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Low social control and physiological deregulation—the stress–disequilibrium theory, towards a new demand–control model

by Robert Karasek, PhD [1]

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Objectives The paper presents a new stress physiological theory to describe how low social control can contribute to the development of chronic disease through the deregulation of physiological systems.

Methods Two presumptions and four operating principles are used to derive very generalized forms of hypotheses about disease (and some hypotheses about growth) with respect to the demand–control model. They are based on a new three-part stress model (controller-system-environment) that represents a nested pair of system–environment relations in a systems dynamics formulation, with control limitations based on the Second Law of Thermodynamics, and mechanisms related to an equilibrium of flows of energy and order. The resulting "associationist" demand–control model outlines the processes by which organisms can either devolve into lower levels of complexity equivalent to chronic disease (job strain) or organize themselves into higher levels of complexity (active work).

Results An explanation is provided for how failures of high-level control capacity could be sufficient to explain the development of chronic disease. A new theory of the development of high-level internal control capacity in complex organisms is presented. An "association-of–parts" theoretical format is claimed to be an acceptable alternative to materialistic explanations for both health and growth.

Conclusions The requirements of explaining new effects of complex work and social structures confirm the need to revise the demand–control model into a more general form.

Key terms control; chronic disease; complexity theory; decision latitude; demand; disequilibrium; physiological deregulation; stress; second law of thermodynamics; systems theory.

There is increasing evidence of a growing chronic disease problem that appears to be associated with contemporary forms of economic and social organization. Much of it involves diseases that are potentially stress-related—such as cardiovascular disease, mental disorders, and musculoskeletal disorders. Four types of evidence now converge to suggest that a significant portion of this burden is work- and economic-system-related, and, then, very possibly, related to low control in social organizations.

This new information raises a question about what the specific operating physiological risk mechanisms are—and why it is taking so long to understand them. To address this question, this paper attempts to present an outline for a new stress physiological theory to describe how low social control can contribute to the development of chronic disease through the deregulation of highly integrated physiological systems. The theory implicitly explores the evidence for the physiological causes of chronic diseases at a high level (ie, a nonreductionist level) and in a congruent manner—to provide a potentially more easily understandable link to the broad social policy consequences implied by the global economy.

To preface the discussion, three summary claims are made about the nature of the current global social challenges to health. It is claimed that there is (i) a convergence in the profile of work-related chronic diseases in advanced societies—diseases which are also increasing, (ii) increasing similarity of psychosocial job characteristics observed in empirical studies around the world, as the global economy increases its reach, and (iii) an increasing accumulation of epidemiologic evidence of a "work relatedness" of a broad range of chronic diseases in which low control of the workplace or economic system is a central cause. For example, reviews

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[1] Department of Psychology, Copenhagen University, Copenhagen, Denmark, and Department of Work Environment, University of Massachusetts at Lowell, Massachusetts, United States.

Reprint requests to: Professor R Karasek, Department of Work Environment, University of Massachusetts at Lowell, MA 01854, USA. [E-mail: robert_karasek@uml.edu]

of 137 studies on heart disease (1), mental disability (2), and musculoskeletal disorders (3) found support for low workplace control as a risk factor for chronic disease. These reviews are tests of the job strain hypothesis of the demand–control model.

The requirements of explaining the phenomena confirm the need to revise the demand–control model itself into a more general form to accommodate the breadth of these new effects of complex work and social structures.

Low control and an explanation of the inverse social class gradient in health

There is also a major debate about the cause of the increasing socioeconomic gradient in health (ie, higher mortality in lower social class) in the face of rising material well-being. The two main causes cited (4) are absolute material deprivation and relative material inequality, but opponents have presented convincing arguments against the comprehensive validity of either explanation.

One little noted problem is that applying the traditional stress models of chronic disease actually exacerbates this mystery. In these models, illness risk is based on high levels of sympathetic arousal (ie, mental demands). However, these demands are actually somewhat higher in higher classes, rather than in lower classes (where physical hazards are far higher). Thus mental demands cannot explain the social gradient in putatively stress-related morbidity. Mental demands may be slightly more common in upper classes, but stress-related disease is surely not.

Toward a theory of low social control and stress-related chronic disease—a high-level physiological theory

It is proposed that what is now needed is a new stress model of how absolute low social control, in major socioeconomic institutions, could cause chronic disease, as a third explanation for the inverse social gradient in health.

Most of the traditional stress models (5–7) utilize the physiological pathway of high levels of sympathetic arousal for extended duration without relaxation as the pathway to illness risk and thus focus on the magnitude of the environmental stressor confronting the individual as the major risk factor—not the individual's limitations of control.

However, the requirement of coordination—of ordering—or of specification of a precise response—is the determining "load" for the central control system in information theoretic and general thermodynamic terms. My major claim is that the Second Law of Thermodynamics limits the possibility of precisely specifying the nature of the response needed by each of a large number of physiological subsystems. Such "coordination burdens" could play a major—but so far underilluminated—role in physiological response pathology. These limits are independent of the better-known limits related to "calories" consumed, calories burned or physical loads applied—which are related to the First Law of Thermodynamics.

The social policy implication of the stress–disequilibrium theory of chronic disease development is that requirements for coordination have been pushed to extremes in the context of the long-term stressor exposure of humans in their social environments—our global economy for example. The result is a diminished capacity for physiological coordination, and finally chronic disease development.

Certainly there is no question that external work demands would lead to internal work demands (ie, physiological loads). Could restriction in the degrees of freedom of the organism's response to the environment—"low external control"—lead to "low internal control"? Low internal control entails restriction in its internal degrees of freedom for physiological coordination. However, if internal control is limited by external control, the implications are significant.

In terms of phylogenetic evolution, it can be recalled that warm-blooded mammals internally devote huge resources to maintaining "control" over physiological states: a regulated "milieu interior." The high cost is an order-of-magnitude higher food intake per unit of body weight by humans when they are compared with reptiles. The payoff is the precise self-regulation that is the foundation for our complex cognitive and social development. What if lack of external social control destroys the expensive internal capacity for self-regulation?

The overwhelming complexity involved in the dynamic understanding of multiple cross-linked physiological systems leads us inevitably to search for a simple "general principle"—to avoid becoming lost in details and expending all our resources. Is there a possibility that a satisfactory higher level explanation (8) could be found—a macrolevel physiological explanation? For example, one related to low social control? Such an explanation would be closer to the necessarily macrolevel social-policy solutions for the aforementioned health risks.

What would "high-level" theory mean in this context? One implication is that a deficiency at a high level alone (eg, low control in social situtations) could be a sufficient explanation of disease, without a major contribution of lower level deficiencies, such as biomolecular deficiencies. With the use of a hypothetical analogy, the meaning of such a provocative proposition is outlined in the following discussion.

Consider a feudal warlord defending his fiefdom from a rival warlord by raising a local army for battle. Suppose only half of the 500 troops needed by the warlord are mustered and that the warlord loses the battle and, with it, his fiefdom. Analysts could look for high- and low-level causes. At the low level, it might be noted, for example, that extended rains fell and the crops planted on the northern slopes of the warlord's valley had low yields, poorly fed locals, and few troops. On the basis of this low-level explanation, it might be suggested that the warlord institute an improved crop fertilizer program to reduce malnutrition and troop failures.

However, a high-level expert—a military strategist—would say that the warlord lost his kingdom simply because he failed to field a large enough army. This is a high-level explanation because it focuses on one of the warlord's two primary functions: (i) fielding an army and (ii) commanding it in battle. The military strategist does not need or want to know "how" the troops get there—only that there are enough. A warlord has many resources with which to get the recruiting job done if some troops fail to appear because of hunger—one of many low-level problems requiring minor tactical solutions, conferring no major advantages by themselves. To the military strategist the low-level explanation related to crops and fertilizer seems to be a marginal and partial approach to the general problem of securing fiefdoms (it is not a *sufficient* cause). The high-level answer is seen as providing a more powerful explanation. These two logics do not really completely exclude each other; instead they relate to different levels of action (8).

One approach to a high-level explanation of the low social control–disease link is to search for a formulation of the limitations on physiological "ordering capacity", a limit on the ability of the organism to internally organize its adaptive interactions with its environments. This search must be based on an understanding of how a new ordering capacity is created.

Outline of the argument

To orient the reader, an outline of the stress–disequilibrium theory is first provided in this paper that is stated in terms common to the tradition of past demand–control research involving psychosocial workplace factors, illness and behavior—even though this paper's focus is rather exclusively on the physiological processes of disease development. Using this language, it could be said then that, in the stress–disequilibrium theory, "control" is reinterpreted more broadly than in past demand–control discussions. In the turbulent new context of the global economy, it means the person's control over the strategies he or she has developed to maintain the stability of his or her "flows" (ie, flows of good, nourishing things: money flows in the door, rent flows out the door). What is important is that the input and output flows are in balance. Maintaining stability of flows for self and for families is always the major "control" challenge of adult lives. Thus "control" (decision latitude) is the freedom for people to act using their repertoire of skills within the social structures in which they have made their main investments and have gained their major life-sustaining rewards.

