TQM, Chaos and Complexity

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Abstract

Management practices of this century have been greatly influenced by Frederick Taylor's concept of scientific management. Taylor's theories can be traced to the paradigm of Newtonian mechanics. In recent years a new paradigm of scientific thought, complexity, has emerged. The premise of the paper is that successful TQM initiatives must borrow perspectives and approaches from both paradigms: indeed, one of the key challenges to quality management is to simultaneously balance the objectives of control and learning. This paper elaborates on the connections between the Newtonian paradigm, scientific management, and TQM; and between chaos and complexity, the learning organization, and TQM. Finally, some normative statements are given as to how TQM can evolve as a complex adaptive system.

Introduction

A paradigm can be considered a set of assumptions from which subsequent theory is developed. A paradigm includes symbolic generalizations, a set of beliefs in particular models of reality, a set of fundamental values, and a set of shared exemplars (Sanford 1992). Paradigms have had a profound impact on the development of theory in the physical sciences (e.g. Kuhn 1970) and social sciences (e.g. Argyris 1980). Paradigms change when anomalies between existing theory and observation occur, when an alternative paradigm is available, and when a critical mass of people have changed their beliefs. New paradigms represent not only a relaxation or alteration of basic assumptions, but also a change in the researchers' collective world view (Kuhn 1970).

The two paradigms that we will contrast here are the *Newtonian* paradigm and the *complexity* paradigm. One might consider these "meta-paradigms", as they represent a great confluence of thought and effort, and have interdisciplinary effect. The Newtonian paradigm uses reductionism to build mathematical models of reality. Systems can be understood by basic physical laws that describe a deterministic world in objective ways. The natural state of the system is equilibrium; disturbances to equilibrium are controlled via negative feedback mechanisms. The complexity paradigm uses systemic inquiry to build fuzzy, multivalent, multi-level and multi-disciplinary representations of reality. Systems can be understood by looking for patterns within their complexity, patterns that describe potential evolutions of the system. Descriptions are indeterminate and complimentary, and observer dependent. Systems transition naturally between equilibrium points through environmental adaptation and self-organization; control and order is emergent rather than hierarchical (Lewin 1992, Waldrop 1992). Table 1 (adapted from Sanford, 1992, p. 200-201) shows the differences between the two paradigms (she refers to the two as *Mechanical* and *Emerging*).

[insert Table 1 here]

This paper describes the development and influence of these two paradigms, in both the physical and organizational sciences. We shall then examine the theory and practice of total quality management (TQM), and show that some aspects of TQM are based on a Newtonian paradigm, while others represent a complexity paradigm. As such, TQM represents a necessary bridge between these two contrasting patterns of thought.

The Newtonian Paradigm

> *"It is hard for us to imagine the force of (Newtonian physics') impact. The basic form of his explanation became the ideal towards which all explanation strived. We have nothing in the modern era to compare with it; no discovery or theory has spread to other fields or captured the general imagination the way Newton did (Garfinkel 1981)."*

The Newtonian paradigm is based on a mechanistic philosophy that states that "the enormous diversity of things found in the world... can all be reduced completely and perfectly and unconditionally (i.e. without approximation and in every possible domain) to nothing more than the effects of some definite and limited general framework of laws" (Bohm, p. 130, 1957). Science has always sought after such laws as part of the immutable truth.

Newton's laws of motion (e.g. F=ma) emphasize that systems are lawful, deterministic, and reversible (Prigogine and Stengers, p. 60, 1984). Any future state of a system (trajectory) can be derived from knowing the forces that are acting on the system and the system's initial condition. This is indicative of the determinism sought after by philosophers of the time. Laplace postulated that if one could know all the underlying equations, no behavior would remain unpredictable (Prigogine and Stengers, p. 75, 1984). The fact that "for every force, there is an equal and opposite force" was consistent with univalent Western logic.

Equilibrium and control are core beliefs in the Newtonian paradigm. Classical science has long held that equilibrium is the natural state of a system. A system perturbed will come to rest. Similarly the second law of thermodynamics states that entropy (the amount of disorder) in the system will not decrease over time. The point at which the system comes to rest, where entropy is maximum, is the state of equilibrium. In seeking equilibrium a system may close itself from the environment, leading to stagnation. The quantitative models of physics and chemistry, as well as our views of social organizations, are built around the concept of equilibrium (Goldstein 1990).

The Newtonian world is understood via reductionism -- the belief that systems are composed of independent elements (basic building blocks) and that one can completely understand a system by breaking it down to its smallest elements and describing how these elements interact (Ackoff 1987). Reductionism can be traced to Greek philosophy, but became a dominant methodological doctrine in the 17th century (Garfinkel 1981). Ackoff gives examples of how reductionism had influenced thought by the turn of the twentieth century:

* physicists used the atom as the basic building block of physical matter
* chemists used the basic chemical elements to describe their phenomena
* biologists described life by the basic unit of the cell
* philosophers argued that certain sensations comprised the ultimate units of experience
* psychologists described the components of personality--id, ego, and superego.

Great successes were derived from use of Newton's laws (Kuhn 1970). These successes, coupled with other factors (Markley 1991), led to the Newtonian paradigm. Newton's successors have attempted to further the paradigm by seeking to unify the theories of science (Kitcher 1981), an exercise that continues today.

