MEASURING COMPLEXITY

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ABSTRACT

Metrics (i.e., numerical values) that measure complexity in problematic situations have numerous benefits in understanding complexity and comparing situations. But such measures have been elusive because of misperceptions of what constitutes complexity. The key to measuring complexity is to understand its nature. Once its nature is understood, it becomes clear that various linguistic adjustments are required to support definitions of metrics, and to understand their significance.

Since the resolution of complexity typically demands significant resources, of the type available in organizations, it is advisable to start to work on complexity with an organizational model in mind. Because of the wide variation in organizations, a surrogate must be chosen that is sufficiently reliable and flexible to be functional. This surrogate is the Coherent Organization, a virtual organization having three levels: producing, strategizing, and mediating between producers and strategists.

A discovery team, comprised of well-informed stakeholders (none of which fully understands the problematic situation, but each of whom has something to contribute beyond a desire to see the complexity resolved) generates data to be used in computing five measures of complexity, while at the same time moving toward an understanding that will position the team to take on the challenge of designing an alternative intended to resolve the problematic situation.

Friedman's Theorem of Non-Assured Model Consistency and Harary's Theorem of Assured Model Consistency provide the essential basis for two generating processes that are used to gather the data for computing the metrics. These are the Nominal Group Technique (NGT) and Interpretive Structural Modeling (ISM), both of which are embedded in a system of management of complexity called Interactive Management (IM). The necessary linguistic adjustments are embedded in this system, which has been tested for more than two decades..

The Miller Index measures the extent of the set of problems perceived by the Discovery team. The Spreadthink Index measures the extent of the differences of opinion within the team on relative importance of the various problems. The De Morgan Index measures the extent of paired relationships among the problems, and the Aristotle Index measures the density of logic embedded in the problematique arising from the group's work using ISM.

The Situational Complexity Index is a composite measure of complexity, computed as the product of three other indices. Empirically-derived values of all of these indexes are shown and the rationale for their definition and use is given.

WHY MEASURE COMPLEXITY?

Numerical indexes of complexity, called “metrics” enable several desirable outcomes to be achieved:

- **Establishing Presence or Absence of Complexity.** Offering numerical evidence of whether complexity is or is not present in some particular situation, or whether the situation is better described as “normal”
- **Enabling Situational Comparisons.** Enabling comparison of different proposed designs, according to which one appears to offer the least degree of complexity
- **Classifying Component Problems.** Classifying component problems in the set of problems to help determine strategies and priorities for resolving these problems
- **Enhancing Perspective.** Bringing supplementary perspectives to bear on complexity.
- **Facilitating Discussion.** Facilitating human interaction by providing augmented linguistics to serve the needs of conversation

Numerical measures that make possible cross-situational complexity comparisons are called “external measures”. Still other measures enable detailed decision-making within a particular situation. Numerical measures that make possible prioritization of activity in a problematic situation are called “internal measures”. Internal measures typically measure monadic features, i.e., matters related to what problems are perceived by individuals and how the individuals perceive the relative importance of the problems. External measures typically measure dyadic or triadic features, i.e., what relationships are perceived by a majority of the participants among pairs of problems, and what consequent triadic relationships occur as a consequence of (a) the dyadic perceptions and (b) the transitive nature of the relationship used for structuring.

Names are assigned to the external metrics in the light of the scientific history behind them. Alternative names may be used, which relate to human behavior in working with complexity.

Generating processes are used which provide the raw data required to determine values of the metrics. Algorithms enable computation of the values of the metrics from the raw data. Empirical evidence from applications shows (a) that the metrics have been tested and found useful in applications and (b) typical values and ranges of values for all of the metrics.

WHY HAVE MEASURES BEEN ELUSIVE?

Measures of complexity have been elusive because there is widespread misunderstanding of what constitutes complexity. This misunderstanding has been propagated by physicists and biologists who have worked with particular situations and assumed that all such situations have the same properties as the situations they work with. These groups have also regularly opined that complexity invariably involves behavior of the same type as that exhibited by certain nonlinear partial differential equations (though without emphasizing this constraint on their interpretations).

WHAT IS THE KEY TO MEASURING COMPLEXITY?

The key to measuring complexity is to understand the nature of complexity. Instead of presuming that it is a property of some ethereal system that is in the eye of some observer, complexity is the frustration that occurs when people cannot understand a problematic situation that is of great importance to them.

Measures of complexity can be grouped loosely into two generating subdivisions and two academic recipient groups. The two generating subdivisions are (a) one founded in physics and biology and (b) one founded in philosophy, logic, and human behavior. The academic recipient groups are management faculty and policy faculty.

Since the Physics-Biology group historically has a stronger scientific tradition than the Philosophy-Logic-Behavior group, it is somewhat surprising that the Physics-Biology group has failed to supply an empirical basis to accompany its theoretical musings; while the Philosophy-Logic-Behavior group has emphasized the empirical correlation with its theoretical results.

Unfortunately the Management-Policy group is heavily dominated by work stemming from the Physics-Biology group, hence faculty are preparing managers and policy specialists to think in terms of metaphors that are not correlated with empirical results.

The possibility of measuring complexity, based on the philosophy-logic-behavior group may possibly be understood better by noting the following story of three people and a tall building.