Currently this scenario is made more complex by the fact that previously existing platforms of stability from outside are being undermined by global economic phenomena. People's previous control strategies may not be enough to maintain equilibrium—large-scale organizations develop new rules undermining the effective application of previous strategies. Without the ability to maintain high-level equilibriums, internal systems become unstable and devolve toward lower levels of functioning. Chronic disease develops via physiological deregulation.

This new perspective also brings with it a somewhat modified perspective of "demands." Since no complex organisms exist without flows, a continual input and output of energy (nutrients, money, etc) from their environments, none exist without demands. None are therefore either truly "stable" (truly stable forms are dead). What could be stable, then, is the constancy of "flows." The internal conditions these flows create, and the consistency of the actions the organism takes in its environment to maintain its flows—these could be stable.

Part I

Understanding the limitations of the physiological ordering capacity—the "missing link" available in the Second Law of Thermodynamics

The application of thermodynamic principles lies at the root of the understanding chemical reaction possibilities. It therefore provides a basis for understanding the limits of plant and animal capacity to transform nutrients and environmental inputs into the capacity to control their own internal and external "work". It is a natural place to start.

The search for limitations in human control capacity begins in the second cornerstone message of thermodynamics: the limits on the efficiency of the transformation of disordered energy into ordered energy in the Second Law of Thermodynamics. The Second Law of Thermodynamics provides this type of limit; the efficiency of a heat engine is always less than 100%. There is always less useful energy (in the form of ordered work from a heat engine) than energy that is input in the form of heat (disordered energy). The following question illustrates some of the differences between the First Law of Thermodynamics and the Second Law of Thermodynamics:

"Can we merely consume more food to resolve our feelings of being out of control in a complex global economy—or—would that merely lead to obesity?" The well-known "calorie calculus" of the First Law does not provide a full answer.

Theoretical biologists are now turning consistently to the thermodynamic principles of the Second Law to explain complex living systems, for example, Recordati's "thermodynamic model of a central nervous system" (9, 10). Kauffman has postulated that the definition of a living entity is based, beyond the ability to reproduce, upon the "ability to perform a thermodynamic work cycle"(11). Prigogene & Stengers (12) have used non-linear forms of thermodynamics to formulate a theory of "self-organizing systems". Environmental economists use the Second Law as their foundation for understanding the limits of sustainability in material goods production: "without reference to entropic throughput 'it is virtually impossible to relate the economy to the environment'" (13).

A three-part stress paradigm—Controller, System and Environment

The stress–disequilibrium theory is based on a new three-level thermodynamic model to describe the process of physiological risk development. This "Environment–System–Controller" model more clearly fits the needs of a stress paradigm. A "stress paradigm" requires an understanding of the following three elements simultaneously: our physiological System, our Environment, and our Controller (the central nervous system). The typical formulation of a stress problem involves an understanding of the effects of the challenges to (i) the central nervous system (CNS) on (ii) physiological systems that come from adapting to (iii) environmental challenges.

The standard model for the Second Law is usually graphically depicted as only a two-part model: a system located within an environment—where two flows of energy or order link the two (top of figure 1). As implications of this classical thermodynamic approach are examined, however, it can immediately be recognized that it needs the aforementioned modification to fit the stress theory. The "Central Controller"—which creates a three-part model (bottom of figure 1) is then added. The new model is actually only a nesting of one standard thermodynamic model within another—thus creating a two-level model. The extension adds a new level involving a central controller (ie, the CNS) to administer homeostatic or allostatic regulation (9) [See principle 1.]

Principle 1. Controller–System–Environment—the three-part stress paradigm

The living system "stress" and can be understood using a three-part model with a System–Environment boundary, and then another boundary defined between the System and a System Controller within it (= a pair of Second-Law models—one "nested" inside the other). Flows of energy and order (and material) among these three entities define their existence and operation. [A presumption]

Formulating ordering capacity limitations from energy in the Second Law of Thermodynamics into order principles

The basic principles of the Second Law of Thermodynamics are simple. The first concepts have to do with the

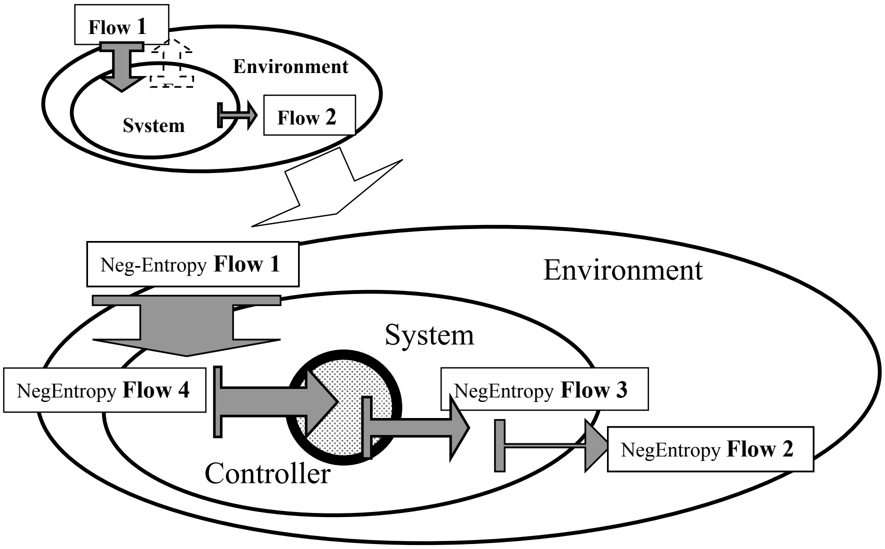

Figure 1. The extended three-part stress model with Controller and Negative Entropy (NegEntropy) flows.

relationship between energy and order. Thermodynamic "work" is ordered energy with few degrees of freedom. A classic example is the piston of a steam engine, in which all energy is channeled into one direction of motion that is predictable and usable. Disordered energy, heat, is energy with many random degrees of freedom, for example, the gas molecules in the steam being input into the steam engine. It is undirected energy. The disorganization component of energy is called entropy. Its opposite, the ordering capacity of energy, is its Negative Entropy (NegEntropy) (which becomes work when energy is "added"—very roughly). Dyson (14) defines the difference between work and heat in this manner: "Heat is disordered energy. Energy can exist without disorder. For example, a flying bullet [p 58]."

Another set of concepts is crucial for the preceding goal, namely, thermodynamics formulates limitations for energy and order transformation. The First Law of Thermodynamics is the well-known principle of the conservation of energy. The Second Law is generally commonly stated to predict that the "order or the universe runs downhill" (towards a totally uniform "grayness" of nothing but random fluctuations). Fortunately for living organisms, this fate occurs only within a closed system. The Second Law yields efficiency criteria that absolutely limit the amount of work (eg, 25% for a steam engine) that can be obtained from an amount of disordered energy (heat). There are no perpetual motion machines—period. This barrier is the root source of the limitations of ordering capacity.

Living systems represent a special type of thermodynamic equilibrium—that of an open system. Maintaining life requires the maintenance of gradients, namely, constant, improbable deviations from "true total equilibrium (dead, inert, a "grey" uniform state)". The concept of equilibrium for stable living systems (homeostasis) thus describes an *equilibrium of flows*.

It is impossible to conceive a living organism without demands. Without demands there would be none of the constant "flows" of energy or nutrients that are constantly transformed into ordered action (work) as needed. This possibility would contradict the Second Law of Thermodynamics and all known biological science. Demands come from "just being alive". With adaptive environmental activity as a goal, the complex system maintains its structure—against the probabilities of the Second Law of Thermodynamics—and from time-to-time also grows.

The inevitable tendency of the system to move towards inert "true equilibrium" can only be offset by the import of energy from outside the System and the export of entropy from the system (ie, importing NegEntropy). Thus the processes of maintaining life within living organisms on earth are dependent on the flow of NegEntropy from the environment into the System to maintain these differentials (NegEntropy, flow 1). [See the top and bottom of figure 1.]

The other flow in the standard model occurs when the ordering capacity is "used up" as the organism does its work in the environment (NegEntropy, flow 2). Extensive coordination of internal physiological processes is required for individual behavior and complex social interactions. All represent "work" according to the aforementioned definition, channeling energy with many degrees of freedom into the constrained release of the energy into a few degrees of freedom—embodying information about just the right time and place and the like. Such actions produce order in the environment and thus decrease its entropy in the environment. This phenomenon represents an export of NegEntropy to the environment from the System (which has gained entropy)—NegEntropy, flow 2.

Crucially, the nesting of one System–Environment pair within another in the three-part stress model gives rise to a second set of energy-to-order flows (NegEntropy flows) as explained later. In this context the Controller exports ordering capacity to the System (here the full physiological system) by coordinating diverse physiological subsystems to achieve the maximal state of readiness for actions in the Environment outside (NegEntropy, flow 3). Very importantly, it also creates a second new flow—which has significant implications in attempts to understand the development and utilization of ordering capacity in complex living systems (NegEntropy, flow 4).