Physical Laws for Social Systems

The influence of Newton's paradigm was not confined to the physical sciences. The ideas were used to explain any system that dealt with laws, with equilibrium, or with natural order, including moral, social, and political order; it became a basic recipe for how new knowledge was obtained (Prigogine and Stengers, p. 29, 1984).

In applying scientific theory to the study of social systems, one must deal with two questions: Are social systems reducible to physical laws (if so, how)? If they are not, then how far can one take metaphor--in this case, the use of scientific theory--to understand social phenomena? Newton implied that *all* systems can be reduced to their representation in physical laws (physicalism). We prefer to think that social systems are *much more complex* than physical systems, because social systems are made up of a complex set of physical systems, and tempered by such notions as perception and free will. As such, we believe that theory from the physical sciences can apply to social systems via a *specification hierarchy*, where lower level theories serve as higher level constructs (or metaphors) (Salthe 1989). Thus, theories of neural networks can be incorporated into theories concerning individual cognition, but do not completely describe it; likewise theories of individual learning compliment, but do not completely describe organizational learning. The use of one level's theories as another's metaphors is not an invitation for methodological sloppiness; it can, however, lead to new insight and creativity via lateral thinking (e.g. de Bono 1969, Nonaka 1991).

Taylor's Scientific Management and the Newtonian Paradigm

Business thought has been greatly influenced by reductionism. The following concepts and practices, all steeped in the Newtonian paradigm, came about in the eighteenth and nineteenth centuries: division of labor, the idea of task, interchangeability of parts, standard procedures, quality control, cost accounting, time and motion study, and organizational charts (George 1968). Frederick W. Taylor was responsible for integrating these ideas with the concepts of the scientific method to design a coherent management philosophy. His principles of scientific management have great influence over management practice of today. Taylor brought analytical logic to management. Taylor's managerial principles (1911) were summarized into four points: (a) develop a science for each person's work, (b) train and develop the workperson, (c) heartily cooperate with others, and (d) divide work and responsibility between labor and management.

It was Taylor's belief that work processes could be studied via the same scientific principles that were applied to studying the basic sciences -- hence the term scientific management. Taylor and other industrial engineers of the time focused on describing work by its elemental tasks, and managing work as such. Under scientific management, work tasks are divided into basic skills, and training and standardized methods helped eliminate differences between peoples' performance. Taylor believed that only management had the intelligence to develop the organization's laws, just as Newton believed that his set of basic laws was developed by a deity. Taylor believed in a "social system determinism" -- that management of the organization could be predictable if we understood the science of management.

The Newtonian organization believes the environment is to a large extent predictable, and therefore the system can be maneuvered in a deterministic, planned way so as to achieve its goals (Spencer 1994). Overall system performance is optimized by optimization of the functional subcomponents, and a bureaucratic hierarchy ensures coordination and accountability. Organizational controls, such as budget, performance review, audits, standards, etc., are used as negative feedback mechanisms for maintaining equilibrium (Leifer 1989; Wheatley 1992; Spencer 1994). The Japanese have a phrase: "the nail that sticks out is hammered down"; organizations seek equipotentiality among all elements. Table 2 summarizes the concepts discussed in this section and their corresponding concept in scientific management.

[insert Table 2 here]

The Complexity Paradigm

> *"There is a revolutionary strategy of mathematical modeling of systems called nonlinear dynamics. While its roots reach back to Newton, Rayleigh, and Poincare, the past two decades have witnessed a revolution in its language, concepts, and techniques for dealing with complex, cooperative systems... The mathematics provide models, simulation, cognitive strategies, and intuitively clear geometric representations for complex systems. It also serves as a unified philosophic view for integrative, hierarchically organized systems, and for dissipative, irreversible, evolutionary dynamics. In short, it is a world view as well as an elegantly simple modeling strategy. It is emerging as the metalanguage, the metaparadigm, of science" (Abraham, et al., p. 1, 1990).*

At the turn of this century, Einstein's theory of relativity changed the view that science was purely objective, and quantum theory destroyed mechanistic determinism through its probabilistic nature and through the principle of complimentarity (Bohm, p. 131, 1957). Within quantum theory Bell's theorem mathematically proves that elements seemingly not coupled in a system can effect one another--connections at a distance; this was confirmed experimentally by Aspect (Gribbin 1984). Such results questioned reductionist strategies.

As Kuhn (1970) points out, while paradigmatic revolutions are discontinuous change, they typically do not occur at one instance in time. Instead, "change occurs through negotiations at multiple sites among those who generate data, interpret them, theorize about them, and extrapolate beyond them to broader cultural and philosophical significances (Hayles, p. 4, 1991)." The language of the old paradigm is likely to be used in the new paradigm, causing further confusion (Kuhn, p. 149, 1970; Hayles, p. 4, 1991). In the Newtonian paradigm, equilibrium is considered the natural state of the system (Kellert 1993); in the complexity paradigm, equilibrium is just one of several states possible--whether equilibrium is natural is situational.

The development of *systems theory* over the last 40 years has greatly influenced the complexity paradigm. General systems theory, as advocated by such people as Ackoff, Checkland, Senge, etc. allows an understanding of the interdependencies of system elements, and how feedback loops (positive and negative) affect the dynamical nature of the system. General systems theory has tended to be qualitative in nature. Quantitative systems theory can be traced to the development of Shannon's entropy-based communication theory, Wiener's control theory and cybernetics, and Forrester's use of system dynamical models to describe socio-technical systems.