Three people were walking down the street in New York City: a physicist, a mathematician, and a mild-mannered newspaper reporter. As they came to the Empire State Building, the physicist remarked "I can leap over that building in a single bound!"

The mathematician asked "Is that a theorem or an axiom?"

The physicist replied "It is axiomatic, therefore I do not need to prove it by experiment."

The mathematician said "I too can leap over that building in a single bound."

The mild-mannered reporter asked "Is that a theorem or an axiom?"

The mathematician replied "It is a theorem. Therefore, I must prove it."

The mathematician moved forward, took a large leap, but failed to get more than a few feet off the ground.

"I am very frustrated," said the mathematician.

"Nonsense," said the physicist. "It is the Empire State Building that is frustrated because you could not jump over it."

The mild-mannered reporter said "I can leap over that building with a single bound." So he stripped off his shirt and, with a single bound, leaped over the Empire State Building. Then, for good measure, he leaped over it again, returning to the group he had left.

The mathematician said "Well, I guess you have proved that you can jump over the Empire State Building, and I suppose that also proves that I am frustrated, but the building is not frustrated."

"Nonsense," said the physicist. "Empirical evidence cannot overturn an axiom."

The Physics-Biology group holds that complexity is in the system that is external to the observer. Devoid of caveats, pronouncements are made that generalize well beyond the bounds of propriety. There is no acknowledgment that there exist formalisms appropriate to logical argument, nor that human beings exhibit limitations which preclude their comprehension of what they are frustrated by at some moment in time.

With few exceptions, the academic establishment accepts this point of view. The consequences of this acceptance for the future of management and policymaking will include a continuation and expansion of the same policy mentality that produced achievements such as the low-flush toilet. It will produce engineers that engineer by mathematics only, without any sense of the need for laboratory confirmation and amendment. It will produce managers that do not understand the need for business plans, and bankers who will fund such organizations.

The Philosophy-Logic-Behavior group holds that the joint recognition of the possibility of formal logic which is tailored to reflect the behavioral pathologies of human beings individually, in groups, and in organizations; enables people to work together to resolve complexity; and that more than two decades of experience with work founded in that belief establishes its validity empirically.

WHAT LANGUAGE IS REQUIRED TO MEASURE COMPLEXITY?

To work effectively with complexity, certain linguistic adjustments are required. These adjustments facilitate analysis, synthesis, and discussion involving complexity. Several linguistic adjustments are offered here. Incorporation of these adjustments into a language of complexity aims to advance Foucault's concept of discursivity[1], i.e., construction of a language that is comprehensive and founded in consistent logic.

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[1] Paul Rabinow, Ed. (1984), *The Foucault Reader*, New York: Pantheon

Since all human construction occurs in the form of models, two little-known theorems of modeling are offered to form a partial basis for the linguistic adjustments. These are expressed as Friedman's Theorem of Non-Conservation of Model Consistency and Harary's Theorem of Assured Model Consistency. Any system of discursivity that does not recognize overtly the import of these two theorems is unlikely to have any staying power.

The contexts in which such adjustments are important are (a) the "coherent organization" and (b) the scholarly communities that contribute to systems thinking and design. The Coherent Organization is a virtual organization, furnishing a context in which complexity is very often located, and wherein it must usually be dealt with if resolution of complexity is desired. The scholarly communities suffer from a plethora of opaque language and inconsistent linguistics across their societies and publications. This shortcoming requires correction.

THE COHERENT ORGANIZATION

By definition, complexity exceeds the grasp of the individual. Often the resolution of complexity requires significant resources that are unlikely to be available except in an organization. But even the conventional concept of organization is not adequate as a context for resolving complexity. This is a time of mergers of large organizations, and of task forces formed from a variety of organizations.

It is even possible that the inability of the individual to comprehend complexity, imprisoned by a constraining institutional setting, is responsible for what has been described as a "flight from science and reason" [Gross, et al, 1996] and for the ascendency and popularity of management gurus [Micklethwait and Wooldridge, 1996].

The Coherent Organization is a virtual organization with three organizational levels. Any conventional organization can be thought of as such an organization or as a changing collection of such organizations. Unfortunately none of the members of this collection nor the whole organization fits the definition of "coherent organization", hence one of the early steps in resolving complexity is to adopt this concept as the context within which resolution of complexity is attempted. This leaves open the later task of correlating the actual organization with the Coherent Organization model; something that is best done when sufficient structure has been discovered to make this possible.

The Coherent Organization is vertically organized into Levels 1, 2, and 3. The population of this organization is greatest at Level 3, the Producing Level, the level in which goods and services are produced. The population is lowest at Level 1, the Strategic Level, the level in which broad goals are enunciated, where most of the organizational authority lies, where budgets are voted on, and where the survival and growth of the organization is pondered. The intermediate level, Level 2, is the Mediating Level. At this level the Level 3 activities and the Level 1 strategies are mediated. In order for this mediation to be effective, people in the Mediating Level (let us call them "middle managers") must be aware of what is happening at both the lower and the higher level. They must also serve to educate the higher level people (let us call them "top managers") with what the producers are doing and what difficulties they are having. They must convey the organizational vision to the producers, lest they misplace their efforts, and convey the problems encountered at the producing level to top managers, lest they misallocate resources..