The addition of the Controller allows a discussion of processes in which the CNS coordination of internal physiological work is well known to exist. These physiological processes and their coordination would be measured in laboratory or clinical monitoring of, for example, blood pressure, blood sugar level, and the like.

Some definitions

Before going further into the ordering capacity challenge, it would be useful to review definitions. "Work" is defined as the purposeful and precise organization of the actions of the organism to meet unpredictable demands for action from the environment (external work). The definition is applicable in both physical and social science contexts. This definition emphasizes that the response of the organism to the environment must be precise. The magnitude of work depends on the amount of ordered energy transferred by the organism (system) to the environment (also how work is defined in physics). In no case is energy transferred without order considered to be "work"—or likely to be useful for the organism. These requirements mean that the degrees of freedom of response available to the organism for effective performance can be small—and can reduce the flexibility of action. Precise and effective action in the external environment requires coordination of internal physiological and behavioral capabilities.

This precise coordination is a different challenge than that of using muscles to lift weights. It is "ordering work," related to the Second Law of Thermodynamics. Internal control is exercised by the Central Controller—for example, the CNS—to orchestrate the energetic and purposeful activity of subsystems into the overall organism response that is exactly suitable to the environmental challenge. It is more like the football place-kicker who must, under the pressure of oncoming defensive players, precisely kick the ball between a narrow set of upright poles—even a slightly missed-placed step loses the game. Total internal physiological work is equal to the (i) internal energy and (ii) internal ordering coordination requirements of both externally focused and homeostatic needs. Environments that require both energetic response and high precision imply high demand and low control situations: the familiar high-strain construct—external strain—from the demand–control model (15, 16).

The traditional demand–control "demands" remain relevant, in that high- or low-level job demands can still be defined, their nature and frequency still assessed, and they can still affect health as previously hypothesized, but the perspective of "quantitative demands" now needs further specification, and, as seen later, there can be many levels of demands to be considered simultaneously.

Control in this discussion—when not more specifically specified—means the ability of the CNS to maintain the organization of the subsystems of the organism in the context of facing an adaptive challenge. External control measures the limitations of the "degrees to freedom" of the organism to operate, as determined by factors outside the control of the organism in its environment. For example, external organizational or environmental restrictions can interfere with the execution of the strategy that the organism has chosen—or—they can limit internal physiological possibilities, limiting internal control (ie, self-regulation). People are such effective self-regulators that they can sometimes exercise control over their external environments. The organism can periodically control its own behavioral context to permit, for example, long-term rest and sleep without threat.

New principles of creating high-level ordering capacity in complex organisms and using it up

Now attention will focus on two new flows (NegEntropy, flows 3 and 4) of the three-part model. The discussion

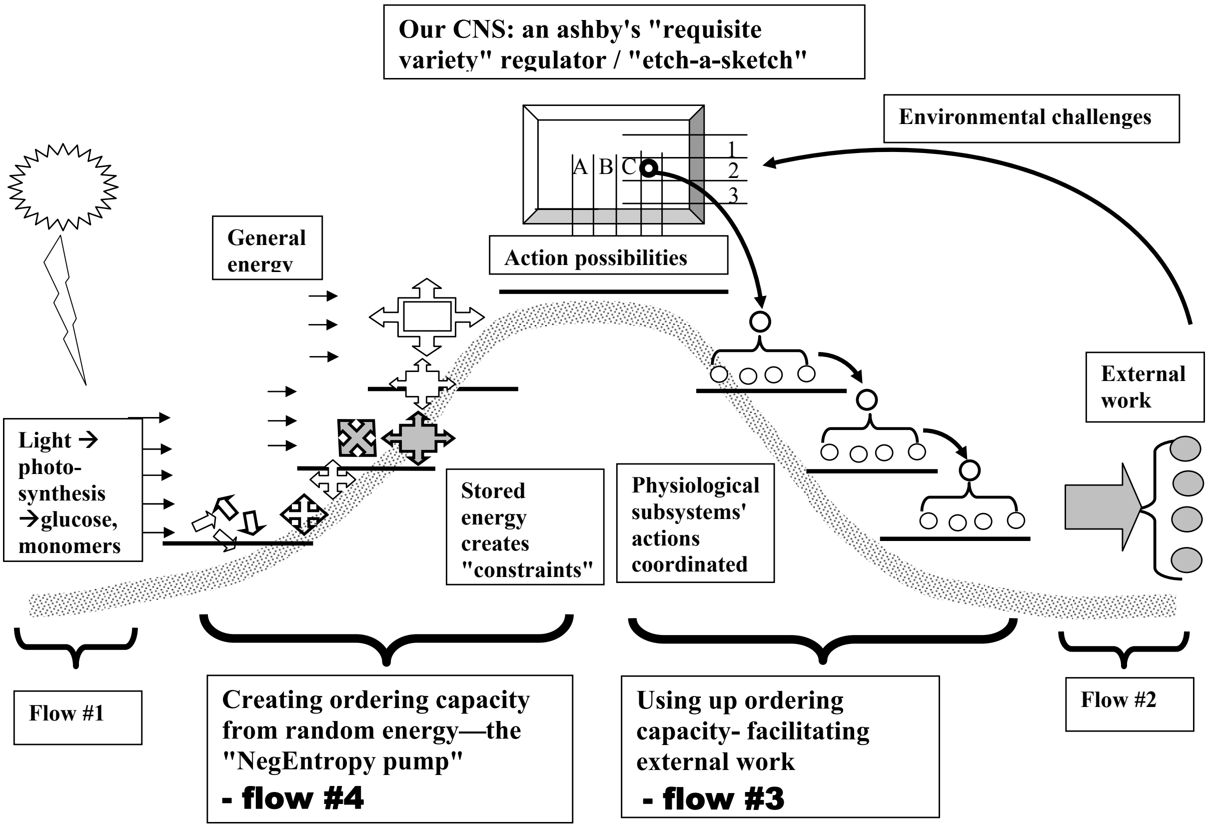

Figure 2. Creating "ordering capacity"—and using it up . . . climbing up—and moving down—the Negative Entropy (NegEntropy) hill.

begins with the simpler of these two flows (NegEntropy, flow 3), namely, what happens when NegEntropy is used up. [See the right side of figure 2.]

Flow 3—regulating the organism—actions at the top

Ashby (17), in his classic chapter "Requisite Variety" lays out the conceptual foundations of a process of internal coordination (regulation) as the organism tries to maintain stability while meeting environmental challenges. The goal of "Regulation [is to] block the flow of variety [from the organism's environment, and thus keep the organism's internal variable stable]. The perfect thermostat would be the one that, in spite of disturbance, kept the temperature constant at the desired level."

Ashby illustrates using a mathematical example, in the form of a column–row matrix in which the unpredictable environment has its actions counteracted by the regulator of the organism so that the organism can maintain its internal physiological stability. In this example, the rows are unpredictable environmental challenges, and the columns are possible responses from the organism attempting to maintain its stability. Stability in the diagram is reflected by the ability to maintain the same output value (internal state value) in the cell representing an intersection of a column and a row—regardless of what "move the environment makes" (ie, what row the environment selects).

Ashby's point is that it is only the existence of very large numbers of columns (possible responses) that can insure a high probability of maintaining the stable output value for the organism, regardless of environmental challenges. The well-equipped regulator can respond to all environmental disturbances in such a manner that all of the outcomes fall within the acceptable range. With this simple example presented in a logically general game theory format, Ashby demonstrates "the law of requisite variety: Only variety in [the regulator] can force down the variety in [the environment]—only variety can destroy variety [p 207]".

Ashby then further defines "controller" as a self-conscious step beyond this fairly simply programmed regulator. The controller further decides which outcome target value to pursue (p 213). However, Ashby's conception can be extended at this point to fit the goals of the stress model. The high-level strategies needed by the CNS to maintain the highest levels of flows require long-term planning (the warlord's job) for the proper utilization of subsystem specialties to assure the greatest surplus capacity for high-level strategic actions.

In the three-part model, the conscious CNS is charged with the job of maintaining the equilibrium of flows through the use of chosen adaptive actions. They are not totally automatic. Choice of one skill over another allows great power in the environment. Mammals can maintain their stability of flows in the context of facing many extreme challenges. In this context, it is interesting to note Guyton's differing viewpoint in his "Introduction" to his classic textbook *Medical Physiology* (18), that all human physiological processes represent a total "autonomicity." The difference from the conventional chemistry and physics description of "System–Environment" processes—and even conventional medical physiological descriptions—reflects the higher level at which the problem is examined in this paper. At the molecular level, chemists can be satisfied with describing how chemical equilibriums occur "automatically" (albeit, at variable rates). However, maintaining equilibrium for human-scale stable action in a complex and variable physical and social environment represents full-time planning, however much routine "autonomicity" it might suggest to some very high-level observer.