As systems theory has been applied across the disciplines, a number of "theoretical fields" have developed consistent with the complexity paradigm: sustainable development and Gaia, post-Darwinian evolution, artificial neural networks, artificial life, cybernetics, postmodernism, virtual organizations, etc. (Lewin 1992, Waldrop, 1992). We wish to focus here specifically on two bodies of theory--nonlinear dynamical systems (or "chaos theory"), and complex adaptive systems--and develop their relationship to the learning organization.

Chaos theory has developed along two dimensions. Experimentalists (as popularized in Gleick 1987) found ways (primarily grounded in topology) to discover deep and complex patterns in seemingly random, or "chaotic" systems. Prigogine and Stengers (1984), among others, use chaos to describe how order can arise from complexity through the process of self-organization. Here is a summary of some of the main points from chaos theory:

- Seemingly random behavior may be the result of simple nonlinear systems (or feedback-coupled linear systems). For example, the deterministic mapping of the logistics equation $\{x_{i+1} = 4x_i (1-x_i)\}$ creates a sequence of numbers that is essentially point by point unpredictable. However, for other parameter values (replace the '4' by a '2') the system moves quickly towards equilibrium, and yet for others, cyclical behavior. This means that: (a) observed randomness *may* not be randomness after all, (b) even simple deterministic systems can have limited predictability, and (c) a system can move from equilibrium to chaos not only through structural changes but also parameter changes.

- Systems exhibiting chaotic behavior can be discovered to be doing so via various topological mappings (such as Poincare sections, or phase diagrams). These graphs depict the dynamical evolution of the system. A chaotic system will tend to remain "attracted" to one or more points in hyperspace, yet never follow the same path--these points are called strange attractors. These systems contrast with other systems whose evolution equilibrates to a single point, or a repeatable cycle of points (limit cycle). A Poincare section of a chaotic system will reveal fractal topology, geometric structures exhibiting fractional dimension and commonplace in nature (e.g. clouds, tree shapes, coastlines, etc.). Fractals show the self-similarity in a system--low level features replicate themselves at higher levels of the system.

- Nonlinear systems can be subject to sensitive dependence to initial conditions--the butterfly effect, so named after the meteorologist Lorenz who proclaimed 'can the flap of a butterfly's wings in one country cause a tornado in another country?' after discovering that a simple set of nonlinear equations evolves *very* differently with minuscule changes in starting values. This occurs because of positive feedback--the output of the system further reinforces the behavior. As Waldrop (1992) points out, this effect has much to do with the apparent "randomness" of system evolution. This sensitivity forces a re-examination of causality--which now must be considered multilevel and multideterminate (Abraham, et al. 1990). Sensitive dependency contrasts with robustness and equifinality, which state that small differences can be ignored (Bush and Dooley 1992). Systems will typically exhibit both sensitive dependency and robustness, depending on their point of evolution.

- Systems that are pushed far-from-equilibrium (at the edge of chaos) can self-organize into new structures. Prigogine and Stengers (1984) show that entropy *can* decrease locally for open, or "dissipative" systems. As energy increases in the system, the system dissipates it through an emerging order. Patterns of thought in the human brain are thought to emerge from such self organization.

- Changes in the essential nature of a system take place when a control parameter passes a critical threshold--a bifurcation. These bifurcations represent natural revolutions (step-changes) of the system. Thus, "step-wise evolution is... natural, not magical. It derives from orderly principles; extraordinary events external to the system need not be invoked to explain it." (Abraham, et al. 1990).

While the concepts of chaos and self-organization have evolved from the physical sciences, the notion of complex adaptive systems has its roots in the biological sciences. A complex adaptive system is, in essence, a learning system. Environmental information is scanned and regularities are refined into schema, or mental models. Different schema exist simultaneously and "compete", based on real-world feedback (Gell-Mann 1994).

Complex adaptive systems do so in 3 ways: direct (cybernetic) adjustment, changing of schema, or "Darwinian" survival of the fittest (Gell-Mann 1994). Because there are competing objectives, though, the system may adopt maladaptive schema. The classical example of this in economics is the "QWERTY" keyboard, which was developed as a means to slow down fast typists, so that the typewriter's mechanical arms would not jam. Now, because of technology lock-in, a less-than-optimal schema dominates and is nearly impossible to displace (Arthur 1990).

As a complex adaptive system interacts with its environment, complexity will increase over time. Competition and environmental feedback push the system to the edge of performance, increasing internal pressures (similar to the far-from-equilibrium concept previously discussed). Pressure is reduced when the systems undergoes "structural deepening" (like a fault line and an earthquake)--functions are added or enhanced that allow the system to operate over a wider range, react to exceptional circumstances, or enhance reliability (Arthur 1994).

The Learning Organization and the Complexity Paradigm

The notion of a complex adaptive system fits well with much existing management thought concerning the learning organization. Lawrence and Dyer's (1983) theory of readaptive organizations recognizes the organization and environment as part of a larger system, with the organization obtaining information and resources from the environment in order to survive.

These environments co-exist and to a large extent are created by the organization--the organization does not play a passive observational role (Weick 1979). Contingency theory, a now widely held precept in management theory, holds that the structures and processes of an organization must be matched with the environment (Lawrence and Lorsch 1967). As the environment increases in complexity, it must develop searching, learning, and decision making capabilities (Senge 1990; Spencer 1994).

