Information that I receive may be processed in different ways and viewed differently by the author, who is a male, a father, and a teacher, all of which may affect different ways the information is processed given the different roles. These different ways of knowing allow one to communicate with someone else with the same way of knowing, while communication with someone else will result in inverse-function noise affecting what is received.

Consider a situation where we have two overlapping groups of language speakers, with one group speaking French and one group speaking Spanish. There is also a group of people using email, and a group not using email. We may model this situation as in Figure 2 which shows multi-headed and multi-footed processes.

There are consequences to modeling a communication system as a multi-headed multi-footed monster. Such a model claims that hierarchies of processes “meet” and that there is a common meeting point that is perhaps critical to the effective operation of the communication system. In addition, meeting points that bracket a set of processes above and below suggests that each of these processes may be treated as a single type of functional unit. The existence of these units has a natural support and the study of these units may be more profitable than the study of units with lesser degrees of support. Each unit may evolve, increasing the rate of survival and reproduction of those creatures with this function.

8 Characterizing Communicative Processes

Being able to precisely characterize a particular communication system allows one to compare communication systems, including deciding whether two systems are equivalent, as well as providing a method by which one can rank communication systems based on their characterization. One may also characterize a system by naming or describing it, based upon its content. The Minimum Description Length (MDL) for a system is the shortest length that can describe and differentiate one process from others in the domain of possible processes [Ris89, WF87]. The Minimal Description (MD) characterizes what makes up a system, and thus identifies what is complex and special about each system. A system which is easy to describe has a relatively short description and a small MDL, while a very complex system, approaching randomness, would have a relatively large MDL.

We are describing only the two informative processes defining the communication system. If we have two processes, and there are many other processes below them on the hierarchy, we may compute the MDL by considering only the complexity of the two informative processes, with no attention being paid to processes below. We might, however, choose to view the world as containing larger processes, e.g., you as a process and me as a process, in which case the MDL would be computed for me or for you and might or might not include this medium. Because the reader differs from the author, the reader function is not a perfect inverse of the writer function, making the MDL much larger than if the author were writing for himself, the reader then being a near-perfect inverse of the writer. The ordering of systems, from simple to complex, can be accomplished by listing the systems in order of their MDL value, e.g.

Order	*Minimum Description Length (MDL) in bits*
1	$10^0 = 1$ (simple)
2	$10^2 = 100$ (medium complexity)
3	$10^5 = 100000$ (very complex)

An ordering such as this may be used to compare communication processes.

9 Summary and Conclusions

A satisfactory definition of communication should describe the phenomenon of interest. A better model will both describe existing events and predict the characteristics of future communications. The best definitions would help explain what is occurring, as well as allow us to describe and predict. The model of communication as complementary informative processes is based on a set of requirements for a definition of communication and a precise definition of information. The precision in this model of information, combined with the precision of the definition of communication, allows us to state explicitly what is and what isn't information and what is and what isn't communication. One may then define *a communication* as what is transmitted from the beginning of one process to the output of a process with the inverse functionality of the first process.

Most phenomena referred to in the form "X to X communication," such as "human to human communication" or "machine to machine communication," are communication under our definition of communication. These expressions imply communication between the same levels of two different hierarchies, or, more formally, between a function $f()$ and its inverse $f^{-1}()$. Defining communication as two complementary processes allows us to both predict what will happen in the presence of noise or the failure of functions to be exact inverses. One can also understand the human aspects of communication, as well as the low level biological and physical phenomena such as speech or hearing and the physical transmission of sound through the atmosphere or the transmission of words through the movement of written pages.

Our precise definition allows us to include phenomena as well as to exclude phenomena. A definition (such as ours) of a phenomenon central to a discipline such as communication may diminish or exclude some phenomena in two ways: by saying that something isn't the concept being defined, or that a characteristic isn't an intrinsic part of the phenomena being defined, decreasing its importance to the definition and to the field, while not excluding it. A precise definition may not explicitly include a number of phenomena of potential interest to communication scholars, while being consistent with less inclusive definitions often used in the field of Communications. Unlike some other definitions, our model suggests that a wide range of phenomena can be viewed as part of a communicative system, but are not necessarily part of communication. For example, given the characteristics of communication described above, this page does not communicate with the reader, but we might say that the author *is* communicating with the reader. Characteristics of communication, such as intention, aren't included directly in the proposed definition; it isn't excluded, but it isn't explicitly included either. The definition discussed here is more inclusive than most other definitions, while at the same time having more rigor than most. This increases our understanding of communication, and can lead to a more stable foundation for the art and science underlying the information and communication professions, including librarianship.

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