Most accounts of functionality are based in etiology, either design or selection. In this paper I give an account of function as serving autonomy, which is the closure of self-maintaining processes, both those that are fully internal and those interacting with the environment. This expands the standard etiological account by systematically including internal organization. The etiological account focuses on external factors, either intentions in design or outcomes in selection, and thus can give only a pattern or epiphenomenal account of functionality. This approach is similar to scientific behaviorism in that it treats the organism as a "black box" and looks only at consequences. B.F. Skinner introduced the term consequence selection for theories that assume differential variation, selection and retention (VSR), of which adaptionism is paradigmatic. This in itself should suggest that something is missing from the standard account.

The etiological account mostly ignores organizational requirements of biological entities, even though these may play a central role in the functionality of the trait in question. It is sufficient under this account to show that a trait was selected to ensure that it is functional, but there is much more to the story. Usually this is filled in with details of the particular case, or in some cases the optimality of evolution is just assumed, automatically making any selected trait functional. One example of the use of optimality is Richard Alexander’s\textsuperscript{4} account of the biology of moral systems. Alexander assumes that ultimate causes (selection) allow us to ignore proximate causes in examining at least some classes of human behavior, though this assumption has been questioned.\textsuperscript{5,6} Other sociobiologists slip into the mistake of assuming optimality without proof. Wilson, for example, knows better,\textsuperscript{7} but slips into some of the worst sort of optimality assumptions in On Human Nature.\textsuperscript{8} See especially the chapter on sex, which is in sharp contrast to the more balanced chapter on aggression that precedes it. Despite numerous arguments against,\textsuperscript{9,10,11} optimality is still widely used in evolutionary arguments (witness, for example, the
session on optimality and self-organization at the 1995 International Society for the History, Philosophy and Social Studies of Biology in Leuven).

In particular, selection alone gives no special role to adaptability, which plays a central role in behavior, especially the evolutionary and developmental genesis of intelligence. Furthermore, although selection may ensure the functionality of a trait, it is doubtful that it constitutes the functionality of the trait for at least the reasons that functional traits can be identified accurately without any knowledge of their origins, and secondly, in order to be selected a trait must already be functional, for that is why it is selected. The Newcastle Complexly Organised Adaptive Systems Group proposes defining adaptiveness in terms of autonomy. A more adaptive trait, under this conception, will likely be selected. The definition also naturally extends to adaptability as higher order adaptiveness, and focuses on the organizational character of adaptiveness, forcing attention on this central biological characteristic. The result is a much richer account of both adaptation and selection. Maturana and Varela originated this approach, but their work has been largely ignored by mainstream biology, perhaps for reasons I will explain below.

I will first describe some textbook cases of organization in biological systems to show the nature of organization and its variety, as well as the importance of process closure to organization. Next I discuss closure more abstractly, but more precisely. This is followed by a definition and discussion of autonomy, then by the basis of functionality in autonomous systems, and, finally, with a discussion of some of the implications for biology.

2. Some examples of biological organization

Organization in biological systems is ubiquitous, but it is often so complex as to be barely tractable. One strategy is to break things down into simpler units, and study them independently. Sometimes this is possible, but often the essential organization is lost by such reductive moves. Science and philosophy can deal effectively only with the tractable, which creates a bias towards studying systems that can be decomposed for study, or (over)simplifying systems to make them easier to analyze. I will try to indicate some of the limits of this strategy throughout this section. First I will look at some relatively simple metabolic pathways that can largely be understood (but not completely, I will argue) at the chemical level.

Consider fermentation, over which there was a long debate as to whether it was a biological or purely chemical phenomenon. As it turns out, fermentation is possible outside cells, but it is not maintained for long. The first chemical models assumed a simple linear process; later more complex linear models were tried. It eventually turned out that the chemical process required early elements later in the process, making it non-linear. This means that there is a certain degree of closure in the process, in which at least some elements (or types in this case, if we assume molecules rather than a fluid) cycle in a closed way. In fermentation in the muscle, glucose is the input, and lactic acid the output. If the process is laid out linearly, there are two places where ADP enters and ATP leaves, one place where ATP enters and ADP leaves, and one place each where nicotinamide andenine (NAD) leaves and NAD+ enters and the contrary. Closing these open loops at the ends requires that products of the process are needed earlier as inputs. This makes the process indecomposable. It should be noted, though, that we can see quite clearly what is going on at each stage as well as throughout the process, so even though the process itself is not reducible to its component stages, the stages are still an important part of the explanation. Note also that an extra ATP molecule is formed, which is used by the muscle for energy, and reduced to ADP, increasing the scope of the cycle. I won’t worry about the source of the sugar here. The history of respiration and oxidative phosphorylation is similar, with the final model the familiar Krebs cycle, which both has cyclic properties like fermentation and also shows similar connections to other processes.