The learning organizational does not despise the uncertainty of random events, but rather attempts to learn and create leverage from such events. Box and Bisgaard (1987) state that systems have two outputs: products/services, and information on how the system might be improved. The learning organization structures its "information system" in such a way as to take advantage of the learning opportunities that stem from unpredictable events. Fuzzy logic, artificial neural networks, and statistical techniques help us uncover knowledge in complex information, and speak to the "multiple truths" (multivalence) present in real systems.

Ashby's law of requisite variety (1958) states that information channels must have sufficient capacity to handle the complexity of the information they are transmitting. If the organization is to "learn" from highly complex signals (those with great entropy), then its communication channels must also be equally complex (Guastello et al. 1995). Information systems are made more complex not by adding <u>more</u> information, or disseminating it in more technologically complex ways, but by finitely increasing the number of connections in the network (Michaels 1991), and adding more nodes to the network:

> "...When the organization gives public voice to the information--to listen to different interpretations and to process them together--the information becomes amplified. In this process of shared reflection, a small finding can grow as it feeds back on itself, building in significance with each new perception or interpretation. As with the creation of fractals, the simple process of iteration eventually reveals the complexity hidden in the issue. From this level of understanding, creative responses emerge and significant changes become possible." (Wheatley, p. 115, 1992)

The learning organization must view itself systemically. A systems perspective dictates that it is the interaction of organizational entities, rather than the organizational entities themselves, that are a source of influence (Zeleny 1989b). This has been recognized in practice in a variety of ways. Perhaps the most profound changes have occurred in organizations' product development practices. Companies well recognize the need to view product development as a system, and have created new approaches that stress the need for coordination among functions. The methodology of quality function deployment (QFD; Akao 1990) uses teams of people from design, manufacturing, sales, marketing, accounting, and even customers and suppliers to gain the necessary perspective. QFD's basic processes involve communication and exposure of assumptions.

The three ways in which a complex adaptive system evolves echo the concepts of organizational learning (Senge 1990). First order, or single-loop learning, involves reducing the gap between a given and desired state (Argyris and Schön 1978). Corrective action, typically in the form of negative feedback, is used to realign the system, correct errors, and reduce uncertainty and waste. Typically the schema of single-loop, cybernetic control is deeply ingrained in an organization because "those in power" have in fact ascended to such positions in large part because of their skills as effective problem solvers and gate keepers (Argyris and Schön 1978). This is an example of a maladaptive schema.

It is often necessary for a system to adapt via alteration of existing or adoption of new schema--this is referred to as double-loop learning. At the root of these schema are assumptions, or held-truths. The first step in changing these belief systems is to heighten awareness that a gap exists between a desired and actual organizational state (Reger et al. 1994; Dooley and Flor 1994). This is accomplished via dialogue (Argyris and Schön 1978; Senge 1990) concerning a vision for the desired organizational state (Reger et al., 1994), and/or, the reality of the current state (Dutton and Dukerich 1991).

This gap can provide motivation for change of schema (Higgins 1989). The individual, and collectively the organizational system and its schema, can be thought of as being at a far-from-equilibrium state, on the edge of a bifurcation point where the system will choose one of several potential paths. Such a system may become highly dependent upon chance events, such as the actions of individuals; this stresses the need for leadership and organizational learning:

> "A system far from equilibrium may be described as organized... because the amplification of a microscopic fluctuation occurring at the "right moment" resulted in favoring one reaction path over a number of equally probable paths. Under certain circumstances, therefore, the role played by individual behavior can be decisive... Self-organizing processes in far-from-equilibrium conditions correspond to a delicate interplay between chance and necessity, between fluctuations and deterministic laws."
> (Prigogine and Stengers 1984)

Organizational systems may be pushed far-from-equilibrium as a result of a crisis (Goldstein 1994). At times, leaders may even create crises to bring about such conditions (Nonaka 1988). It may be possible, however, that an organization, or parts of it, may *naturally* adapt to such a far-from-equilibrium state. Theoretical research has found that systems which place themselves "at the edge of chaos" may in fact be the most adaptive and creative (Kauffman 1993). Could this be true in organizational systems? Consider the process of product innovation.

Innovation has been characterized as "being inherently uncertain, dynamic, and a ... random process" (Cheng and Van de Ven 1994). Individual, chance events play a large role in the discovery process. History is littered with inventions brought about by a researcher's "mistake" (e.g. post-it notes). Yet there is evidence that some degree of order may exist, implicit to the observed randomness, suggesting that such systems are operating at the edge of chaos (i.e. they have chaotic dynamics of low dimensional order).

Cheng and Van de Ven (1994) and Koput (1992) have found numerical evidence for chaos at the beginning of the innovation process. Leonard-Barton (1988) found evidence for a "nonlinear process involving complex recursive cycles of adaptation" (Jayanthi and Sinha 1994) in a series of case studies. The studies of Tyre and Orlikowski (1994) suggest that random events in the innovation process trigger adaptive cycles. Jayanthi and Sinha (1994) found numerical evidence of chaos in the activities bridging innovation and production. There are a number of other numerical studies which show evidence of chaotic dynamics in other organizational processes (Kiel 1994; Guastello 1995; Guastello et al. 1995). Thus, there is a body of evidence which suggests that at least some of the organization's activities can be represented by chaotic dynamics, and hence subject to the butterfly effect and fractal growth patterns.