This model of the Coherent Organization is consistent with an older model sometimes applied in organizational planning; where the concept of strategic, tactical, and operational practice has sometimes been useful. However the model of the Coherent Organization was essentially an empirical outgrowth of two investigations that were carried out with Interactive Management [Warfield and Cárdenas, 1994]. One of these investigations produced "The Alberts Pattern" [Alberts, 1995], and the other produced "The Cárdenas-Rivas Pattern"[Cárdenas and Rivas, 1995]. None of these investigators began with the concept of Coherent Organization; but they developed structural patterns that showed three-level structures. Moreover, each provided the necessary language to enable coherence among the three levels, using the detailed structures developed at the Producing Level.

To carry this discussion further requires linguistic adjustments that enable more details to be advanced.

REPLACE "THE PROBLEM" WITH "THE PROBLEM SET"

Extensive empirical evidence in working with complexity has made clear that the statement "let's begin by defining the problem" is the opening scene of an evolving linguistic nightmare. Whenever complexity is involved, hundreds of cases have shown that the producing level will identify dozens or even hundreds of problems. A problem must be seen as follows:

a) A **human construct**, in which an individual asserts an intangible condition that the individual finds unsatisfactory, requiring corrective action
b) A **component of a set** of problems (which cannot **also** be called "the" problem, if dialog is to be coherent)
c) A **component of a structure** in which an interrelationship among the problems is shown by means of a graphic called a **problematique** [Warfield and Perino, 1999].

Results from hundreds of cases indicate that a typical number of problems in such a problem set will be about 100, but the number has ranged from about 30 to about 700. In such instances, the word "problem" has to be used consistent with the three attributes cited above. This linguistic adjustment clarifies the urgency of developing and analyzing the set, interrelationships among its members, and options for alleviating individual problems enroute to a larger outcome. Seen against this background of complexity, Ashby's Law of Requisite Variety [Ashby, 1958] becomes more than an intuitively attractive concept, demanding incorporation into activities aimed at resolving complexity, where it serves, at minimum, as a reminder that the variety in the inquiry should be uncovered before striving to design for resolution. .

REPLACE "COMPLEX PROBLEM" WITH "PROBLEMATIQUE"

Having defined "problematique" as a structure showing how a set of problems is interrelated by means of the relationship "significantly aggravates" [Warfield and Perino, 1999], the tendency to use the term "complex problem" to represent what is happening should be suppressed in favor of the term "problematique". This practice inserts into the language the idea that it is now possible to show how the different component problems of what might otherwise be called a "complex problem" are interrelated, leaving aside the human tendency to want to think in terms of a one-element set (e.g., "the problem", free of interacting members).

REPLACE "COMPLEX SYSTEM" WITH "PROBLEMATIC SITUATION"

The term "problematic situation" (or, in short form, the "situation") brings little constraint to a conversation. It just indicates the recognition that something is wrong, and people are not at all certain of what to do about it. The term "complex system", on the other hand, already implies that there is a "system", and that it has the property of being "complex". Both of these component terms beg the question of what the system is and how it is known to be complex. Yet when such language is used, it is commonplace to suppose (paradoxically) that everyone knows what the system is and knows that it is complex; and this knowledge is present, even in the absence of a definition of what the system is in the particular case in point. Also there is no explanation of why a certain system is thought to be complex, while another would not be. Nor is it clear how a tangible system can have the same property as an intangible concept of a possible future system, even though both may be declared to be complex by some.

REPLACE "SOLUTIONS" WITH "OPTIONS"

Commonly, software marketers have chosen the word "solution" to represent a software product. This is possibly the most presumptuous linguistic ploy yet devised for marketing purposes (remarkable, given the plethora of marketing ploys!). It presupposes, linguistically, that what the buyer purchases will solve whatever problems the buyer may have (and certainly not introduce new ones!). And later the buyer is told that once he rips open the shrink-wrapped container that holds the compact disc with the software, he is agreeing that the only liability of the seller is to replace the disc if it is mechanically flawed or turns out not to have the software on the disc. Moreover, when the user seeks to install the software, he is once again asked to agree to a statement that relieves the seller of all responsibility for what might ensue if the product is used.

The fact that the term "system" has come to be so widely used to represent "computer system" was strongly disliked by Sir Geoffrey Vickers. He gave his views as follows [Vickers, 1980]:

"The concept of systemic relations, though not new, has been developed in the last few decades to an extent which should be welcome, since it is the key to understanding the situations in which we intervene when we exercise what initiative we have and especially to the dialectic nature of human history. It has, however, become so closely associated with man-made systems, technological designs and computer science that the word 'system' is in danger of becoming unusable in the context of human history and human culture. I seek to contribute something to its rescue and restoration. For we need it for understanding and for action in human and social contexts..."

The term "solution", like the term "system" has become so heavily embedded in the language that even when the foregoing argument has been advanced, people continue to stay with that old language. Use of such language is a form of linguistic pollution.

It is a feature of complexity that no one knows at the beginning of an inquiry what might be done to resolve it. Naming something as a "solution" at the outset of inquiry is both empty and presumptive, and therefore must be ruled out in any work presented as being based in science. Yet if anything is to be done, some options for action must be generated.