A more complex process is the metabolism of the cell, used by Maturana and Varela as their paradigm for autopoiesis. They connect autopoiesis with autonomy, which seems correct
to me, but their notion of complete closure of autopoiesis creates problems that I will have more
to say about later. They hold that we can make an autopoietic cut between the self-producing
organization and its metabolic substrate such that the former is completely closed. Whether or
not we accept this assumption, we can accept their description of the cell as a chemical system
whose processes have a certain topology (i.e., the chemical processes intersect in a specific way).
The energy producing processes discussed above are not themselves constitutive of the
autopoietic organization, but any autopoietic organization will have an energy producing
substrate with suitable topology. In the cell, certain molecules are produced, which in turn, by
their localization and properties determine the topology of the relations of production in general.
The production of components results in relations of specification, which hold within the
topological substrate defined by the constitutive relations resulting from localized production.
Relations of order determine the dynamics of the autopoietic organization, but result from the
concatenation of the relations of constitution, specification and order. This seems circular, but
mainly kinetics and interactions of chemical processes establish the relations of order in the cell,
in a network of parallel and sequential relations of constitution. The resulting complex system
is self-producing in the sense that very processes that are constitutive also specify the processes
and their interactions and the overall integration of those processes in such a way as to ensure
the maintenance of the higher level processes in the cell.

Moving up a level to whole organisms, Schaffner considered C. elegans, a nematode
whose genetics, muscular and neural structure are almost completely known. Although Schaffner
was primarily concerned with evaluating the Developmentalist Challenge, his observations are
useful here. He notes, for example, that whereas there are some cases in which one gene affects
one neural connection, which affects one part of behavior (not a very useful one in itself), in
most cases there are many-many relations among genes, neural connections and behavior,
suggesting more complex cyclic functions. In fact, some of these more complex neural networks
and gene-neural network relations have been worked out, confirming the non-linear nature of
the processes. Furthermore, networks of neural networks are involved in some behaviors, and
can produce variant behaviors depending on external stimuli, introducing even more complexity
and feedback. From the perspective of an individual C. elegans, some processes are linear from
DNA to behavior, whereas others involve internal closure, while for others the closure includes
environmental interactions. It is worth noting here that the reproduction-selection feedback
cycle allows even the linear processes to contribute to maintenance in a cyclic way at the lineage
level. In other words, closure is achieved for the process not in the organism, but in its lineage.

My next example is the life cycle of the liver fluke, Fasciola hepatica, which infects
sheep and snails. Its life cycle might be said to start with eggs from sheep gut droppings that end
up in water and infest snails, through which they develop a number of stages, eventually
encysting on vegetation that is eaten by the sheep, in which the adults lay eggs, closing the cycle.
The closure here is again through a lineage, not for an individual organism, which dies before
completing a cycle. The development of F. hepatica needs to be highly organised in order to
permit the moves from one life stage to another in such a way as to preserve the lineage. If we
assume this organization is autopoietic, then all of the information required for maintaining the
cycle must be contained within the organism, including its capacity to reproduce. This would
make the fluke autonomous at the individual level. I will argue later that closure considerations
require that this be modified somewhat.

My last example is mating in the brook stickleback (Culea inconstans), discussed by
McLennan. It applies the notion of closure to animal-animal interactions through behavior.
Essential background information in this case is that the male stickleback makes a nest and cares
for the eggs, ovulating females have a special coloration, male sticklebacks show a special
nuptial coloration during mating season and while protecting eggs, and that sticklebacks will eat
each others eggs if they get the chance. The female stickleback shows aggressive behavior
except when in the reproducitively receptive phase. Females will tend to mate with the winners
of fights between courting males, presumably to increase territory and chances of lineage
survival. Males are aggressive towards other males, and to non-receptive females, presumably
because they represent a threat to territory and to egg clutches. Males court both nuptially colored females and those that are not, but spend more time with the nuptially colored females, and become more choosy the more egg clutches they (the males) have. Note that the behavioral closure here is directed towards reproduction, and a full explanation requires consideration of reproductive success. Male behavior is significantly altered by external stimuli, but the behavioral alterations do not benefit the male directly (and so is not autopoietic at the individual level). Note also that both male and female choice are involved, and that it is not possible to localize control in one or the other, as would be required if reproduction were autopoietic in the individual. Successful reproduction requires coordination. In many species, this sort of coordination can be much more complex. One complexity to McLennan’s story is that related species have developed in different ways, and indicate that female coloration developed before male coloration, but subsequently male coloration has become more complex, suggesting the existence of different selection regimes. Experiments yet to be done on male and female mate choice and a number of other factors are required before the full nature of the organization required by the problem of reproductive coordination in various species of stickleback can be fully understood. *C. inconstans* obviously shows such coordination, but its exact function requires comparative evolutionary studies. At the explanatory level, closure has a much broader scope than within species of sticklebacks.