The learning organization is one that allows self-organization, rather than attempting to control the bifurcation through planned change. This idea is operationalized in modern management practice as "empowerment". Empowerment means not only giving individuals and teams the authority to make decisions, but also making information concerning all aspects of the organization readily available--this informs individuals of the alternatives available at the bifurcation points. Empowered individuals or groups of individuals that self-organize may be thought to attract to certain recurrent patterns of behavior.

Stacey (1992) suggests there is a necessary tension between equilibrium and change, between the efficiency of the status quo and the self-organizing features of a learning organization. This demands that the organization be good at working in both paradigms: "Normal, day-to-day management must rely on decision making through a logical, analytical process. But the extraordinary management required to uncover strategic issues and handle them in innovative ways has to rely on decision making that results from an exploratory, experimental process based on intuition and reasoning by analogy (Stacey, p. 14, 1992)." We shall explore this tension in the next section. Table 3 summarizes some of the relationships between chaos theory and the learning organization.

[insert Table 3 here]

Overview of TQM

Organization-wide quality improvement, known as "Total Quality Management" (TQM) has become a common practice among manufacturing, service, and public sector entities. This strategy implies a whole host of organizational practices: focus on customers, process analysis and improvement, study and reduction of variation, empowerment and teamwork, etc. These practices affect the technical, social, and sociotechnical aspects of the organization, and thus rely upon a broad base of relevant theory.

The key point in any discussion of quality is the concept of 'customer'. We tend to associate customer with 'consumer', i.e., the end user of the product or service. A broader definition of customer would be "anyone who receives my product or service;" this makes it possible then to discuss both internal and external customers. All models of organizational quality (e.g., Malcolm Baldrige National Quality Award criteria (1993), Deming (1986), Juran (1988), Feigenbaum (1983), etc.) possess the attribute of being leader driven, customer focused systems. Customer requirements must be completely understood, and all internal operations should be focused on providing value to the customer. Likewise, customer feedback becomes a mechanism for process improvement, and customer satisfaction can be a key indicator of an organization's quality performance.

The manner in which customer quality is improved is by focus on organizational processes. This requires the ability to define key processes in terms of customers, suppliers, resources, environment, and transformations. Once key processes are defined, quality characteristics that will be measured and used to infer process behavior are chosen. Data on the quality characteristics is analyzed and subsequent action is taken. This "problem solving" typically follows the steps of the scientific method, i.e., hypothesize (Plan), test (Do), analyze (Study), and act upon results (Act), or PDSA.

Statistical methods are typically used to analyze data within PDSA. Variation in the data is composed from two sources: common causes and special causes. Common causes are those sources of variation that represent the process routine. They represent variation or uncertainty that is expected from the existing process. Special causes are sources of variation that cannot be considered part of the routine process, and thus are deterring the process from operating in its most economical fashion (Shewhart 1931). PDSA can be used to identify special causes and remove them, so that the process is operating in its most economical state. Once the process has been brought into a state of statistical control, changes in the process routine can be made and thus reduce the variation due to common causes. It is well understood that changes in the process routine constitute the majority of opportunity for process improvement.

In order for all the process analysis and subsequent activity to work, the organization needs to develop its internal human resources to their full potential, and develop organizational structures that encourage development of organizational knowledge. Typically, teams of individuals are used for process improvement, and training and education support the teams' missions. Team success depends to some extent on how well they are supported. This in turn requires empowerment of the workforce. Participatory management and employee involvement are typical management components within TQM. These changes in behavior and attitude are essential in successful TQM. For example, TQM requires the organization to move from authoritarian leadership to facilitation leadership--such changes in organizational culture may be the most difficult step in implementing TQM.

In summary, the quality system starts with customer focus, which leads to using the scientific method (PDSA) to improve organizational processes. Process improvement takes place in the context of gathering and understanding process data and using multiple knowledge resources (teams) to synthesize that knowledge. Process improvement can only succeed in a nurturing environment, typified by employee empowerment, management facilitation, and change in organizational culture.

Anderson, Dooley, and Misterek (1992) claim that quality improvement efforts (either at the team or organizational levels) draw upon five theoretical areas: domain knowledge (knowledge pertinent to the specific application) and the four requisite areas of statistics, cognitive psychology, organization behavior and theory, and systems theory. One needs to understand systemically the process being studied (systems theory) and data coming from that process that is indicative of its behavior (statistics). One needs to understand the social (organization behavior and theory) and technical (domain knowledge) factors involved in the process. Finally, one must know how to learn about the process in greater detail, and how human perception affects and is affected by such knowledge (cognitive psychology). Thus, quality improvement draws upon a rich body of theory. In the final section of the paper we shall discuss how chaos and complexity theory may be woven into and influence the field.

TQM: The Paradox of Control and Learning

There is growing evidence that organizations have had difficulty in successfully implementing TQM, and that individuals' positive perceptions of TQM is dwindling (Dooley and Flor 1994). Contingency theorists (Laza and Wheaton 1990; Spencer 1994) and a large-scale, global study by Ernst & Young and the American Quality Foundation (1992) support the contention that not all quality practices are universally valid and beneficial, and that the practices implemented have to be carefully selected, depending on the nature of the process being improved and the particular point in the organization's evolutionary history (see, for example, Schein's (1992) discussion on the importance of an organization's historical context).

