Hierarchic Social Entropy: An Information Theoretic Measure of Robot Group Diversity

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How should diversity be quantified? Shannon faced a similar problem when he sought to quantify the uncertainty, or randomness, of an information source (Shannon, 1949). The uncertainty of an information source has important implications for communications systems, particularly with regard to the minimum band width required to transmit error-free messages. Interestingly, the properties Shannon sought in a measure of information uncertainty are also useful in the measurement of societal diversity (Shannon, 1949). In fact, researchers in a number of disciplines have adopted information theoretic concepts of diversity. As an example, consider this passage from Wilson's book The Diversity of Life (Wilson, 1992):

> Suppose that we encounter a fauna of butterflies consisting of 1 million individuals divided into 100 species. Say one of the species is extremely abundant, represented by 990,000 individuals, and each of the other species therefore comprises an average of about 100 individuals. One hundred species are present but, as we walk along the forest paths and across the fields, we encounter the abundant butterfly most of the time and each of the other species only rarely ... In a nearby locality we encounter a second butterfly fauna, comprising the same 100 species, but this time all are equally abundant, represented by 10,000 individuals each. This is a fauna of high equitability, in fact the highest possible. Intuitively we feel that the high-equitability fauna is the more diverse of the two, since each butterfly encountered in turn is less predictable and therefore gives us more information on average.

Wilson's view embraces the idea that societies with members equally distributed among subsets are the most diverse. It also suggests that diversity and information are closely related concepts. Information entropy is used in a number of related fields as well. It is used by ecologists as a means of evaluating species' diversity (Lurie et al., 1983; Lurie and Wagensberg, 1980; Magurran, 1988), by sociologists as a model of societal evolution (Bailey, 1990), and by taxonomists as a tool for evaluating classification methodologies (Sneath and Sokal, 1973; Jardine and Sibson, 1971).

Shannon's measure, *information entropy*, is easily adapted to suit the needs of a societal diversity metric (Shannon, 1949). Bailey popularized the application of information entropy to the study of social groups in his book Social Entropy Theory (Bailey, 1990). Although the formulation of simple social entropy for robot groups is somewhat different than Bailey's formulation for human societies, we adopt his term here.

Boundary Maintenance in Living Systems Theory and Social Entropy Theory

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Social Entropy Theory (Bailey, 1990, 1994) views the social system as an entity that seeks to maintain internal entropy at some optimal level below maximum entropy. The role of the boundary is crucial in this task. The societal boundary must be able to open in the proper manner and at the proper time to ensure that adequate inputs of energy and information can be attained from the environment, that refuse or harmful material can be properly extruded from the system, and that needed exports of matter- energy and information can be moved across the boundary.

Conversely the boundary must be able to close in the proper manner and at the proper time in order to ensure that the system remains secure from threats outside in the environment (prohibits harmful inputs), and also guards against the loss of valuable internal resources (prohibits harmful outflows). Thus, the functions of boundary maintenance are fourfold: to open in a manner that (1) ensures needed inputs and (2) ensures needed outputs, and to close in a manner that (3) prohibits harmful inputs and (4) prohibits loss of valuable matter-energy or information through harmful outputs.

Social Entropy Theory states that the social system functions on a daily basis by regulating six key system components: Population (P), Information (I), Space (S), Technology (T), Organization (O), and Level of Living (L), which can be remembered by the alternative acronyms of PILOTS or PISTOL. This framework can be used to analyze the large variety of flows across the body of a given social system.

These flows across social boundaries can be roughly divided into matter-energy flows, or information flows (Miller, 1978). We can identify eight essential dimensions presented in that can be represented in terms of flows or movement across boundaries. These are: (1) human population; (2) elements from the internal environment (for example, plants, animals, or minerals); (3) energy; (4) culture; (5) technology; (6) information; (7) organization; and (8) level of living (for example, wealth).

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Social groups obviously can vary widely in their ability to achieve their specific boundary maintenance goals. Efficacy in boundary control can depend upon a number of factors, including the following:

1. The distance from the central decider (government) to the boundary.
2. Accessibility of the boundary.
3. Physical conditions, terrain, and topography at the boundary.
4. Length of the boundary.
5. Form of the boundary, and so forth.

The physical form of the boundary can vary widely. In some cases it may be basically only an "informational" boundary consisting of a line on the ground, or merely a sign indicating the location of the boundary. In other cases the boundary might be a wire, or a small fence, or a very large and impenetrable fence or wall such as the Berlin Wall. In some cases it is unguarded. In other the boundary is an expanse of territory that is heavily guarded and filled with land mines, such as the North Korean-South Korean De-Militarized Zone (DMZ). Although it is a gross generalization, we can say that the boundaries that control the flow of matter-energy tend to be the more traditional physical boundaries such as gates, fences, and steel shutters. These gates and shutters are often mechanized, and can thus be controlled through motors that are capable of moving them rather rapidly.