AN ALTERNATIVE IS A SET OF MUTUALLY-REINFORCING OPTIONS

Systems language often displays the terms "option" and "alternative" interchangeably. It should be clear that, when complexity is involved, at least a two-level language is needed. This is recognized when the word "option" is seen as a component of some possible "alternative", i.e., a set of interacting options that could be chosen to try to resolve a problematic situation.

RECOGNIZE "HIERARCHY" AND "CYCLE" AS COMPONENTS OF A LARGER STRUCTURE

Structural features of information; i.e., relationship patterns developed during hundreds of case studies belie the common belief that structure is almost always hierarchical. On the contrary, purely hierarchical structure is almost as uncommon as just-mined gold nuggets in the mall. A typical structure is comprised of an integrated set of components, some hierarchical and some cyclic [Zamierowski, et al, 1976]. Purely cyclic structures are also seldom found. But the structural statistics show that about 99% of all problematiques contain at least one cycle. Researchers who discuss only hierarchical structure are automatically to be distrusted. It is incredibly difficult to prove that conceptual structures are free of cycles in any particular instance involving complexity. When discussing purely hierarchical structure, the better part of valor is to indicate that the presence of cyclic substructures remain to be investigated. This will demonstrate that the inquirer is, at least, aware that such substructures are possible.

AVOID METAPHORS FROM PHYSICS AND BIOLOGY

Disciplinary scholars from physics and biology both assert that they are scholars of complexity[2]. Unfortunately neither of these groups knows a lot about complexity[3] even though they may be immersed in it. To understand complexity, at minimum, one must understand thought about

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[2] The Santa Fe Institute is widely seen as a major source of complexity theory (NOT complexity science, since that would involve empirical evidence, and the European biologists are following a somewhat similar pattern of exposition: Laboratories are expensive).

[3] In several interviews described in the American press, inability to define complexity has been demonstrated, by relevant authors, see, e.g., Johnson, George (1997), "Researchers on Complexity Ponder What It's All About", *The New York Times*, May 6, 1997, see page C1. Johnson is affiliated also with the Santa Fe Institute.

thought as provided by scholars from Aristotle to Peirce, with a special stopover at the works of De Morgan and Boole. In the era of complexity, the right to make assertions that ignore the theory of relations, and assert that social systems somehow obey non-linear partial differential equations, is not conferred along with the doctoral diploma or even with a Nobel Prize, popular assumptions notwithstanding!!!

The common metaphors from physics and biology, wherein sublanguage is asserted to occupy a site that ought to be reserved for higher-level, more-encompassing concepts should not be tolerated in the halls of scholars of systems and of complexity.

Nor do physicists and biologists have the right to occupy a definitive, overarching place in management theory or in the theory of organizations merely because physical components and biological components display structure, or because solutions to differential equations behave in a certain way. (The rise of positivism and its awful consequences have been well-illustrated by Hayek in one of his lesser-known, but sterling works [Hayek, 1952, 1979]. Very likely none of the physicists and biologists who discuss complexity are aware of this highly-scholarly and well-documented work or of its implications for those who misplace emphasis, distorting science.)

Linguistic adjustments do not merely substitute one term or phrase for another, but must also include a form of "linguistic cleansing" (sorry about that), where inappropriate language is purged from the conversational domain. If metaphorical language is to be acceptable at all, it must be properly located in the confines of the Coherent Organization, where such language (when present at all) normally appears at Level 1, since it is essentially unservicable at Levels 2 and 3. If used at Level 1 to reveal strategy, middle managers will be strained to mediate a linkage with the producing level.

FRIEDMAN'S THEOREM OF NON-ASSURED MODEL CONSISTENCY

George Friedman developed a very comprehensive "constraint theory" [Friedman, 1967]. One of the most important contributions in this theory is a result that I have named "Friedman's Theorem of Non-Conservation of Model Consistency".

Imagine that a group is studying a problematic situation, and that various models have been constructed by subgroups. Suppose that each subgroup's model has been tested and found to be consistent. Then it is proposed to merge these models into an higher level model. Friedman's Theorem is stated as follows:

When a group of models, each of which is internally consistent, is aggregated into a single composite model; there is no assurance of conservation of consistency. (This applies, e.g., to the aggregation of a group of individually-consistent mental models to form a single model.)

Friedman's Theorem tells us what cannot be taken for granted. It is a warning, implying that Harary's Theorem should be used whenever a model is developed that relies on inputs from more than one individual or group. Harary's Theorem of Model Consistency [Harary, et al, 1965] is stated as follows (Virtually none of the popular systems methods incorporate this):

Logical consistency of a set of relations (constraints) represented by a square Boolean matrix M, such that M = M + I, where I is the identity matrix, is assured, provided (a) the relationship represented by M is transitive and (b) the Boolean square of the matrix M is equal to the matrix M. [Note: Most, but not all of the relationships of physics are transitive.]

Harary's Theorem is based in De Morgan's theory of relations and the concept of transitive relationships, topics that are avoided by many authors who may be unaware of their importance. Yet this particular theorem is probably the single most important one ever developed for constructing logic patterns that illuminate complexity. It is for that reason that ISM software has been developed which enable individuals or groups to construct patterns using transitive relationships. Using such software, model consistency is guaranteed. If Harary's Theorem is ignored, Friedman's Theorem steps into the conceptual breach, and surfaces as the dominant consideration, reminding us that no assurance can be had that the resulting model is consistent.

