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CAUSALITY AS CONSTRAINT

INTRODUCTION

Suppose you are trying to arrange furniture you already own in your new house. "Each piece of furniture has some weak constraints associated with it. For example, the bed must go against a wall because the headboard is rickety; two small tables go on either side of the bed; the couch is missing its back legs and so sits on books, which means it must go against a wall so that the back is not visible, and so on. The constraints associated with each piece of furniture are weak because each one can be satisfied in many ways; the bed, for example, can be put against any of several walls. However, once the bed is placed, the entire arrangement may be determined: there may be only one other wall large enough for the couch, the tables must go next to the bed, and so forth" (Kosslyn & Koenig, 1992, p. 111).

How are we to understand the relationship between the constraints and the particular furniture arrangement that results? Despite deliberately sidestepping causal language in formulating that question, it is difficult to avoid the sense that "simultaneous constraint satisfaction" as occurs in Kosslyn and Koenig's example is somehow responsible for the way the furniture gets arranged. This example suggests that constraints satisfy at least one oft-touted requirement of causal relationships: constraints support what philosophers call "counterfactual conditionals", that is, if it were not for the constraints the resulting furniture arrangement would not be what it is. And yet it is clear that the constraints don't cause the furniture arrangement the same way cue sticks cause cue balls to move. As Salthe says, although constraints carry information that has meaning for the entities involved in natural processes, the information is not dynamically involved in the processes (Salthe, 1985, p. 71).

The concept of constraint was first used formally in the Physical Mechanics. Although never actually defining it, Lindsay uses the term in his introductory textbook first to refer to the way in which the motion of a simple pendulum or a particle on an inclined plane (Lindsay, 1961, p. 35) is "*compelled by the geometry of its environment* to move on some specified curve or surface" (*ibid.*, p. 239, my emphasis). Later on, in his explanation of oscillations, Lindsay states that "some of the most important cases of constrained motion are those in which particles are *connected by rods and strings*", and cannot, therefore, move any which way. In his explanation of D'Alembert's Principle, Lindsay states that "If the masses were subject to no constraints (i.e. if they were not connected in any way or forced to move along certain curves or surfaces) ..." (*ibid.*, p. 251); and in his discussion of Gauss' Principle of Least Constraint Lindsay states, "The system being subjected to certain constraints (i.e. the masses being perhaps connected to each other by rods or cords, or constrained to move along certain curves or surfaces) ..." (*ibid.*, p. 254). I assume that in the last clause the word "constrained" means, as in the earlier quotes, either

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"forced" or "compelled". Those are the only four references to the term in the book!

In mechanics, then, constraints are features either of the object's connections with the environment or of the environment in which the object is embedded. Constraints are, therefore, emphatically not examples of what used to be called "primary qualities", intrinsic features of a system which it exhibits regardless of the circumstances in which it is placed. Constraints are relational properties. But they are not simply relationships among components within a system, which is why Pattee refuses to label a chemical bond a constraint. Constraints are relational properties components acquire in virtue of being embedded in a higher level system.

The connection of the tibia and the peronei to the knee joint *constrains* the movement of the lower leg in such a way that it makes no sense to examine the tibia's physiology, for example, independently of the knee. The tibia's connection to the knee gives the former characteristics which it wouldn't have otherwise: it can move in some ways but not others. The constraints which the connections subject the lower leg to reduce the number of ways in which the leg can move: it can bend backwards but not forwards, for example. In this example a constraint is a reduction of the leg's state space. This is the most common understanding of the term "constraint".

In the rest of the paper I wish to show that constraints not only reduce the alternatives — they also create alternatives. Constraints, that is, can also *create* properties which a component exhibits in virtue of its embeddedness in a system, properties it would otherwise not have. We need, therefore, to understand how constraints can both close up and open up options in this way.