Notice, however, that even physical boundaries that are regulated to either bar or admit physical (matter-energy) flows, also require the use of information. Thus, boundary regulation is generally not solely accomplished through physical (matter-energy) processing or solely through information-processing, but is a combination of both.

For example, consider the common occurrence of visitors approaching the gate of a walled mansion in a wealthy residential area. Assume that this is the front gate, and is deemed a "public entrance." Assume also that it is never used for "transducer" functions such as garbage removal (another gate, in the rear, serves this purpose), nor for exits of persons from the mansion (yet another gate, a side exit gate, serves this function). ... It is always closed to outputs, and it is variable with regard to its openness of input....

Notice however, that while the gate is a matter-energy (physical) barrier, and is regulating the flow of matter-energy (primarily people), this regulation ultimately depends not only on matter-energy, but also on information. After the people approach the gate, the gate will remain closed, and they will not be allowed to enter unless some information is received by the decider that indicates that entry would be warranted, and would not be harmful to the group (family) residing in the mansion. This information must be transmitted by some form, such as direct voice transmission (speaking), wireless voice transmission, wired voice transmission, video, and so forth.

The length or distance of the information transmission required for gate regulation may vary widely, from a short-distance transmission to a gate-keeper such as an onsite guard stationed at the gate, to a much longer distance transmission to some more remote gate-keeping location. The particular information to be transmitted needs to be sufficient as a signal either to admit, or not admit.

This can be determined in a number of ways, such as the clothing of the persons desiring entry, an identification badge, or credentials (Miller, 1978), passports, passwords, and so forth. Since all of these are increasingly easy to imitate and thus to falsify, security decisions will increasingly be determined through data that is more difficult to alter. This includes biometric data such as fingerprints, unique blood vessel patterns in the face, patterns in the eyes, or even ultimately through rapid DNA determination conducted at the site.

While information is always required, along with matter-energy to process the admittance or barring of entry of matter-energy at a physical barrier, the reverse is also true. That is, the decision to either admit or bar information generally also necessitates the utilization not only of information, but also of some matter-energy or physical apparatus ("hardware"). That is, while information may be transmitted in via a "wireless" device, at some point, generally the organization and decoding of the message (and perhaps in between, as in the case of a satellite or transmission tower) there is "hardware" (matter-energy). You may devise a password to determine whether the information is to be admitted, and you may consider this password to be "information" rather than a physical entity, or matter-energy. Nevertheless, unless you imbed this information in some form of hardware (for example, your computer) it generally cannot fulfill its safeguarding function.

Thus, it is axiomatic that even when using matter-energy boundaries to control matter-energy flows, information processing is required. Conversely, even when using information boundaries to control information flows, matter energy is required. To summarize, it takes matter-energy to process information, and information to process matter-energy.

The classical distinction is that thermodynamics systems are "isolated" systems, whose boundaries are closed to flows of both energy and information (Bertalanffy, 1968). ... No living system such as a social system could conceivably exist in such a permanently closed fashion. Thus, in contrast to isolated or closed systems, social systems are said to be "open systems" (Bertalanffy, 1968; Parsons, 1951).

However, this term has often been used without clarification, implying that all social systems are permanently open. Often the types of flows that social systems are supposedly open to are not specified. ... While it is doubtful that any social system could survive if it remained permanently closed, it is theoretically possible (but highly unlikely) that a social system could exist in a permanently open state. However, this would certainly not provide an optimal quality of life. As we have indicated previously, a social group with no security measures in place to bar nonmembers can suffer not only losses such as the theft of resources, but also dilution of group identity, and contamination of its information base or ideology. Perhaps the sort of social group most likely to survive with totally open boundaries is one with minimal resources, and minimal invitations, theft, or contamination attractions.

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The average society cannot leave itself perpetually open even to flows of potentially valuable raw materials or food or energy, as it would then face subsequent problems of transportation and storage. It cannot leave itself open to unregulated information inputs without danger of information overload, which can be a rather severe problem (Miller, 1978). Similarly, it cannot leave itself perpetually open to exports of matter-energy or information without the risk of having all of its needed resources diminished.

... doubtless some societies would be willing to receive inputs of goods without reciprocating through exportation, but this is obviously difficult to achieve in a world of shortages. Probably the contemporary society that comes closest to this is North Korea, as it lacks a market economy, and can afford comparatively few exports, as the goods of the sort it produces are generally needed at home. However, it does welcome inputs in the form of humanitarian food aid, and does receive such aid from a number of countries.