Sitkin, Sutcliffe, and Schroeder (1994) have articulated a theory which encapsulates this idea of "contingent TQM"; their model also parallels our notions here of Newtonian and complexity-based organizational practices by focusing contingencies on situational uncertainty: "the effectiveness of TQC (total quality control) and TQL (total quality learning) is fully contingent on the degree of situation uncertainty for which it is being used (p. 555)." Per our discussions, control is equated with the Newtonian paradigm, and organizational learning (and creativity and innovation) with the complexity paradigm. The bottom line is: one must manage systems to be in control and out of control (i.e. learning by experimentation) at the same time.

In the following dialogue further evidence is brought to light to support Sitkin et al.'s (1994) assertion that TQM practice need be contingent on uncertainty, and will provide some normative suggestions as to how TQM practice can be "adapted" to better fit appropriate context.

Process-Level Issues

It is at the process level that one most clearly sees the influence of Newtonian paradigm practices in TQM. To start with, quality is defined unambiguously--deterministically--via specifications. Where fuzziness does exist, such as in the case of "customer satisfaction", it is appropriately operationally defined so that metrics can be objectively developed and used for decision making.

The control of the measurement process is essential to the subsequent control of the process. ISO 9001 guidelines for quality systems (1987) place heavy emphasis on control of metrology, data records, and documentation.

One of the core practices of all TQM efforts is to improve process quality via reduction of variation. Through simplification and standardization of process methods, process and hence product variation is continually reduced. Product variation away from design intent is minimized, and customer satisfaction increases. In Newtonian terms, the goal is to maximize entropy.

A sequential, iterative learning model representative of the scientific method, such as Plan-Do-Study-Act (PDSA), is often applied in such situations. The "plan" stage does in fact represent a planned change, and the "check" and "act" steps form negative feedback loops under which change success is assessed and new methods are standardized into the existing, equilibrium system. Each cycle of PDSA represents not only a reduction in process variation per se, but also a reduction in uncertainty. PDSA, because it works on only one hypothesis at a time, is best in situations where uncertainty is low, or one is known to be near the "optimal".

For example, PDSA is embodied in the statistical method of response surface methodology (RSM) (Box, Hunter, and Hunter 1978). If one is operating in a region near the global optimum, RSM will design experiments in a sequential fashion which will lead one quite quickly to the optimum; if one is only near a local optimum, and the response surface is "complex" (i.e. multi-peaked), then RSM will get "stuck in a rut". Similarly, the PDSA loop typically assumes that the schema one is using to frame the problem is in fact correct--thus PDSA can be thought of as an enactment of single loop learning. If the schema is invalid, however, PDSA will give one better and better answers to the wrong questions. In such situations, one might be best to adopt a technique out of the complexity paradigm, such as genetic algorithms (Holland 1992) or conceptualizations thereof, which place several schema in competition with one another simultaneously.

Even though PDSA is well thought of as part of the Newtonian paradigm, effective learning, even at the process level, can be quite complex. Such effective learning occurs when one PDSA cycle feeds another, and when PDSA's are embedded in one another. It is when a single PDSA cycle occurs in isolation--when solutions and experiences do not become public and exploration is discontinuous--that the learning process can become ineffective.

In using PDSA one takes a very analytical view of the process and its components. The tools which TQM has available for such tasks are rooted in reductionism. In situations where the process in question is "mechanical" (used in a general sense--a payroll process is highly mechanical also) these tools can lead to very efficient problem solving. For example, the cause and effect diagram attempts to describe a (quality) problem by its constituent possible causes, and is organized by both structural and causal precedence. The cause and effect diagram is an outgrowth of reductionism: a process can be understood by its causal relationships, and these causal relationships can be tracked back to individual elements within the hierarchy of structure and function. The cause and effect diagram has proven itself extremely effective in industrial problem solving, and is a tool which is fairly robust to misuse. In situations where the process is question is not "mechanical" but in fact more complex in its interactions and cause-effect relationships, a cause and effect diagram may introduce bias in process understanding. It is incapable of modeling interactions between elements of the system, or feedback from effect to cause (i.e. it assumes unidirectional causality). In such situations, a systems diagram may be much more effective (Senge 1990). Thus, the complexity of the process in question must be matched with the complexity of the tool used. In situations where the process is mechanical and rational, the conventional tools of quality control coupled with the PDSA methodology are optimal; in situations where processes are complex and behavior is irrational, systemic-based analysis tools aligned with evolutionary strategies may be much more appropriate.

Statistical methods are heavily used in quality improvement efforts. In that they are rational tools which assume objectivity, they are reflective of the Newtonian paradigm; in that they shed light on complex systems through probabilistic descriptions, they are more indicative of the complexity paradigm. They cannot be fully appropriated to either paradigm.

Shewhart's invention of the control chart (1931) in the 1920's was a recognition that standard methods in statistics were inadequate because they did not capture the dynamical nature of the process. Still today few statistical tools exist that can be easily used to describe time-related behavior when such data is coming from a complex process (Dooley 1994; Guastello 1995). Priesmeyer (1992) and Guastello (1995) have investigated chaotic attractors in production data; more such analysis needs to be done.