STAKEHOLDERS ARE NECESSARY IN RESOLVING COMPLEXITY, BUT THEY ARE NOT NECESSARILY SUFFICIENT

Victims of bureaucratic insults love to assert how important it is that stakeholders be involved in whatever is done that affects them. It is necessary to involve stakeholders, but merely being a stakeholder does not qualify someone to take part in the necessary discoveries that are involved in working to resolve complexity. It seems redundant to say that complexity involves great difficulty of comprehension, and that merely being a stakeholder provides no assurance of ability to help with the essential discoveries. Among other things, representative government has been institutionalized in recognition of the physical impossibility of direct and everyday involvement of all stakeholders. What is important is that the people constructing the models are both stakeholders and highly informed about what problems should be in the problem set, and that whatever they produce should be openly visible to all those who are already stakeholders, and those who may become stakeholders when action is initiated to resolve the complexity. (A famous American academic, W. L. Everitt, once said "In education, we are constantly recovering from the effects of our last 'solution'"). It is for this reason that the word "stakeholder" is distinguished from the word "participant".

DISCURSIVITY AND COMPLEXITY

It is now possible to apply what has been said so far in this article to discuss complexity. Whenever it is intended to understand and resolve complexity, a Coherent Organization is defined, and synthesized as necessary to accommodate the perceived scope of the problematic situation, remembering the distinction between stakeholder and participant.

The problem set to be discovered at a given time is greatest in size at the Producer Level, hence model construction is carried out from a beginning with persons operating at that level and knowledgeable of the problems arising at that level. After the problem set has been identified and the problematique has been constructed, it is normally possible to determine categories for the problems, and the set of categories is conceptually passed on from the Producer Level to the Mediating Level. This set of categories, in turn, is further categorized into a set of areas, and the set of areas is conceptually passed on to the Strategic Level. It is the task of middle management to learn and to mediate any differences in perspective, in order to attain a coherent model. From that point forward in time, incremental changes are made to reflect changing conditions. In this way the Coherent Organization stays coherent through time. Continuing visibility is achieved through the Corporate Observatorium [Warfield, 1996].

Each major problematic situation is dealt with in the same way, with recourse to its own Coherent Organization. Invariably problematiques are produced and interpreted, and options are chosen related to each problem in the problematique in the light of the structural interpretation that can be presented by a person who has mastered the way to interpret problematiques. (It is not something that can be casually done, but significant education and experience in interpreting structural models is necessary [Fertig, 1980; Perino, 1999].)

WHAT THEORY UNDERLINES THE MEASUREMENTS?

The Work Program of Complexity can be summarily outlined with the aid of the linguistic adjustments set forth. It consists of a sequence of two steps: Discovery and Resolution. The general philosophy underlying it is that since no one understands the complexity, collective discovery is essential. This Program is based in twenty **laws of complexity** [Warfield, 1999; Kapelouzos, 1989].

Discovery involves two steps: Description and Diagnosis. Description involves preliminary statement of the problematic situation (in general terms, to focus the work), generation of the problem set by the Discovery Team, placement of the members of the problem set into categories (then assigning titles to the categories, for use by the middle managers), and construction of the problematique (assisted by the appropriate software which implements **Harary's Theorem of Assured Model Consistency**). Application of Harary's Theorem enables this Work Program to avoid the perils described in **Friedman's Theorem of Non-Assured Model Consistency,** even though there is heavy emphasis on group work.

The second step in Discovery, the Diagnosis, is carried out initially by an individual who is expert in interpreting the problematique, and who then presents it to the developers of the problematique for validation and/or amendment.

Resolution involves two steps: Design and Implementation. Design involves the generation of the options set by the Design Team, an informed group, correlating options with problems and problem categories; followed by the construction of one or more alternatives as collections of options. In matching options with problems, **Ashby's Law of Requisite Variety** is a governing concept in arriving at design alternatives. Choice of an alternative opens the door to Implementation.

Communication of the results of the group work is carried out in part through the Corporate

Observatorium, which houses the group's products for ready review and observation. The Observatorium is kept up to date as Implementation proceeds.

WHAT EMPIRICAL EVIDENCE SHEDS LIGHT ON A TYPICAL RANGE OF VALUES OF THE METRICS?

Interactive Management, first named as such in 1980 and continuing to be applied since that time, has yielded data that give insights into the likely range of values of the metrics. To understand the data, one benefits by understanding the generating processes that produce the data. It is also relevant to understand that the data are by-products of group work aimed at resolving the problematic situation, and are not merely processes aimed only at producing raw data for metrics. Status of the data as by-products of motivated work lends extra credence to the data, since the data generation is accompanied by progress toward resolution of the complexity.

WHAT IS MEANT BY A PROCESS-BASED METRIC?

All of the metrics to be described here are process-based metrics. This means that they arise from well-defined processes with features that are tied to human behavior in the processes that are used. This occurs because the processes themselves have been designed in the light of well-known behavioral pathologies. Among the pathologies that are essentially neutralized by these processes are: limited span of immediate memory, restricted experience accompanied by strong belief based in partial information, groupthink, clanthink, and structural incompetence.