Using up coordination capacity. As actions are taken by the Controller to precisely specify the physiological System response, the degree of freedom between subsystems declines—and entropy drops. "Doing work" requires the Controller to coordinate the action of the physiological subsystems (NegEntropy, flow 3). This process represents an export of NegEntropy to the physiological System from the Controller (which gains NegEntropy—disorder). In terms of the Second Law of Thermodynamics, this action produces work in the physiological System from disorganized energy. The high-level, organism-controlling, Ashby-like CNS NegEntropy is consumed. [See the right side of figure 2.]

This is the internal organizational cost of coordination for the physiological processes. The coordination plan allows only very specific results to occur with a generalized energy input. The CNS exports order to the physiological system, for example, by regulating body temperature or responding to a fight–flight challenge, or, in this case, by winning a battle advantage—all of which uses up ordering capacity to prepare the organism for environmental work. [See principle 2.]

Principle 2. Work—expending ordering capacity—NegEntropy, flow 3

One level coordinates actions of the elements in the level below it, depleting negative entropy at the upper level and facilitating ordered work at the lower level. Unitary actions of an organism are based on the coordination of subunit actions. [An operating principle]

An analytic tool for measuring ordering capacity—degree of freedom. The assessment of negative entropy–entropy is based on an enumeration of the total possible states that the elements of a system can occupy ("phase space"). The more states, the greater the entropy, that is, the greater the unpredictability that any very specific combination of system elements would randomly occur (eg, correctly guessing a many-digit lottery number).

Such a formulation is also consistent with recent empirical data on levels of cardiac risk in stressor exposure before fatal arrhythmias. Skinner et al found that a reduction in the degrees of freedom of the cardiac system—as assessed by the "correlation dimension"—from 2.5 to under 1.2 (1.0 being the theoretical minimum) was associated with lethal tachycardia in pigs (19) and in human cardiac patients (20).

According to these results, the concepts of "ordering capacity" that follow would be based (i) on the number of physiologically independent control subsystems available to facilitate the environmental response or homeostatic adjustment and (ii) on the available dynamic range of control of each of these systems. The more independently physiological systems function and the larger their dynamic ranges, the more degree of freedom in high-level response, and the greater the potential "health" of the response capacity.

Flow 4—the missing flow—creating ordering capacity, the NegEntropy pump

The central thermodynamic challenge is the problem of turning large amounts of "cheap" disorganized energy into significant amounts of precisely ordered energy ("expensive" energy). Generalized (disordered) energy is cheap in that it is relatively plentiful. Its problem is its disorganization—a lot of disorganized energy is often worse than no energy at all (eg, explosions).

Thus there is one important new explanatory challenge at this point. The following question must be answered: "How can the understanding of the simple sources of 'ordered energy' that are known in the natural environment [eg, photosynthesis, adenosine triphosphate (ATP), etc] be transformed into a model for the creation of high-level ordering capacity—NegEntropy, flow 4—that the CNS requires?" In other words, "How do we create high-level ordering capacity?"

The steam engine creates a higher level ordering capacity from its steam input. The physical properties of the steam engine—its piston-size stroke, and insulating properties—represent a "constraint structure" that determines how it "squeezes" all the random degree of freedom of the energy of the steam molecules into the limited but very useful variability of the steam engine's one-degree-of-freedom reciprocating stroke. This "constraint on degrees of freedom" idea yields a very important example of a general principle for the later biological discussion.

Beyond the important "constraint" clue, this example shows that separate, but linked thermodynamic analyses must be performed at multiple levels for an understanding of the implications of the Second Law of Thermodynamics on the overall ordering capacity of a complex biological system. [See principle 3.]

Principle 3. Independence of levels

Each System–Environment relationship that can operate as its own bound thermodynamic entity (with the determination of flows in and out of energy, order, and materials assessed using the First Law of Thermodynamics and the Second Law of Thermodynamics) can be considered to be a separate level. [A presumption]

A simple example of how ordering capacity at a "higher level" is created might be the building of a huge concrete bridge across the Rhine. The first stage is to construct the formwork for the concrete bridge. In the last stage, hundreds of tons of free-flowing concrete are poured that harden after a few days into an elegant structure able to carry enormous traffic loads. The first step, construction of the bridge formwork, is a rickety-looking affair, based on the simplest and lowest level of components—plywood panels—but it is a supremely accurate process that takes many months of meticulous, albeit low-level, labor. Too, the resulting formwork must be very precise in that the concrete must be put into the right place the first time. By carefully expending much "ordering capacity" at a low level, one can create a very large-capacity ordering structure at a higher level—a beautiful bridge capable of decades of regional transport service.

If the concrete bridge analogy is extended to biological systems, the plywood might be likened to a specific enzyme in a cell, representing "stored energy" at a low level (albeit a moderately complex output at its own level). It is very low in NegEntropy when compared with the complex protein output of the final process. The biological "wash" of amino acid molecules, plus generalized energy (ATP, oxygen, etc) consists of cheap, low NegEntropy inputs (relatively). However, without the precise "formwork" of the chemical enzymes, this process would lead to useless, possibly toxic, biological waste.

As the organism adds levels of functional complexity—in order to achieve the goal of precise regulation—it must add levels of control specificity. To get a high level of complex ordering capacity, one must add a constraint structure at each new level of organization to reduce the enormous range of possible states to the small number that represent the action possibilities of the organism. The organism requires very specific actions—albeit with some variety, as already noted—but the huge variability produced by assemblages of millions of molecular-level input components yields an astronomically large number of alternatives—leaving a negligible possibility that the right combinations would occur at random.

As each level of functional organization is created, some actions must be tested and reinforced, while others are tested and rejected. Through this process "constraints" are created on the available range of actions. The organism creates, for example, an enzyme that promotes a special type of reaction, but does nothing to promote another reaction. Thus the created constraints are really pathways that are favored and that use up much of the reaction resources. The "constraint structure" is actually a specific-action promoter designed to facilitate precise regulation at a higher level. Another example—systems of negative-feedback loops that are constantly returning the system to equilibrium after its small departures— also represents such "structure", created at one level, and a platform for action at the preceding level. [If the deviations are too large, the feedback mechanisms become nonlinear and lose stability and the system can become "chaotic".]

Sequential steps of this process, each building on the level below, can eventually allow the cheap "wash" of large amounts of disorganized energy input at high levels to become complex work at higher levels; this is the "NegEntropy pump" (depicted on the left side of figure 2). What is created at the highest level of the Controller is then a set of high-energy action-potential possibilities available for use as environmental challenges arise. This "fully loaded", high-level repertoire would correspond with Ashby's image of the "responder" for a complex organism with maximal variety. [See principle 4 and the left side of figure 2.]

Principle 4. Creation of constraint-based ordering capacity—NegEntropy, flow 4

One level creates the elements to build constraint structures at the level above it, supporting a NegEntropy creation process at the upper level (ie, ordered work at one level produces outputs that are input to an ordering process at the next higher level. [An operating principle]

[A side note to physicists: (i) The ordered energy at the high level actually originates from disordered energy input at a high level, when constrained by the high-level platform structure discussed earlier. Thus, precisely, NegEntropy is not really "pumped up" through different levels. (ii) Separately, the potential expenditure of NegEntropy at high levels to accomplish a multilevel action can be a constant drain on NegEntropy at lower levels because the lower level systems need to be in a state of "constant readiness" for precise actions (ie, troops awaiting the day of battle), forgoing some states and selecting others. Perhaps neural networks help achieve such coordination (9, p 296). (iii) The NegEntropy discussions presume linear system response, just up to the nonlinear borderline (beyond that come chaotic behavior and changed equilibria (p 12).]

Up and down the NegEntropy hill—using up ordering capacity

The discussion of flow 4 illuminates an important point. The need for periodic activity of the NegEntropy pump to restore ordering capacity can explain the rhythmical and cyclical nature of life activity in complex systems. While the system is saving up ordering capacity, it cannot use this same ordered energy to do work outside the system. Thus internally ("anabolically") focused activity occurs during one period, followed by the restored capacity to do external work ("catabolic") in the following period, which depletes the internal capacity and initiates a new cycle (involving NegEntropy, flow 3 and flow 4). This is also the nature of the cycles noted in the classic example of operation in the Second Law of Thermodynamics: the steam engine. Here, the use of the term "anabolic" does not only mean a contribution to the construction and rehabilitation of cell structures and the like, but also a creation of multilevel usable (albeit low order) energy stores.

Multiple levels—independent, linked and contingent

Are the levels of ordering capacity tightly linked or are they independent? Both. Principle 3 states that each level can be understood on the basis of the laws of thermodynamics applied independently to that level. However, actions are also linked across levels—as the NegEntropy pump illustrates. It can take much time before the stored work outputs of one level have created a sufficient "constraint structure" at the next level for work at the higher level to be made possible—efficiency limitations always apply to delay this readiness. In this respect—in the short term—the effectiveness of one level is independent of the levels below. In the long term, however, low-level contributions routinely specifically build precisely this platform for higher level function—which is evidence of linkage between the levels. This phenomenon has important implications for "functional" chronic diseases that affect high-level physiological processes.