Statistical tests of hypotheses look at signal to noise ratios; they question if the magnitude of an observed signal is significantly larger than the "background noise", or experimental error. If it is not, then the effect is not statistically significant, because it may have arisen from other random and unpredictable causes. If, however, the system being measured is actually deterministically chaotic (or at least a majority of the observed variance is from deterministic chaos), then the statistical test is not comparing the effect (usually linear) to background noise, but rather to other nonlinear effects. Thus the presence of statistical significance *could* in some situations only mean that the observed linear effect is bigger than the unpredictable nonlinear effect. If this indeed were the case, it may change the way decisions are made on the basis of statistical hypothesis testing.

Organizational-Level Issues

At the organizational level one sees a mixture of Newtonian and complexity-based practices in TQM. Consider consensus in group decision making. Consensus seeks the middle ground of low differentiation--it is an attempt to reduce variation in the schema held by group members . As an end result, this can lead to a decision that has been well thought out from a variety of perspectives, and has wide approval. If divergent thought does not take place while gathering consensus, the group decision may be inadequate (Guastello et al. 1995). What appears to be consensus may be group think.

Goldstein advocates facilitator-led difference questioning to enhance the divergent process (1988). de Bono's six thinking hats method (1985) can be one way in which divergent ideas are surfaced; for example, white hat thinking (factual) is contrasted with red hat thinking (emotive), yellow hat thinking (optimism) is contrasted with black hat thinking (pessimism). Dialogue, where people suspend their assumptions in a search for truth (Argyris and Schön 1978, de Bono 1990, Senge 1990) also encourages a divergent process. More typically people in a group engage in discussion, a debate between opposing viewpoints.

TQM creates a focus on continuous measurement (of the product, the process, and the customer). The capability to experiment, and learn about the current reality, is becoming more valued than expertise. Change is occurring so rapidly and widely now that domain expertise alone is not sufficient; rather one must learn how to procedurally interact with the environment and learn from such interactions. This is evident in trends in corporate training programs, as domain independent skills such as statistics, problem solving, and team building are being taught widely (Anderson, et al. 1994).

Feedback can lead to self-organization. Via the concept of "internal customer", people inside the organization form a chain of customers eventually reaching out to the external customer. Customer needs are back propagated through the system, and the organization can become customer focused. Quality function deployment (Akao 1990) and hoshin kanri (Akao 1991) are methodologies that use a chain of matrices to cascade customer requirements throughout the system. Thus information is iterated, amplified, and understood from multiple perspectives. Organizations are also seeing the value in having internal personnel meet the external customer face-to-face; this also breaks down information barriers (Zimmerman and Hurst 1993; Kiel 1994). Organizations have also become more honest in their communications with employees, to create a better sense of reality among all organizational members.

The whole TQM "movement" can be viewed as a self-organizing phenomenon. TQM principles have been in existence for decades. As complexity theory states, systems will not transform unless taken to far-from-equilibrium conditions. This was the case of Western business practice--even though the concepts and tools existed, it was not until the "quality crisis" (the inability of Western products to compete with Asian counterparts) occurred that management thinking shifted (Guastello et al. 1995). Under far-from-equilibrium conditions, the influence of individuals can be significant. In TQM, the influence of leadership has been essential. It was the *crisis* that brought organizations far-from-equilibrium, and it was *leadership* that influenced the potential paths of the newly emergent orders. It is highly unlikely that leadership itself without crisis could have created the TQM of today. Nonaka (1988) conjectures that it may be necessary at times to *create* a crisis within the organization to hasten change.

Traditional organizational change models in TQM are influenced by equilibrium concepts (Goldstein 1991, Guastello et al. 1995). Lewin's change model (1947) includes four steps: unfreezing, learning, internalization, and refreezing. The unfreezing is a cathartic process of increasing forces towards change and/or decreasing forces resisting change. Resistance to change in organizations can come when the system blocks information from the environment to remain stable. After moving to a new equilibrium state through learning and internalization, the system is refrozen. This model is very similar to Juran's breakthrough sequence (Juran and Gryna 1980), and the Japanese QC Story (Kume 1985), which show how process improvement must be followed by standardization and "holding the gains". These models are not counter to the classical view of equilibrium. In fact, even the analogies of force fields comes directly from classical science.

TQM equilibrium is being reinforced by the development of normative practices (Bush and Dooley 1989, Dooley et al. 1990), the most influential of these being the Malcolm Baldrige National Quality Award criteria (Garvin 1991, U.S. Dept. of Commerce 1993). The criteria lay out in great detail the elements of a "world-class" TQM system, even to the point of allocating weights towards certain elements, such as customer satisfaction or strategic quality planning. In a similar manner, the European Economic Community is introducing the ISO 9000 quality management system criteria; suppliers and sellers in European markets must show conformance to these criteria to do business. Individual organizations are using these criteria internally to standardize their practices, and externally to assure uniformity in their supplier base.

While many of Baldrige's core values are consistent with complexity, the world-wide spread of these normative practices is leading to a state of maximum entropy, where there will be a degree of uniformity in organizational practice. The danger exists however we may be self-organizing at a less-than-optimal point. The state of knowledge today about how to improve quality may *not* be adequate. If so, then we should continue on with more divergence in practice and subsequent communication and learning (Zeleny 1989a). If everyone is doing the same thing, TQM's evolutionary path will have been chosen.