WHAT PROCESSES ARE USED?

Two generating processes are sufficient to provide the raw data for all of the complexity metrics to be described. These are the "Nominal Group Technique (NGT)" and "Interpretive Structural Modeling (ISM)". Both of these processes have been described in great detail in the literature. The shortened descriptions given here offer the minimum process definition needed to explain the development of values for the complexity metrics.

WHAT ARE THE ADVANTAGES OF USING THESE PROCESSES?

By standardizing on the generating processes, one requirement of the scientific method is honored. That is the part which requires replication. If the process is replicated from one application to another, the growing body of data that is accrued allows interpretation across problematic situations. If processes are not followed faithfully, little of lasting scientific value is accrued from whatever applications are being pursued, no matter what local gains are achieved..

WHICH INTERNAL COMPLEXITY MEASURES ARE NGT-BASED?

In a typical application of NGT, there is generated a problem set, consisting of N problems. From this set of N problems, a subset ("the selected subset") of V problems is chosen. This subset consists of all the members of the original set which at least one person from the participant group perceived to be among the top 5 in importance. The two numbers N and V, provide raw data required to compute values for two of the internal complexity measures, the Miller Index and the Spreadthink Index. These two metrics reflect only individual perceptions of what problems are present, and their perceived relative importance, independent of what may later be discovered and made visible about the interactions among the problems.

WHAT DATA ARE AVAILABLE FOR THE RANGES AND TYPICAL VALUES OF THESE INTERNAL MEASURES?

The Miller Index. The Miller Index is computed from the simple formula N/7. The name of this metric is chosen to acknowledge the fundamental research of George A. Miller, who discovered the famous "magical number seven, plus or minus two". If one thinks of functioning human memory as somewhat like the random access memory (RAM) of a computer, this memory can function properly only if the data it is required to process at any given time do not exceed in size the "magical number". In light of this, if the number N happens to be 7, the value of the Miller Index will be 1.0.

This value of 1 for the Miller Index gives a dividing point between the Normal Domain and the Domain of Complexity. In simplest terms, an individual cannot process more than 7 of the N problems at a time, and that is why the Miller Index is a measure of complexity. It might be called, in functional terms, the "Short-Term Memory Inadequacy Index." Additional research is available to suggest that perhaps the number that separates the Normal Domain from the Domain of Complexity ought to be lower than seven[4]

The Spreadthink Index. The Spreadthink Index is a measure of the dissension among the participant group on the relative importance of the N problems they have generated and from which they have chosen V as the "selected subset". The NGT voting system enables each voter to choose privately the 5 most important problems as he or she sees matters. The aggregate of all choices contains V members. The Spreadthink Index is computed from the simple formula V/5.

If all voters are in agreement on the most important subset, the value of the Spreadthink Index will be 1.0. This might be expected if everyone had the same high-quality understanding of the problematic situation. But of the hundreds of applications carried out over two decades of experience with Interactive Management, such an agreement has never been seen. This is why it is reasonable to suppose that one aspect of complexity lies in human differences of belief. (This discussion assumes that N is greater than or equal to 5, which has always been true in applications.)

Table 1 shows summary data from 43 cases stemming from applications of NGT during the decade of the 1980s.. The detailed data appeared in print some time ago.[5]

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[4] Complementary views on this subject are offered by Simon (1974) and Warfield (1988).

[5] These data appeared first in Appendix 5 in [Warfield, 1990, 1994].

Table 1. NGT Internal Complexity Metrics Data from 43 Pre-1990 Cases			
Metric	**Minimum Value**	**Maximum Value**	**Average Value**
Miller Index	**5.1**	**18.1**	**9.2**
Spreadthink Index	**3.8**	**13.4**	**6.8**

Because of rapid expansion of the use of Interactive Management in the 1990s and the dispersal of applications, it has not been possible to continue to track all applications. But some additional information coming from Ford Motor Company applications will appear later in this paper. Also it is believed that the maximum value of N ever found was 97.

WHAT EXTERNAL MEASURES ARE ISM-BASED?
WHAT ARE TYPICAL VALUES OF THESE MEASURES?

Interpretive Structural Modeling (ISM) and the Problematique that its application produces in a given problematic situation offer data to compute two external measures of complexity. These are the De Morgan Index and the Aristotle Index. To comprehend these metrics, it is necessary to understand the nature of the problematique, and how raw data can be extracted from it.

Experience shows that in any application of ISM, i.e., in any attempt to carry out a program aimed at resolving complexity, it is wise to start with the development of a problematique.[6] Typically this is done by beginning with the NGT to generate a problem set, continuing by voting to choose the selected subset of V problems. Then the V problems are structured using ISM based on the relationship "significantly aggravates". The structure that is produced by this means is called "the problematique". It may be clear that this structure will differ from one application to another, but it always is based in the same relationship. The basic idea is to comprehend how some problems aggravate other problems, to help get a grasp on the situation as a whole, and to help develop priorities for projects aimed at resolving complexity.

The De Morgan Index requires the computation of the number of ordered relationship pairs (dyads), showing how one problem, say "problem A", significantly aggravates another problem, say "problem B".