Fundamental biological processes related to ordering capacity principles—introduction to principles 5 and 6

The four principles already presented—a three-level stress model, creation of higher level ordering capacity, using-up ordering capacity, and independence and linkage of levels—together provide the platform for understanding both the creation of and limits to high-level ordering capacity, namely, the Ashby-like alternative strategies that allow the organism as a whole to survive and thrive. However, as these principles are taken together in the necessary multiple-level manner, new principles of function emerge. Fortunately, these turn out to be consistent with the well-known basic physiological processes involved in the central regulation of complex organisms. Two of these two intermediate level principles are briefly discussed in the section that follows (ie, homeostasis and return-to-baseline phenomena). In homeostatic "protection," the higher levels provide supportive contexts for successful lower level function—which allows the lower levels to generate the surplus that supports higher level action. The return-to-baseline principle is a very basic statement of the requirements of the Second Law of Thermodynamics with regard to rest states.

Homeostasis

The success of the high- and low-level processes is linked in a number of ways. The low-level processes cannot operate effectively without the correct context (the right body temperature, blood acidity level, ion concentrations, blood oxygen level, etc). Indeed the very "tightness" of this regulatory stability is the basis for the efficiency of the lower level processes. Complex organisms have achieved a very special relationship among their subsystems in which the high-level system is sufficiently effective to create the context for effective low-level processes—which in turn supply the high-level system with its resources for multiple action strategies. This relationship is reflected in discussions of "homeostasis." The higher levels in the NegEntropy pump have the responsibility of maintaining the stability of lower level "production processes"—otherwise the lower levels cannot perform. Without lower level performance, eventually there is no stored work output to support the higher level organizational capacity. For example, if food intake cannot support the appropriate metabolic rate, body temperature regulation is inhibited.

It can be noted that this explanation does not make the distinction made by McEwen (7), of allostatic (environmentally adaptive) physiological systems versus homeostatic platform systems. Here, systems at all levels can be regarded as actively adapting to their environments—or as serving as stability protection platforms, depending upon the context in which they are viewed. [See principle 5.]

Principle 5. High-level protection of low-level contexts.

The higher levels must provide the internal environmental stability for the level(s) below. This support allows the production of the outputs of the lower levels to continue, which are the needed inputs for the upper level. The concept of "homeostasis" implies a platform of a stable "milieu interior" upon which a higher level of functions can be built. [An operating principle]

Return-to-baseline–refresh

The common maxim of physiological health—restore all gradients—is actually a direct reflection of the principles of the Second Law of Thermodynamics. The efficiency of the transformation of disordered energy into order is highest in the condition of the largest differentials for the NegEntropy "flows." Restoring the gradients might, for example, reset chemical potentials to their maximum—and it can be done with "cheap" disordered energy. But this process is not costless. It is like reformatting the hard drive of a computer—all of the bits are now "1". The "refresh" involves the loss of all specific information, potentially stored in gradient strengths in some cases. Usually this can not be tolerated, and therefore the process may have to occur only at especially selected times, for example, during sleep. [See principle 6.]

Principle 6. Restore all gradients.

All gradients must be returned to their maximum for efficient order-to-energy processes to occur. This restoration can occur through the input of disordered energy (low NegEntropy) from above, and it temporarily suspends the ordering capacity of the levels. [An operating principle]

In some high-level situations, the restoration must occur at a time judged as "protected" when the organism is not vulnerable, since during this time of refreshing, no control possibilities are available to the system involved. A high-level physiological example of "restoration" may possibly be found in the role of sleep and REM (rapid eye movement) dreaming, which is especially prominent in the most complex self-regulators—mammals. Sleep certainly occurs during time intervals that the high-level CNS has selected as a "protected time". During sleep many of the regulatory processes that the CNS normally controls are decoupled—"offline". [There is no control of body temperature during REM.] During REM, periodic massive undirected generalized-energy inputs (PGO spiking activity, similar to the sweeping, nonspecific neuronal arousal of an epileptic seizure) (21) restore many high-level CNS gradients (this is a speculation). The implication is that the very highest central control functions (and low level) are returned—cheaply—to their "zero" state during sleep, particularly during REM. Extended failure to restore via sleep and REM due to "socially induced" incessant activity and treadmill limitations many result in poor gradient strength, and it certainly leads to a greater degree of autonomic deregulation than is ever naturally observed in nature (22).

Monitoring biological variability and ordering capacity

After this "refresh", the system, in its "zero state", would no longer "remember" any of its day-labor operating settings. It now has zero information; in other words, it is high in entropy and low in NegEntropy.

However, it should be observed that this is probably *not* the physicist's entropy of the ideal gas—totally random states. More likely, each of the many subsystems of the organism has been restored to maximal operating capacity and displays its natural input and output rhythms. It might appear to display a high entropy-like variability, but it is actually like Skinner's low-dimensional chaos (which he has clearly identified as the reflection of relatively low numbers of degrees of freedom).

Thus what is most likely to be observed in biological monitoring is then a variability that reflects a myriad of separate physiological systems in a maximum potential state, all "waking up and flexing their muscles" at their own natural frequencies—before being called to attain certain specific potentials in the early morning. This situation would actually represent high NegEntropy, an Ashby-like high-ordering capacity, ready to create efficient order in the system and, in turn, allowing the system to organize parts of its environment.

There has been much scientific observation that the greater the range of variation displayed by physiological systems, the healthier the organism, by Skinner (19, 20), and by Lipsitz & Goldberger (23). It is also consistent with Bernston et al's formulation (24) that was used in the later analysis of heart rate variability, that greater robustness in cardiac control comes from the multiplicity of coordinated, but otherwise independent, physiological systems.

Most of the discussions in stress physiology concern molecular and psychoendocrine processes that take place on intermediate biological levels. The two intermediate-level processes just discussed, in turn, support the the two highest level principles, at which both the goals of this paper can finally be addressed—illness and health. These are the familiar targets of the hypotheses for the demand–control model. Systems can be forced out of stability, and they drop back to lower levels of functional capacity and systems. However, from time to time, low- and intermediate-level processes can also create new combinations of capabilities that represent growth towards new higher levels of organization. These latter arguments can only be presented in outline form in the current contribution.

The early path of disease development—threatened equilibriums

Step I

Step I of the stress–disease process has already been demonstrated by decades of research; the stability that the organism normally enjoys may be disrupted by an overload of environmental demands—stressors—either larger demands or more incessant in duration, as described by Selye (6) and, more recently, by McEwen (7).

However, a second problem is the reduction of the ordering capacity of the Central Controller (in living organisms, the CNS) since the number of control strategies available is diminished (17). In this case, the Controller has an insufficient ordering capacity, fewer degrees of freedom of action, to maintain the highly coordinated response necessary to effectively respond to the challenge. This situation leads to deregulation consequences and disease. It could easily be the result of a long-term external constraint on function—many more control states are removed from accessibility, and for a longer period.

The addition of the "control" issue in is paper brings with it the coordination and Second Law limitations that supplement Selye by providing a system's dynamic and time-related logical structure for disequilibrium transitions, as well as by bringing attention to a second set of environmental causes of disease.

Thus both continual high levels of demands without relaxation and overwhelmed or restricted control capacities can contribute to the equilibrium shifts of the disease process. This is, of course, no more than the standard summary physiological explanation of the high demand–low control "job strain" hypothesis. While the demand–control model also had an origin based on sociological findings (15, 16, 25), physiological evidence from Dement's sleep deprivation research in relation to the negative effects of depleted ordering capacity (22) provided formative physiological evidence for the original model. Thus this current stress–disequilibrium theory could be said to attempt to provide a more-elaborated and generalized explanation of the job strain hypotheses of the demand–control model.

Step 2: equilibrium shift—the stress definition

According to Selye's explanation of stress-related disease processes (6), after an initial successful response to a stressor by an organism, the stressor exposure may continue and initiate the preliminary stages of a disease process, "exhaustion." To handle a load that is overwhelming its primary response system, the organism shifts to an alternative subsystem (to Selye's "compensation", and then to "discompensation").

After repeated attempts to manage workloads within overwhelmed subsystems or with an insufficient ordering capacity, the costs of inefficient performance mount up. The secondary systems are slower by definition and are harder to coordinate and less efficient (26). The possibility of maintaining mutual coordination of the ensemble of subsystems diminishes—organizing capacity is overloaded or "stressed" (reflected in the theory title: stress–disequilibrium). As has been stated by Karasek & Theorell (15), "Stress is a systemic concept [p 87]. Stress is an overload of the system's internal control capabilities. It is an inability to maintain the coordination and regulation of the subsystems needed for effective performance.

Step 3: Restabilized operation with diminished capacity—chronic disease

Spontaneous reorganization, reflecting the ambient resource limitation and representing a lower overall cost of organization in the context of the disrupted situation (lower NegEntropic costs in the long term), is likely to occur. At this point, the system shifts from linear to nonlinear response ("chaos"). This reorganization will permanently change the equilibrium.