CONSTRAINTS IN INFORMATION THEORY

In Information Theory the concept of constraint is used to refer, not to physical features, but to rules for reducing randomness in order to minimize the transmission error rate. Random, equiprobable signals are "noise", they cannot communicate. In order to be able to transmit or decipher a message sent by radar or telegraph, there must be a clear demarcation between message and background noise. The transmitter as well as the receiver, therefore, must reduce the randomness in the sequence of signals: the transmitter must encode the message according to certain rules; the receiver, in turn, will also apply the rules to decipher the message.

When signals in a sequence are random and equiprobable (the information counterpart to equilibrium and maximum entropy), what Lila Gatlin calls *potential* information or message variety is at its maximum (Gatlin, 1972). However, although in those circumstances you *could* say much, you in fact *do* say nothing, an important point since information simpliciter is often erroneously equated (by Hayles, 1990, for example) with equilibrium, suggesting that random signals can transmit actual information. Not so; when signals are equiprobable message variety is a great but idle potential. No contrasts = no message, pure noise. "Capacity is of no value if it cannot be utilized" (Gatlin, 1972, p. 99). *Actual information content* requires an ordering process that takes the system away from total randomness. Altering the probability distribution of signals in order to turn potential information into actual information is called "redundancy", and it is "one of the most important concepts in information theory. Redundancy is essentially a constraint [which reduces] the number of ways in which the various parts of a system can be arranged" (Campbell, 1982, p. 28).

Shannon & Weaver's theorems *are* two such ordering processes.

(D1): *Context-free redundancy*

The "most random state is the maximum entropy state and this is characterized by events which are both independent and equiprobable" (Gatlin, 1972, p. 87). Below I will examine the role of constraints in thermodynamic systems; let us look at their role in communications first.

Since random, equiprobable signals can carry no information, to convey a message the random distribution of signals must be constrained such that it *diverges from chance, randomness and equiprobability*. One way to do so is to narrow the number of alternatives. At the limit (one alternative with probability 1), there would be one signal repeated over and over. Regularly pulsing flashes from a lighthouse carry information precisely because their regularity is far from randomness and equiprobability, and is differentiable from the background noise. The probability distribution of letters in a particular language is another form of this D1-type of "context-free" constraint. Some letters in the English language appear more often than others. Given that x's and z's appear infrequently in English, finding an overwhelming number of x's and z's in a text and relatively few a's and e's sends the message that the text may by Hunglish, but is definitely not English. D1-type constraints on signal transmission increase improbability by creating order, pattern, which then has the capacity to carry information. Even a Martian who sees the regularly pulsing flashes of light can tell that there is a message. Robert Artigiani reminded me of Marshall McLuhan's comment that a lightbulb is pure information (personal communication). Thus far the information-theoretic concept of constraint parallels that of mechanics.

The price paid for depending solely on D1-type constraints, however, is high because reliability of transmission is inversely related to message variety. At first glance, therefore, there is an inverse correlation between imposing constraints so as to be able to send some message and the ability to say a lot in that message. At a certain point the amount of redundancy stifles the variety of what can be said. No pattern whatsoever conveys no information, but the same pattern repeated over and over again conveys no new information. The drawback with D1-type constraints, in other words, is that they are "expensive": "if increased too much, they place severe limits on the variety of messages which can be sent" (Pattee, 1973, p. 119).

Is there a thermodynamic version of all this? A container filled with evenly diffused molecules of gas is in equilibrium. A system such as this with no temperature gradient can perform no work. Moving a piston such that the gas molecules are constrained to one side of the container takes the system far from equilibrium in the sense of inhomogeneity, the thermodynamic counterpart to the regularly pulsing flashes of light. The system can now do work, the thermodynamic counterpart to "carrying information".