That the problematique offers many possible ordered pairs can be seen by examining a typical problematique, shown in Figure 1. This problematique was developed by a group of military personnel intent on considering new logistics strategy to replace an earlier strategy that was implemented during the "cold war". The subject of this problematique is irrelevant to the computation of the indexes, but may help to make the discussion more concrete and to serve to

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[6] "...there was one element that was capable of describing the history of thought: this was what one could call the element of problems or, more exactly, problemizations.", quoting M. Foucault [Rabinow 1984, p. 388]..

illustrate the types of numbers that come out of a problematique. It is possible to determine the number V from the problematique by counting how many problems appear there: V = 23.

The problematique furnishes raw data for two external metrics of complexity. It also furnishes raw data for several metrics for individual problems in the selected subset. The choice of the names of De Morgan and Aristotle for the two external metrics reflects the fundamental contributions these two made to formal logic, the syllogism, categories, and the theory of relations.

The De Morgan Index.

One problem (y) on the problematique is said to be "reachable" from another one (x) if and only if a directed path exists on the problematique from x to y. A directed path is any path that follows the directions of the arrows (including the suppressed arrows contained in a cycle—i.e., a structure such that each problem in the cycle significantly aggravates each other problem in the cycle). Reachability corresponds to significant aggravation. The directed paths enable the development of a list of ordered pairs of problems (dyads) such that (a) the second member in the ordered pair is reachable from the first member and (b) the first member significantly aggravates the second member. It is possible to count the number K of such pairs. This number K is the number of relationships shown on the problematique.

The De Morgan Index is found from the simple formula K/10. The divisor 10 is chosen to make the value of this index equal to 1 for a structure in which the number of ordered pair-relationships is 10. One structure with this property is a linear, 5-element structure (all arrows on a line) connecting 5 problems. This structure seems appropriate as a representative of what one mind can construct, comprehend and interpret. If the De Morgan Index for a problematique exceeds 1, it means complexity is present. The larger the number is compared to 1, the more the complexity that is present.

The Aristotle Index.

Aristotle is well-known for many contributions, but probably the best-known of his contributions is the syllogism, which has occupied the attention of philosophers ever since its development centuries before the birth of Christ. The syllogism involves three elements, A, B, and C, and one relation symbolized by R. Two premises are represented as ARB and BRC. If the two premises are accepted, then it is concluded that ARC.

Apparently De Morgan was the first to explain that the validity of the syllogism was not limited to a single relationship, but rather to a class of relationships which he called "transitive". And also he recognized that if the relationship were not transitive, then the conclusion could not be presumed to follow necessarily from the two premises. (The relationship ARC might still be true