Since the circumstance is a reaction to an inability to generate sufficient ordering capacity, the system tends to find an equilibrium for the diminished environmental response to adapt to its depleted potential. Thus significant negative change occurs in the capabilites of the organism. The process of movement toward less-effective equilibriums under conditions of the loss of the organism's ordering capacity is defined as chronic disease development (principle 7). Such a very general explanation of the chronic disease process could fit any number of physiological systems—singly or several simultaneously. Indeed, this explanation would be expected to lead to multiple, related chronic diseases—a situation termed "comorbidity".

Principle 7. Disequilibrium-based dissolution of system coordination—disease.

A system or level that cannot coordinate its subelements or whose subelements cannot maintain their functions, may not be able to maintain equilibrium based on past levels of environmental flows. Instability may occur, followed by the development of alternative integrations of subelements at a diminished level of environmental function (ie, chronic disease). [An implication]

Status of the evidence

Using these principles, we can trace a path along which the ordering capacity may be "pumped-up through seven levels of physiological control" (the choice of the seven levels is rather arbitrary)—from the photosynthesis of organic molecules, all the way up to the control of complex behavior in human fight–flight social behavior. Empirical research long ago demonstrated that Second Law limitations do indeed directly govern the chemical processes, at least the lowest two levels of this formulation. [See table 1.] For example, the basic equation of chemical reactions, the Gibbs free-energy equation, can be used to predict the human body's basic molecular and protein-synthesis chemical reactions with a high level of empirical accuracy. The equation predicts reaction rates based on the internal ordered energy of inputs (ie, their NegEntropy), temperature (ie, ambient disordered heat energy), and then the entropy (NegEntropy) of their outputs (level one of the seven levels). This output NegEntropy is dependent on the structural properties of molecules—their atomic component reactivities, their bond geometries, and the like—in turn reflecting the degrees of freedom available and restricted in molecular structure. One example is the way in which permutations of molecular geometry determines molecular properties. Molecular geometries of enzymes are central in determining their ability to powerfully promote or inhibit faster chemical reaction rates (level two of the seven levels).

Table 1. Status of the evidence—Second Law ordering capacity limiting evidence through seven levels of human physiological function.

Level	Status of evidence	Example
Level 1: simple organic molecule creation	Second Law limits evidence	Photosynthesis
Level 2: complex protein creation	Second Law limits evidence	Amino acids into complex proteins and enzymes
Level 3: environmentally modulated molecular systems	- ? - Second-Law tests could be designed	Calcium channel linkages between heart muscle cells (?)
Level 4: organelles and single-cell organisms	-??-	1. Single-cell organisms 2. Multicell differentiations: slime mold
Level 5: centrally controlled molecular-level physiological processes within complex organisms	-? - Second-Law tests could be designed	Centrally controlled metabolism via an insulin-based circulatory system
Level 6: environmentally modulated macro-control of organ systems	Second Law limits consistent evidence	Autonomic regulation of cardiac output
Level 7: maintenance of internal stability by the organism in environmental adaptation	Second Law limits consistent evidence	Chronic disease and evidence of low workplace and social control

Furthermore, evidence of Second-Law-like limitations can be found at the top levels, both at level seven (the chronic disease of low control–high demand psychosocial epidemiology noted earlier), and in the research described later at level six, namely, autonomic regulation of cardiac output (24). In doing so, an attempt can be made to demonstrate, via a continuum of evidence, that laws that are obviously valid at lower levels also apply to higher level phenomena. [Such cross-level validity of principles certainly does not automatically hold across scientific levels, of course.] Indeed, there is relatively little evidence of Second Law limitations at the middle levels (levels 3, 4, and 5 of the seven levels). Thus an unbroken chain of evidence for a limitation of ordering capacity—the necessary strong confirmation of the overall validity of the theory in a Second Law context—is still a work in progress. The theory is only a hypothesis. However, the suggestion is clear.

For example, at level six, Collins et al (27) have shown a strong association between low workplace social control and diminished cardiac high-frequency power (ie, parasympathetic cardiac autonomic control capacity)—in 48-hour Holter monitoring during a work- and restday period for a sample of 36 healthy middle-aged men in high-strain and low-stain jobs (jobs assessed by questionnaire, event diary, and occupational titles). Low job control was associated with significant reductions in vagal control of the heart or parasympathetic response that persisted after work, during the entire 48-hour monitoring period (P=0.004). Low external control at work (also high strain work) appeared to be associated with a "depletion" of vagal control capacity from the week's work that persisted for most of the weekend. [See figure 3.]

This demonstration of an extended limitation of normal function of the autonomic nervous system may help explain, for example, the increased risk of high blood pressure with high job-strain-related elevations in blood pressure (28). Heart rate has been described by Sloan et al (29) as having the function of stabilizing blood pressure through its response variability. In this case, the heart rate is the Controller, and blood pressure is the Controlled. It can be easily hypothesized that parasympathetic vagal response controls the heart rate (at least its main influence). With heart rate variability controlling blood pressure, a two-step link to a chronic disease endpoint occurs, and also forms empirical support of broader hypotheses about chronic disease development.

This phenomenon is also consistent with the observation that the purpose of the variability in the Controller's response is to maintain the stability of the organism in the face of environmental demands.

Vagal response appears to "do the work" of central cardiac control by first responding to the environment and then reducing (30, 31) its irregularity and

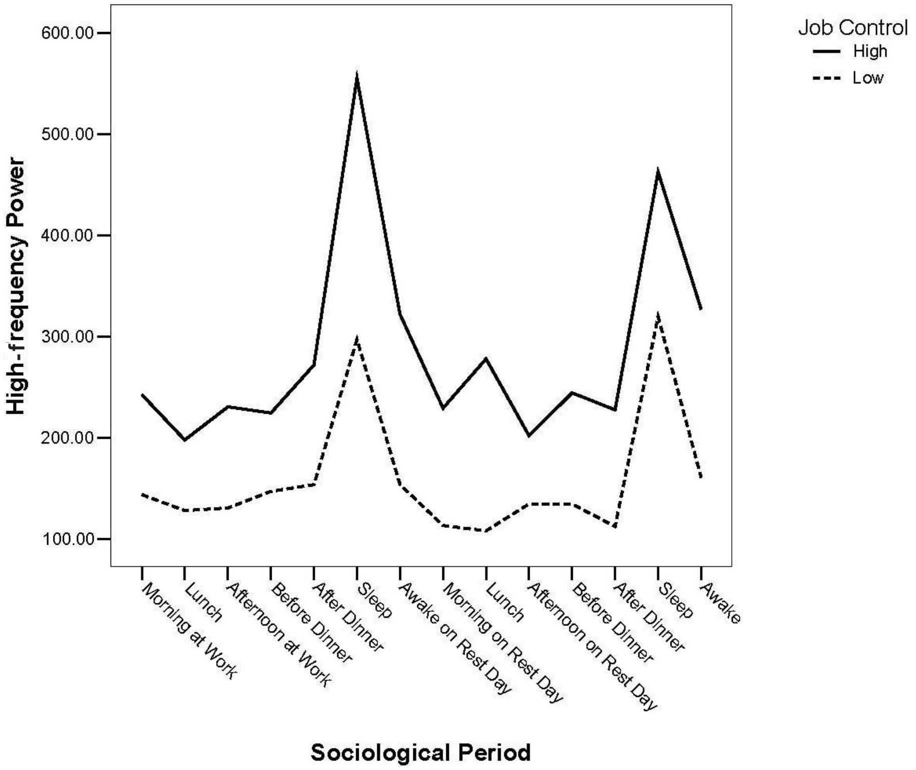

Figure 3. High-frequency power by job control.

superfluous reactivity of response by quickly returning the system to its baseline level.

A second piece of evidence is available here for the model structure of the Controller, the Controlled (the System), and the environment (stressor source) in this paper. In this case, the Controller is measured by the high-frequency power of the heart rate signal via the vagus, and the Controlled is the heart rate itself, directly measured. The specific hypothesis is that the Central Controller (in this case, the brainstem source of vagal control—high-frequency power) has a thermodynamically limited ordering capacity—it can become exhausted. This ordering capacity is hypothesized to be reflected in a progressive decrease in the complex variability of its control signals and an increase in the complex variability of the Controlled, the heart rate, as exhaustion occurs (both measured using approximate entropy (32). Using data from 36 healthy persons during Holter monitoring on a workday and the subsequent rest day, the predicted patterns were observed in a preliminary analysis. For the Controller, the variability of the signal of the high-frequency power decreased during the course of the day and reached a minimum as the end of the day approached (however, a partial minimum was observed already at the end of the workday period) (31). Then, as predicted, the variability in the high-frequency power increased strongly during three segments of the sleep process to reach a maximum upon waking. In a separate data set from 30 healthy persons (33), the opposite pattern of variability was displayed—as predicted—for the Controlled heart rate signal (heart rate approximate entropy) during the daily cycle. A variability maximum occurred as midnight approached, and a minimum occurred at approximately 0600.