If nature relied solely on D1-type thermodynamic constraints, however, matter would clump but there would be no complexity, the thermodynamic analog to increased message variety. Gatlin quotes Weaver as saying that "this word 'information' in communication theory relates not so much to what you do say, as to what you could say". What is needed, therefore, is a type of constraint which limits the amount of randomness without eliminating disorder altogether; sufficient leeway must remain for new messages to be expressable. This is precisely what Shannon proved: that the need to reduce error by constraining the number of alternatives need not restrict the ability to transmit messages, for there exists a code that will provide the desired degree of accuracy without cramping the ability to transmit messages. Although, as noted earlier, one ordinarily thinks of a constraint as limiting freedom, "control constraints must also create freedom in some sense" (*ibid.*, p. 85). Actual information, that is, treads a fine line between total randomness and pure disorder. How to decrease entropy while simultaneously increasing the number of possible messages?

(D2): *Context-sensitive constraints*

In every language some letters or words are more likely to occur not just because of the overall probability distribution of letters, but depending on what letter or letters, *preceded* them, i.e. depending on what happened around them. In English, the occurrence of the letter "q" dramatically raises the probability that the next letter will be a "u". D2-type constraints are such that the *components* of a system no longer are independent of each other. This kind of constraint imposes conditional probabilities on the relationships among the letters on top of the context-free constraints mentioned earlier (which make the letters of the language in any alphabet no longer equiprobable). Gatlin calls this type of constraint "context-sensitive" constraints. There can be a series of such constraints. Syntactic requirements for a well-formed formula make nouns, verbs, adjectives and adverbs in a sentence no longer independent of each other. On top of the conditional probabilities that increase the probability (in English) that a "u" will appear *given a "q"*, syntax subjects word order to even higher level contextual constraints: for example, given the word "the" it is highly unlikely that an adverb will follow. And so on up a hierarchy of such constraints to the sophisticated poetic level of the requirements for writing sonnets or haiku.

The advantage of context-sensitive constraints is that they permit unlimited possibilities in message variety despite limited channel capacity. A great variety of messages can be sent without being hampered by the error-rate: context sensitive constraints are as efficient but not as expensive as context-free redundancy. "It can be increased by a reasonable amount without cramping the message source too severely (...)" (*ibid.*, p. 119). The fact that spoken Mandarin limits words to one or two syllables requires adding the context-sensitive constraint of inflection to permit potential message variety.

Imposing D1-type constraints to an extreme would result in the repetition of only one signal, the regularly pulsing flash of light from the lighthouse, say. The information transmitted using this D1-type of constraints is self-referential in the sense that it identifies the regularly pulsating flash of light as information. As Bob Artigiani puts it, for the Martian the D1 constraint on a sequence of signals amounts to transmitting "Message", "Message", "Message". It is the regularity's divergence from equiprobability that conveys information, but the only information it conveys is *that* there is information. D1 constraints cannot carry semantic meaning, nor can they create information. Since D2-type constraints, on the other hand, embody conditional probabilities, that is, of the probability of x *given* the context in which it is embedded, i.e. given the presence of y and z, signals or processes constrained by conditional probabilities refer not just *to* themselves; they embody and transmit information about what happened before and what is going on around them. That is, signals subject to D2 type constraints refer to the contextual web (temporal and spatial) in which that particular signal or event is embedded. The information such signals or processes carry is *of* the organization of the network; the actual information content is *about* the overall *web*, not just of its components. The potential information contextual constraints create is thus *relational* information. Relational constraints on *sequences* of letters allow words with the ability to refer to be expressed. Progressively higher level constraints allow sentences expressing even more complex semantic information to be articulated. As Bob Artigiani puts it, "meaning is the experience by parts of their interaction with the environment". It is because of his awareness of a network of relationships that the sailor, unlike the Martian, can understand that the flashes of light he sees mean "Land!". The sailor sees the flash of light *as* a node in a complex network of relationships, in particular Morse code, plus the convention that the sequence three short, three long and three short MEANS help!, etc. Indeed, the sailor is a *sailor* (and not just a man adrift on a boat) only because he himself is embedded in a network of D2-type relationships (such as navigation, tacking into the wind, etc).