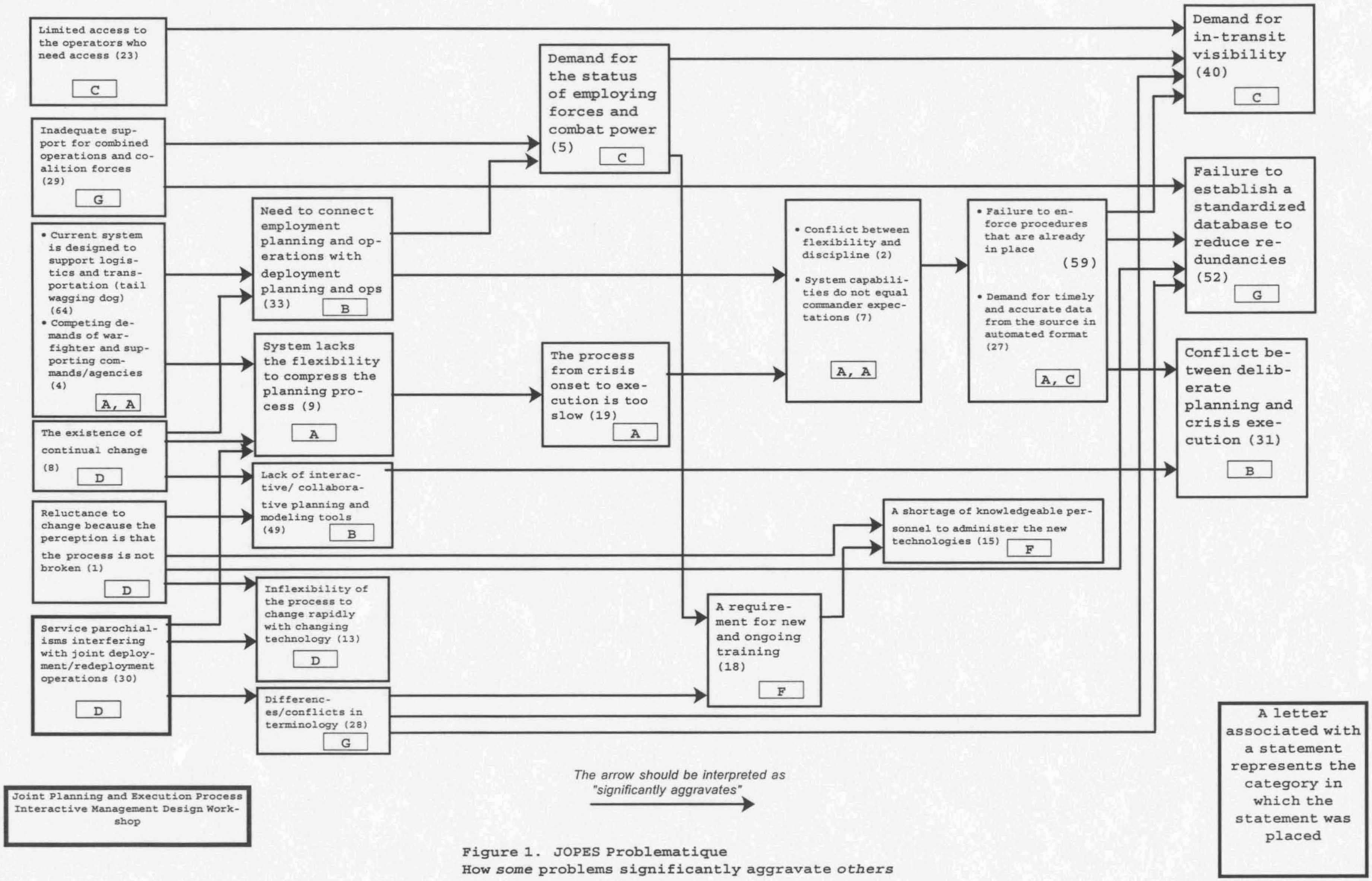

Figure 1. JOPES Problematique
How *some* problems significantly aggravate *others*

in particular cases, but not as a necessary consequence of the premises.) There is a strong and unbreakable link between Aristotle and De Morgan. This connection was recognized by Charles S. Peirce, who elaborated on the iimportance of these matters.

While the De Morgan Index is based in dyads on the problematique, the Aristotle Index is based on triads on the problematique. On the problematique in Figure 1, it is possible to trace out three-problem sequences of the form stated, and to count the number Z of such sequences. This number Z is the number of syllogisms appearing on the problematique. For the example problematique shown in Figure 1 this number is 324!!! It seems impossible for a human being to develop such a tightly-linked logic structure without the aid of software that is based in Harary's Theorem of Assured Consistency. The ISM process is based in this Theorem, enabling the individual or a dialoging group to develop such tightly-linked syllogistic structures.

The same structure used to normalize the De Morgan Index is used to normalize the Aristotle Index. The Index is computed from the simple formula Z/10. As before, a value of 1 is taken as lying at the border between the Domain of Normality and the Domain of Complexity.

WHAT SINGLE METRIC IS CO-BASED BETWEEN NGT AND ISM?

It is often useful to have a single metric to compare complexity among a group of problematic situations. Use of such a metric clearly does not preclude use of the other metrics, hence such a metric should be considered as complementary to them. A single metric, called the Situation Complexity Index (SCI) has been proposed. It is computed as the product of the Miller Index, the Spreadthink Index, and the De Morgan Index.

If all of the component indexes take the value 1, clearly so does the SCI. Hence, as usual, the value of 1 can be taken as lying at the borderline between the Domain of Normality and the Domain of Complexity.

Table 1 showed values of the Miller Index and the Spreadthink Index stemming from Interactive Management workshops carried out in the 1980s in a variety of locations with a variety of problematic situations. Only the process served as the linking agent. In the 1990s numerous (well over 50) Interactive Management workshops were held in one organization, the Ford Motor Company, once again on a variety of problematic situations, but all referring to design and manufacture of vehicles. Fortunately it was possible to take data on these applications.

Tables 2 and 3 show values of the SCI and other numerical values stemming from these activities [Staley, 1995]. (These Tables are shown separately only to facilitate typesetting and paging. If the page could be presumed large enough, they would have been combined into a single table. The average values of the metrics, shown in Table 3, reflect the combined data from the two tables.)

TABLE 2

VALUES OF METRICS OF COMPLEXITY FROM FORD MOTOR COMPANY PROJECTS

IM WORK-SHOP NUMBER	THEME OF PROBLEMATIQUE	NUMBER N OF PROBLEMS GENERATED	NUMBER V OF PROBLEMS SELECTED	NUMBER OF PROBLEMS STRUCTURED	NUMBER K OF RELATION-SHIPS	SITUATION-AL COMPLEXITY INDEX SCI
1	Analytical Powertrain	127	35	26	230	2921
6	Rapid Response Manufacturing	81	42	29	202	1963
8	Product Information Management	76	37	24	110	884
9	Air Conditioner Hose System	58	23	23	137	522
19	Product Drawing Information	103	33	33	323	3137
12A	Single CAD System Strategy	48	34	22	157	732
12B	Hybrid CAD System Strategy	59	32	23	243	1310
12C	Single-by-Process CAD Strategy	63	25	25	272	1224

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CONCLUSIONS

At present, the literature and practice related to complexity relies on extensive linguistic pollution that is no longer acceptable, in the light of the social difficulties arising from inept work related to complexity.

In order to create a functional state of discursivity regarding complexity, linguistic adjustments are necessary, to make the language suitable for carrying out the Work Program of Complexity in the Coherent Organization as the basis for striving to resolve complexity.

Once such discursivity is achieved, it becomes relatively easy to define metrics of complexity, and to use such metrics for purposes of helping achieve greater understanding of particular situations.

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