A shift to suboptimal cardiac regulatory patterns in high strain–low control work was also observed in a 36-person sample. The coordination of cardiovascular control was found to be substantially dependent on the nature of the worker's job situation—using Bernston-like (24) patterns of cardiovascular control over a work- and restday monitoring period (30, 31). The most common pattern under "relaxed" circumstances was also the dominant pattern during the sleep periods for all of the participants in the study. However, this pattern was less common for workers in high-strain jobs and was almost unobservable during the workday for exhausted persons.

In the preceding discussion, it was attempted to demonstrate, at the sixth of the seven proposed levels of human physiological complexity, that limitations of ordering capacity exist. They have been shown to be affected by external constraints that can affect the internal stability of regulation and thus the likelihood of maintaining and extending overall "health (ie, a high-level capacity to successfully adapt to the environment).

Concluding remarks

A Second-Law-based thermodynamic formulation was outlined to explain how low external control could possibly restrict internal physiological self-regulation and cause chronic disease. Empirical support for this formulation is presented in a short review. The initial definition of external control makes it clear that a person's external social-action strategies for addressing external challenges can be cut off by external organizational constraints in the social world—cutting out major portions of his or her Ashby-response matrix. The general processes have also been examined through which low external control prevents the development of internal ordering capacity to begin with. For example, low-level inputs are not synthesized, homeostatic contexts are not maintained, and the translation of inputs into effective high-level action platforms is not accomplished. These occurrences can be, in turn, due to a myriad of social determinants that limit the options available in a socially constrained world.

An important implication of the theory is that an overwhelmed ordering capacity for the organism as a whole could cause the failure of high-level functions first, since this is the originating location of coordinated response.

In the long term, low-level processes would indeed contribute to ordering capacity by contributing to the building of the control capacity platform—the reflection of a link between the levels. However, in the short term, such a contribution may not have had time to occur because of the many efficiency limitations, reflecting the independence of levels—and leaving higher levels vulnerable in terms of their own level-limited ordering capacity.

In this case, the high-level failures of control capacity themselves could be sufficient to explain disease—as in the case of the unsuccessful warlord mentioned earlier in this paper. The onset of acute disease could occur without the failure of low-level functions (eg, ventricular tachycardia, asthmatic attacks—of course, further review would be needed to test such hypotheses specifically). However, at least theoretically, this could be the case. It is a reason that social organizational changes in control structures could have direct health-promoting effects.

Part II

Towards a new demand–control model—comments on growth, development, and creativity (the active work theme)

The preceding discussion involved the description of the low social control associated with illness. However, positive formulations of social control, leading to growth and development, have always been a central component of the demand–control approach. Indeed, the interaction of stressors and control, leading, on one hand (with low control), to stress-related illness and, on the other (with high control—and given moderate stressor levels), to healthy growth and development is the central concept of the demand–control formulation.

Thus commenting on the growth implications in the context of the new intellectual vocabulary already introduced in this paper can hardly be avoided.

Building on the multilevel order and energy concepts of the extended thermodynamic model, we can deduce several specific implications of the ordering-capacity perspective—for the growth of an organism, as well as its disease. The process of growth moves in the opposite direction, that of disease development. It describes how subsystems may be organized into higher-level units with integrated functioning. Health is the maintenance of the maximum operating capacity of the organism with respect to meeting environmental challenges—in the long term. A healthy person seeks to maintain the most-effective equilibrium-based processes for its current subsystem organization (its "capabilities")—and, in fact, naturally moves periodically towards improved capability. The goal of "capability maintenance" means that the organism resists forced transformation of its internal organizing routines in a manner that causes a reduction in capacity—towards a less effective set of equilibrium processes

The process of growth, high-level capability development, is based on the collection of subskills into new macrolevel combinations, for which the cost of organizing information drops (reduced NegEntropy expended)—providing an even higher level of control effectiveness to allow the organism increased adaptive capacity.

The principles of growth that follow are both extensions of the framework just presented for disease development. They also form the central proposition in the "conducive production model", which is the extension of the demand–control conceptions in the direction of active work. In the case of the conducivity model (15, 34, 35), the discussion has been pursued entirely at the level of human skill development and economic organization—not physiology. But, as can be seen in the following text, the generality of the ordering-capacity formulations in Part I of the paper yield predictions at both levels.

The conducivity model is related to visionary Scandinavian work-change programs (36, 37), and also to the program for "developmental work" (38). The conducivity model is also a member of a group of similar skill-based productivity theories from other well-known contributors, for example, Florida's "creative class" (39), Sen's "capabilities" (40), Stewart's "intellectual capital" (41), Toeffler's "prosumption" (42, 43), and Sveiby & Risling's "knowledge management" (44).

In all of these skill-based models of economic productivity, the focus is on sets of skills or capabilities that can grow into other capabilities; the focus is not on material objects. This focus provides quite a different basis for human economic activity than, for example, John Locke's material-based property value, which is the logical core of market economic logic. This "skill-output" (value) is invested in growth-capable entities.

Thus it is interesting that at least many of the same principles of growth can be sketched—using the Second-Law-based framework at both the macro- and the microlevel.

Now, for a discussion of the concept of skill. First, the term "skills" is defined broadly enough so that skills can refer to internal physiological capabilities—or human behavioral capabilities at the level of the social situation. Either way, it could be said that skills are the behavioral "tools" of the CNS for maintaining the stability of flows. All complex organisms—even simple enzymes, it could be said—have their "tools" for getting their jobs done. A skill is a coping characteristic of a complex organism—a way of organizing its behavior to maintain its flows ever more efficiently.

Second, there is one interesting "apparent exception" to the claim that the growth and health principles are the same at the micro- and macrolevels. Most of the aforementioned skill-based productivity formulations regrettably omit the "equilibrium" requirements central in the stress–disequilibrium formulation (although this is certainly not true for Sen (40) and for the conductivity model. [See figure 4 in an earlier paper (35).] In the case of individual economic activity, equilibrium depends on secure material well-being (food, shelter, etc)—as a necessary platform for any of the further creative growth of skills, represented by this form of social development, but such requirements are rarely discussed in classic, market-based economic theory. Perhaps the reason for this omission can be found in economists' focus, not so much on individual stability, but on "stabile growth" of the entire society of independent actors—on the macrolevel properties of the economy as a whole as a system. However, I would claim that the results show that an individual platform of welfare stability really *is* necessary to make these forms of innovative and creative economic growth truly feasible—just as in the physiological case.

Third, skills "want to be used", that is, they bring their own form of motivation. This is one interpretation of the large body of biochemical and physiological literature on "self-organizing systems", new creative forms "spontaneously" occurring in complex molecular chemical reactions (12). Furthermore, this phenomenon can be seen in the case of skills at the human personal and behavioral level—the violinist who "wants" to play the violin. Skills—thus so broadly defined—can give rise to social motivation as well. For example, a group of craftsmen meet on the street—a painter, an electrician, and a carpenter. They think: "If we now only had a mason and a plumber, we could build this house, which we are sure our neighbor down the street would need." There is a social motivation to (i) be in this group, (ii) find a plumber and mason, and (iii) close the deal with the house-needing neighbor.

Fourth, making a combination of skills is a "meta-coping skill" in itself (ie, an even more general-level ability). In this case, the organism can "grow", that is, re-organize its behavior by creating new combinations of skills to maintain its flows—ever more efficiently—generating an even larger potential surplus. It also requires that the organism—by chance—encounters a new energy source in the environment. In such cases, the person (ie, organism) will be able to develop a new form of internal stability (ie, self-regulate) while addressing even greater challenges—challenges that, if successfully met, could insure an ever greater input of resources and, consequently, even greater surpluses. In such combinations of capabilities, specializations become differentiated as subcomponents of the new, higher level organization are defined.

The subcapabilities are linked by rules—by negative feedback loops, as it were—which insure the stability of the new, higher level structure. These rules will define a new internal "division of labor". We can see such a process reflected in principle 8—in the last Second-Law-based principles of ordering capacity.

> **Principle 8.** Creation of new high-level system stability—growth.
>
> From time-to-time, it occurs that multiple, lower level elements coordinate their functions and differentiate their actions to create a new unitary capability at a higher level. They organize themselves in a new, collaborative manner so as to be able to gain increased energy or input from their environment, in such a way as to be able to sustain themselves with the new input (creation of a new, high-level function). [An implication]

Fifth, to sustain the greatest number of alternative, new, high-level skill combinations, the greatest variety of inputs must be available at the lower level—in this case, subskills. Ashby's theory of requisite variety can here be understood in a somewhat different manner, as an input condition.

Implications—an associative future for the demand–control (association) model

The 30th birthday of the demand–control model provided an opportunity to address the two extensions of the demand–control model: (i) the conductivity model extension of active work to political economy and (ii) the stress–disequilibrium theory extension of job strain to physiology, medical research, and systems theory.