Constraints, therefore, do not function just by closing off possibilities; contextual constraints are also the mechanism whereby the creation of a new level of organization with greater degrees of freedom, takes place. The amount of actual information, Gatlin says, "is a measure of all the constraints placed upon a sequence of symbols" (Gatlin, 1972, p. 94). Altering the contextual constraints creates the possibility of new meaning. The creative possibilities of metaphor are a function of the capacity of sentences (not letters) to convey semantic information, a capacity created by the very contextual constraints operating first at the level of letters, then at the level of words, and so on.

Can we find any analogs to this kind of process in dissipative and autocatalytic structures?

The emergence of the macroscopic structure of Bénard cells coincides with the appearance of contextual constraints as molecules become correlated (i.e. when the behavior of each molecule depends on what is happening around it). To borrow an example from Waldrop illustrating autocatalysis, assume that you start out with just many small molecules floating around randomly in a primordial soup. No constraints = no form or structure. Assume next that some molecules (catalysts) are able to bind two other molecules together into a large molecule. Suppose molecule A catalyzes the formation of molecule B, which in turn is able to catalyze the formation of a third molecule C; C catalyzes D, and so on, so that "somewhere down the line you might very well have found a molecule Z that closed the loop and catalyzes the creation of molecule A" (Waldrop, 1993, p. 123).

The "organizational closure" autocatalysis effects is such that a boundary between the autocatalytic web and the background soup from which it emerged has been formed. The autocatalytic web is distinguishable from its environment; it is a structure of processes (Earley, 1981). Interactions among molecules created the web; but once the molecules are captured by the web in which they are embedded (a web which, from a different point of view, the very connections among the molecules produced) means that they are no longer independent of each other. *Given* the presence of molecule C, for example, the appearance of molecule D becomes more likely. Just as u follows q in English, the probability that molecule C or D will occur is no longer a matter of simple deviation from equiprobability (whether any such probability distribution occurs, see Ulanowicz, 1994): it has become a matter of conditional probability.

CONSTRAINTS AND MESSAGE VARIETY

Just as words and sentences can be meaningful in a way that phonemes alone cannot, the emergent higher level of organization (the autocatalytic web as a whole) can access more and different states than the isolated components from which it was formed. Proteins, which in one sense are nothing other than a folded up chain of amino acids, can perform enzymatic or catalytic functions that a linear chain of amino acids cannot. Chemical phenomena can access states that physical phenomena cannot; biological phenomena can access states that chemical processes cannot. The same applies *mutatis mutandis* to the emergence of e.g. the level of a cell from the level of organelles, tissues from cells, etc. Greater number of degrees of freedom is one way increased complexity is identified. The higher level of organization is more than the sum of its parts in that sense. The explosion of potential message variety characterizing the appearance of each new level of organization (the fact that a higher level can do qualitatively different things than the earlier one) correlates with the greater number of degrees of freedom that each new dimension provides. Gatlin argues that the explosion of phenotypes that took place with the appearance of the vertebrates occurred because vertebrates managed to maintain D1 constant while allowing D2 to expand. Perhaps this combination accessed what Lewin identifies as the area in which complex structures emerge, "the site of maximum computational capability", Langton's "edge of chaos", or Ulanowicz's "window of vitality" (see Lewin, 1993; Langton, 1995; Ulanowicz, 1994).

Contextual constraints thus perform double duty. From the combined effects of contextual constraints operating on matter and energy flows, structures and patterns at increasingly higher levels of organization emerge. Furthermore, the orderly context of the system in which the parts are now embedded alters and redefines their behavior. The dynamical framework of the whole constrains the behavior of the components, a form of interlevel (in this case top-down) causality. The dynamics of the system as a whole thus provides "the framework for the behavioral characteristics and activities of the parts (Zeleny, 1980, p. 20). Molecules C and D are now different than they were before — they are *components* of a whole, and their behavior is therefore constrained (in the sense of having a reduced number of alternative ways they can behave) by the higher level in which they are now embedded. C exhibits certain traits only because of the presence of D, E and F, that is, only because it is captured in an autocatalytic web. In contrast to grains of sand, which acquire no new properties in a sand dune, the relationship of C to D is now unlike the merely external, spatial relationship among grains of sand in a sand dune: C and D are internally related in the sense that, unlike grains of sand, molecules C and D have characteristics they would not have outside the network of relationships. The constraints which the whole imposes on the parts, while restrictive in the sense that they reduce the number of ways in which the parts can be arranged, are also creative in a different sense. Once captured into a hive, bees become "drones", "workers", "queen bees", etc. A "component" or a "node" is such only because of its role in a web of relationships.