The way to avoid this is for every organization to experiment with TQM practice and develop their own theory. There is a tendency however, because of impatience for quick results, to look for "cook-book" answers--a canned list of steps that will solve everything. Again, this type of thinking is based in determinism. In looking for such answers, organizations often look towards one of the quality gurus (e.g. Deming, Juran, Crosby, Feigenbaum, Taguchi, Shainen, Tribus, etc.). Without asking to be so, these gurus have been put on a pedestal, as people look for yet another set of natural laws. A summary of the connections between TQM, the Newtonian paradigm, and the complexity paradigm is given in Table 4.

[insert Table 4 here]

Beyond TQM

Many of the organizational, planning, and strategic elements of TQM are indicative of a complexity paradigm; many of the problem solving tools, and the spread of normative practices, are indicative of a Newtonian paradigm. Perhaps this is right and just--as Stacey (1992) points out, there is a necessary tension between the analytical efficiency of the status quo and the self-organizing dynamic of change. Perhaps it also is a natural outcome the new emphasis on quality.

Consider the three typical ways in which process-level operations are judged: quality, cost, and productivity. The Newtonian paradigm, as operationalized by scientific management, placed cost and productivity as primary and quality as a constraint. Cost and productivity have always been artificial measures however (Misterek et al. 1992). They are allocated and calculated in whatever way best fits the internal operations of the firm. While quality was considered a constraint, it too could be internally defined--as design specifications with certain ranges of tolerances--and its performance was administered via the quality control department. When quality became Quality, however, an external view was demanded. Customers defined quality, and thus performance became more complex to measure, for it depended on the whole system, and psychological perceptions of the customer. Quality forced a systemic view, which led us naturally to practices in line with the complexity paradigm.

It is not surprising that the tools of the Newtonian paradigm will continue to be effective for improving the quality of work-level processes. We have in fact, designed these systems (physical and otherwise) using linear principles, so our study of them with linear-based tools should yield satisfactory results. Our social (organizational) systems however are now often designed from nonlinear as opposed to linear principles. If we continue to use the same linear-based tools we will be disappointed in the results. We believe that TQM theory and practice can benefit from further coupling with theory from the complexity paradigm; the following advancements are sought:

- The theoretical links between deterministic chaos and statistical randomness need to be identified.
- Better statistical tools and statistical approaches are needed in order to observe, identify, analyze, and improve nonlinear dynamical systems.
- More and better tools which promote systemic thinking must be developed.

- Better communication strategies--those that allow all members of an organization to sense and interpret the environment--need to be developed and implemented.
- Parallel learning models (as opposed to the sequential scientific method) need to be developed and tested; investigation of use of genetic algorithms for quality problem solving must occur.
- Methods which encourage dialogue and divergent thinking need to become more widely used.
- Change models using theories of self-organization need to be further developed and tested.

Finally, if we believe that we are at the beginning of a new paradigm of management practice, then we must be comfortable with the fact that our state of knowledge about complex organizations is far from complete. Rather than converge to a set of normative practices via the Baldrige criteria and ISO 9000 standards, organizations should be actively experimenting with different approaches, and learning and communicating. Just as we strive for *learning organizations*, TQM must strive to be a *learning body of theory and practice.*

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Newtonian	Complexity
Values	
univalence	multivalence
objectivism	perception, subjectivism
Beliefs	
equilibrium	whole system evolution
control	regeneration
Symbolic Generalizations	
predictability (linearity)	harmony (non-linearity)
determinism	indeterminism
physicalism	multi-level representations
Shared Exemplars	
reductionism	systemic inquiry
mathematical models	fuzzy models, statistical models

Table 1 Newtonian Paradigm vs. Complexity Paradigm (adapted from Sanford, 1992)

Newtonian Concept	Scientific Management
determinism	every operation as a predictable science
reductionism	division of labor, tasks
equilibrium	organizational controls
deity-defined laws	management-defined laws
maximum entropy	standardized behavior through methods analysis, training

Table 2 Newtonian Concepts and Scientific Management

Chaos Theory Concept	The Learning Organization
deterministic chaos	fuzzy logic, statistical reasoning
strange attractors	statistical tendencies, group norms, consensus
bifurcations	innovation
sensitive dependency	positive feedback, "act local, think global", leadership during critical events/periods
self-organization	adaptation

Table 3 Chaos Theory and the Learning Organization

Newtonian Paradigm

Determinism & Deity-Defined Laws
recipe-type solutions
manager as director
guru-defined approaches
competitive benchmarking

Reductionism
problem solving tools
cause and effect notions
isolated learning
statistical tests of hypotheses

Equilibrium & Maximum Entropy
Lewin's and Juran's change models
international standards
reduction of product/process variation

Complexity Paradigm

Deterministic Chaos
experimentation over expertise
understanding variation
pilot programs
dynamical statistical methods

Self Organization
measurement and feedback
customer-driven organization
role of leadership
manager as facilitator
cyclical learning
empowerment, self-directed work teams
divergent thinking, dialogue
competitive quality crisis
planning for learning

Sensitive Dependency
role of leadership
design for robustness
systemic thinking

Strange Attractors
learning networks
process benchmarking

Table 4 TQM practices as Indicative of a Newtonian or Complexity Paradigm

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