We can now see that there is a very general notion that underlies both of these extensions—as well as the original demand–control model. Both extensions are based on theories that relate to the "associations of parts"—whether this is in terms of (i) new combinations of skills and people with skills or (ii) the coordination of physiological subsystems. This perspective differs from the standard perspective of materialism (the core of our global economy's value system)—which focuses more on the inherent qualities or value of the material object itself. This associational theme can be glimpsed in the short summaries that follow.

To say it with the fewest words, the demand–control model describes how systems can either organize themselves into higher levels of complexity (active hypothesis) or dissolve into systems with lower levels of complexity (strain hypothesis) (ie, systems that grow and develop or systems no longer able to sustain their original complexity and capability). The key issues are coordination, the association of parts (rather than the physical reality of the parts themselves)—and how the dynamics of such interactions are determined by limits imposed by the Second Law of Thermodynamics.

In the active direction, subsystems are coordinated in new ways, organized into higher levels of organization—partly on the basis of the spontaneous occurrence of new inside or outside connections and partly on the basis of well-planned preparation (subskills are organized into meta-skills, people are organized into workgroups, etc). These higher levels of organization (physiological function, higher order skills, or effective social groups) are able to accomplish more successful adaptation to the environment with less internal capacity being expended (in this case, it is of course ordering capacity—local NegEntropy resources—not conventional energy, like calories)—thus gaining more resources for the organism.

In the strain direction, complex sets of subsystems—requiring a constant flow of ordered energy—face challenges that cannot fit the normal stability conditions for function. Overall control strategies fail. Attempts to maintain coping action overwhelm both subsystems and the overall coordination of subsystems. The suboptimality of response is too large, and the internal costs of maintaining a coping response cannot be maintained. A spontaneous reorganization of subsystems occurs, tending towards a new equilibrium of function, but one that involves a reduced overall environmental coping capacity for the organism. One example would be chronic disease onset. In another field, such an outcome could also be imagined for a workgroup under pressure. In the case of a high-level skill, the subskills could be remembered, but the high-level capacity pulling them all together into a coordinated performance would no longer be possible—the violin concert performance fails.

It is interesting—and hopefully not just suspect—that similar principles can be found for all of the aforementioned, quite different fields of complex organization. Internal physiological systems (at many possible physiological levels) and sets of skills organized into meta-skills, or even of persons organized into groups, display the aforementioned set of principles at multiple levels. The detailed examples have been described in greater detail in other manuscripts (35, 45, 46).

For this reason, there appears to be a very broad logical level at which a more-generalized form of the demand–control model can function. This form is now referred to as the "associationist" demand–control model. This version is a systems-dynamic format that outlines general process—involving associations of subsystems—representing both a decline in capability and a growth in capability for the overall organism. It has predictions that are also congruent with those in a number of areas of social science and medical science research.

Fortunately, it is not necessary to contradict previous demand–control hypotheses. They can be understood as appropriate specifications of these general principles in the context they were developed for. One example is the large company and national labor relations framework (social welfare state background) for the work-characteristic definitions used in testing the original demand–control model and measures of job conditions in large companies (where it takes a specific form in the widely used Job Content Questionnaire JCQ 1.0). The extensions expand the original vocabulary of the demand–control model beyond work psychology and sociology, but these new formulations are neither inconsistent with the earlier material nor do they reject it. They are merely more-general formulations and address new areas. These broader formulations should make it easier to link to the many related theories that could jointly serve as the necessarily broad platform for any new political syntheses. Future work-environment research in the global economy also requires this more-generalized vocabulary. Even the development of the extended version of the Job Content Questionnaire—JCQ 2.0—needs it.

Concluding remarks

Since there is such breadth implied by the re-definitions given in this paper—and in the examples offered from very diverse fields—it can be imagined that there could be many reasonable challenges to this claim of generality. The claim is not that it excludes other explanations, but rather that it provides an additional form of explanation, one which is relevant on many levels and in many contexts. But, in any case, if so, many criticisms might be made of such a broad approach, why attempt it at all?

One criticism, for example, is that, the stress–disequilibrium physiological theory is too complex. Why forsake the simplicity of the original demand–control model and its simple questions? My answer here is that the complexity is already here in the field, and stress physiologists who have a humanistic point of view focused on worker-well-being or who want to restore the macrolevel perspective in physiology could be helped by a system-based model for addressing this new complexity. The competition for research funding is now mainly between microbiologists and molecular geneticists who "mine" huge and complex mountains of data on RNA (ribonucleic acid) code sequences and the like—but who offer no hypotheses at all about the daily adaptive demands or overloads of the organism.

In the political area, others have noted that there has been a "vacuum" arising in political–economic discourse in recent decades—with only a market-basic logic presumptively relevant for all society-level action. Again, more complexity is part of the solution, not the problem. The difficulty here is that the goals of all social collectivities (ie, work)—which are platforms of personal and social equilibrium—can be undermined (hollowed-out) if there is only a single logic: capitalism's "productivity calculus". This simplification invalidates a broader range of a necessary "older" logic–value system that supported constructive social behavior. When broad goals are undermined by the calculus and language of productivity calculus, older vocabularies can also become fraudulent (ie, "flexibility", "participation") when co-opted by a "productivity-calculus-based" simplification of the original concepts. This collapse of alternative validations leads to a loss of workers' control on a very high social level.

How could it have come to pass that current answers to social questions are becoming "so small and narrow" in this manner? One answer is that the questions the currently reigning logics were posed to resolve—several hundred years ago—are too small to provide answers for the problems of today.

To illustrate this point, these past historical contexts can be briefly alluded to. First, as job-stress scientists, we must now confront the mind-numbing effects of the "mind–body dualism" thinking and an overwhelming emphasis on a deluge of empirical, microlevel factual detail as an explanation for illness development. This situation can slow down our true progress. This dualism between pure thought and the material world (res cognita and res extensa) had its origins in Descartes' *Meditations*, from 1643 in France, as Damasio has noted (47). The English empirical philosophers of the 17th century built upon Descartes' split and reinforced the dominance of simple empiricism, for example, Locke, in his *Essay on Human Understanding* (48), in which he attributes all human motivation to sensory pain and pleasure data.

Of course, it was also John Locke again, in an even more influential later work (the second treatise in *Two Treatises of Government*) (49), who offered a new validation for society overall—based on the possession of material property (a mixture of labor and material substance) and a social process of representative democratic decision making to protect this property. And then, prophetically, in crucial footnotes in later editions of his second treatise, Locke violated his original limitations on the amount of wealth an individual could accumulate through his or her labor (originally not more than one could consume without spoilage) and advocated unlimited wealth accumulation (49, 50). This situation was to be allowed when the accumulation was justified by a higher "productivity" of the natural resources it employed (ie, more output per unit of input)—since, presumably, this extra value would filter down to all members of society. The footnotes were the origin of the "productivity calculus". It took Marx's comprehensive 19th century critique of this original form of capitalism's primitive inequity to finally transform this social system into the modern welfare state's secure distribution of basic material benefits (visible, at least, in the better examples).

Both Descartes and Locke overcame the supreme challenge of their day in their fights against absolutist theocratic thinking. That thinking claimed control over the temporal economy and politics (Locke's challenge) and the space of both purposeful and spiritual thought (Descartes' challenge). Locke's intellectual heirs aggresively extended this fight against absolute monarchical control. For example, Bentham (51) argued against the need for any form of social decision making at all when a market calculation of pain and pleasure utility could be made. Adam Smith (52), with his "invisible hand", further undermined alternative social logics to capitalism's market calculus. In fact these additions set the stage for the current simplifications.

However, overall, Descartes' and Locke's struggles added complexity to their contemporary absolutist discussions. Our modern world owes much to the struggles. In fact our modern world could be said to stand today precisely on the two central intellectual pillars Locke and Descartes created. We would hardly want (i) a return to theocratic absolutism (in fact, the fundamentalism of today), nor would we want (ii) to lose our efficiency in generating material well-being, the platform for further social development. And yet Locke's and Descartes' original challenges are too simplistic to support answers for us now. We are now overwhelmed with other challenges. The limitations in our social thinking that are the by-products of their contributions are now slowing down our true progress.

We live on a planet for which the dominant social philosophy supports "value" (ie, market value), based on the most effective process of transformation of physical resource inputs into physical consumption outputs—and this is unsustainable—physically. Furthermore, the consequently rampant "materialism" and "productivity-based logic" threaten to displace the validity of all other social dialogues (from so many other times, social spheres, and cultures). In fact, we face a potentially even more disastrous depletion of resources—socially than physically. We could lose the diverse explanatory frameworks that make up the backbone of our species' social organizational response reservoir, and the adaptive capacity it supports. At risk is the social, high-level, Ashby-like reservoir of Homo Sapiens' behavioral variety.

Thus, the collapse of all alternative logics into materialism now requires a re-expansion of our social thinking. The attempts to "expand" the demand–control model represent one approach to this challenge. In the process, a new, more general "association-of-parts" format for the model is provided that makes it possible to link it more easily with many other intellectual contributions—from many areas—which are taking up this same social challenge.

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