D2 constraints, that is, create new possibilities while at the same time increasing order. How is this possible? The answer is a version of Russell's type-token distinction[1]: the *potential* message variety in the sense of new possibilities which the D2 ordering process creates is at a level other than that on which the constraints operate. *The local order that contextual constraints effect at the component level is more than offset by the increased potential message variety occasioned by the new level of organization which the contextual constraints enable.* D2 type constraints create hierarchies. Once the hierarchy is established, the "bits" that created them acquire — at the cost of a reduced number of ways they can be arranged — an identity they previously did not have: they are now "components" or "nodes". of a higher level whole. In organizing the higher level whole by correlating the parts, contextual constraints increased the number of states the newly created *system as a whole* can access. Contextual constraints are thus nature's own answer to the problem posed by Maxwell's demon. Contextual constraints are a demon with a Janus nature: acting as Dr. Jekyll they impose order by limiting alternatives; as Mr. Hyde they create potential message variety through reintroducing disorder at a higher level. And it is as Mr. Hyde that they are responsible for the creative evolutionary progress of nature. The increasing complexity of evolution is a function of the operation of contextual constraints. Parts no longer independent of each other constitute the self-organization of a higher level; as such contextual constraints are the "agents" of interlevel, bottom-up causality. Acting top-down they simultaneously create new roles for those parts as they correlate them.

Because the word "constraints" suggests a reduction in the number of options a system has open to it, not the possibility of opening up a new repertoire of alternatives through self-organization, some authors (Popper, 1990; Depew & Weber, 1994; Ulanowicz, 1994) have called the creativity of enabling constraints the system's "propensities". Insofar as the term "propensities" carries with it the connotation of "predictability", however, it too is problematic: emergent properties are unpredictable. Salthe calls enabling constraints "initiating conditions". Regardless of the terminology agreed upon, for Depew and Weber the "propensities" of organisms (Depew & Weber, 1994, p. 487), because they are real and objective, are responsible for self-organization and can "provide an objective foundation for probability theory itself" (*ibid.*, p. 488). The problem with phrasing it this way, however, is that since the term "dispositional" can only be cashed out in terms of probability, explaining propensities in terms of an object's "dispositional properties" already presupposes the notion of probability. Ulanowicz analyzes propensities in terms of the reduction of probabilities, which is fine for D1-type constraints. But as we have just seen, D2 context-sensitive constraints not only reduce the number of ways the parts of a system can be arranged; they simultaneously increase the things that the system can do. While altering the behavior of the components (in the sense of reducing the number of alternative ways they can behave), contextual constraints simultaneously create a level of organization with a renewed capacity to surprise (Casti, 1994)!

Depew and Weber claim that the probability distribution of propensities is not just a matter of epistemology, that is, of the subjective probability involved in the reduction of ignorance or the renewed capacity to surprise. They claim that propensities are more than an epistemological description; propensities identify ontological processes that can serve as the basis for assigning probabilities. If this paper is correct, the ontology can be located in the way contextual constraints (on a linear sequence of amino acids, for example) self-organize the related components into a higher level (a protein) which in turn can access more and different states (enzymatic function). It is the emergence of a new function, enzymatic activity, that surprises. Contextual constraints operating "bottom up" (as "enabling constraints") are responsible for the formation of higher level wholes with emergent properties. In fact, as recent newspaper reports on the fact that scientists continue to discover that proteins can do more and different things that were ever thought possible, all the possibilities which contextual constraints create are not yet known. The potential which enabling constraints create is real.

CONSTRAINTS AND STATE SPACE

What are constraints, then? Constraints are alterations in the probability distribution of a system's state space. As enabling constraints operating bottom up, contextual constraints free up a set of states which the higher level system of relationships they create can now access. Systems of relationships themselves can in turn become related (the earlier relationships now becoming the relata in a new relationship), thus evolving into systems of ever higher level relationships with creative new properties of their own. Once the higher systemic level is in place, it acts as a top-down selective constraint on the (now) lower level components from which it organized, altering the number of ways they can be arranged.

D2-type contextual constraints partially decouple the whole from its environment and from its components by creating and regulating a whole/part hierarchical system. The dynamics of the system function so as to renew the system as a whole, not its individual components. As structures of relationships Bénard cells are Bénard cells whether they consist of water or other viscous materials. An autocatalytic structure orders the processes whereby molecules are taken in as food and those dumped into the environment as waste. Furthermore, autocatalytic structures streamline their processes (Ulanowicz, 1994) so as to increase the energy throughput (the autocatalytic version of "efficiency") by preferring certain pathways and discarding others. To identify a set of processes as a "Bénard cell" is thus to identify an emergent, supervenient property which contextual constraints have created, that is, it is to identify a macrostate which can be accessed by different microstates (Depew & Weber, 1994, p. 471).

Likewise, the dynamics of the system as a whole determines which molecules are "fit" to survive or to be imported into the system, and which are not. The property "fitness" thus refers to D2 constraints operating top-down: the dynamical framework in which the components are embedded (for example, the ecological niche in which a species is found) rules on the adequacy of the components by selecting among those components. "Selecting" here, once again, means "reducing alternatives". But as in the opening example (the furniture arrangement), such top-down selective constraints are often weak constraints: they can be satisfied in many ways. As Depew and Weber note, "fitness" is a supervenient property. The point of the above discussion, of course, is that the creation of a new level of organization effected by D2 contextual constraints *is* the emergence of a supervenient property which, as such, is partially independent of its specific components.

When several weak constraints must be satisfied simultaneously, however, the situation can begin to look deterministic. In the furniture example the many different weak constraints that needed to be simultaneously satisfied makes the system converge on only one possible arrangement. I suspect that it might be possible to reconceptualize those forces referred to as "causes" within the mechanistic framework as the limit of constraint satisfaction: those cases in which the probability of the occurrence of a particular situation given a certain set of constraints approaches unity. But that is another paper.

CONCLUSION

I close with the following observations pertinent to philosophy of mind: for centuries the problem of intentional action has been a philosophical headache. How does an intention "cause" action? How do a bunch of neurons "become" a mind capable of intentionality? Certainly while causality was explained mechanistically, as the collision-like relationship of billiard balls, intentional behavior was inexplicable. And if a whole could have no properties over and above those of the aggregation of its components, then the emergence of mind was indeed a mysterious process. If causality is reconceptualized in terms of the operation of constraints, intentional behavior can be rethought as an example of constraints operating top-down. The emergence of mental properties like intentionality can in turn be understood in terms of the workings of contextual (enabling) constraints operating bottom up. Likewise, while causality was understood mechanistically, formal and final causes, and in particular their role in self-organization (in the sense which Kant uses it in the *Critique of Teleological Judgment* — leaves produce a tree which in turn is produced by the leaves) were inexplicable because they involved "a kind of causality unknown to us", as Kant phrases it. Appreciating the Janus nature of contextual constraints makes this kind of whole/part and part/whole interactions understandable.

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NOTES

[1] I Recall Russell's problem: A barber in a village shaves all the townspeople who do not shave themselves. Who shaves the barber ? Russell's solution was to argue that classes belong to a higher logical type than the elements that compose that class.

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