These examples cover metabolic cycles, cellular metabolism, genetically related behavior and neural nets, development and behavior, each taken from a model case or cases on which much study has been devoted. Is there anything that ties them together, and what might we say about autonomy and function?

3. Closure of processes and interactions

A process is closed if and only if it requires no inputs or outputs at the level at which it is defined. Clearly, fermentation and respiration are not closed, since they require an input of glucose directly into the process itself, at the same level as the process occurs, despite the loops in the process. There is no sense in which these processes are autonomous. Maturana and Varela specifically exclude these processes from the autopoiesis of the cell, making them a necessary substrate. However, it is unclear that there is any internal organization in cell metabolism subject to a total autopoietic cut. Lest one think that I am exaggerating the position, I offer the following quote:

Accordingly, an autopoietic organization constitutes a closed domain of relations specified only with respect to the autopoietic organization that these relations constitute, and, thus, it defines a ‘space’ in which it can be realized as a concrete system; a space whose dimensions are the relations of production of the components that realize it.

(Maturana and Varela p. 88)

It should be obvious that this closure of autopoiesis ensures autonomy in any intuitive sense. But I am sceptical that there are any organisms in which the autopoietic organization can be separated except in an ad hoc way from organization involving heteropoietic interactions with the environment and other organisms. This presents a problem if we accept the identification of autopoiesis with autonomy. Unfortunately, Maturana and Varela give us little to go on as to what constitutes cellular autopoiesis. They talk of DNA, RNA and transcription to proteins under the control of cellular conditions, suggesting that at least some cellular conditions do not contribute to autopoiesis. For example, we might assume that the ability of the lac-operon to operate under suitable conditions is under cell control, but the presence of lactose is not. Similarly, respiration and fermentation, though requiring inputs, are implied by the nature of other constituents of the cell (assuming the presence of glucose). Thus autopoiesis might be saved.

On the other hand, I think these ideas break down if we start to look too closely. First, the emphasis on DNA is less now than it was in 1972, and the Developmental Challenge (for references, see Schaffner) has been gaining in the last few years. In some instances, at least, the developmental approach to hereditary systems is a better model than molecular determinism. The developmental systems approach, in particular, places many inheritance maintenance
processes outside the organism, let alone outside molecular activity, on which Maturana and Varela base their three components of autopoiesis: constitution, specificity and organization.

Place a laboratory rat in a blender, and blend thoroughly. All of the chemical components are there to make a rat, but a rat emerging from the blended results would be a miracle. The blender disrupts the organization by disrupting the local constitution, and thus the local topology, which Maturana and Varela take to determine the autopoietic processes. I have a feeling that even if the chemicals were localized and specified much as they are in a rat, a rat would still not emerge. I suspect that we would end up with a rat-like object that might last for a while, like fermentation outside yeast, but which would decay appallingly quickly. The problem is that if the autopoietic cut is dynamical, the autopoietic part would be dynamically isolated, and could not control its substrate. It must, therefore, either not be fully closed, or else it is a non-dynamical abstraction. A second argument: suppose a simple bacterium is made from its blended components using nanotools to place all the components in the right places to allow metabolism. In the natural course of affairs, the organization is passed on by replication; the manufactured bacterium would be heteropoietic even if it had just the same internal properties as a natural bacterium. This suggests that autopoiesis is not in the cell, and that there is something wrong with the concept.

The nature of process individuation and organization requires a deeper analysis. Dividing a complex system into parts in order to explain how it functions, unless the processes make natural unities, is somewhat artificial, and leaves part of the explanation open, as we saw in the cases of fermentation and respiration, in which input of glucose and output of ATP connects quite strongly with other systems. Our group at Newcastle has been using my notion of cohesion for some time to analyze identity in dynamical systems. Basically, cohesion is the logical closure of the relations among elements of a thing that keep it from being disrupted by internal and external forces. In addition, the cohesion is stronger within the system than to any other system or component, so cohesion both unifies and individuates. I believe it is the unique dynamical criterion for identity. Cohesion can be strong or weak, relatively local (as in a rock crystal), or relatively global (as in an organism). Anything that is autopoietic is cohesive, but not the converse. Our manufactured bacterium would have the same cohesion conditions as a natural one, and since the cohesion is the complex functional organization that makes up autopoiesis in a natural cell (at least approximately), it would be just as autonomous as a natural cell. Thus we avoid the paradox that isomorphic organisms could one be autonomous and the other not.

For processes, cohesion ensures identity only if the process is more closely connected with itself than with other processes. That fermentation and respiration subside outside cells suggests strongly that they are not autonomous. If we close the connections to glucose source and muscle action, we are lead quickly towards blood circulation, digestion and movement, and then to food seeking and satiation behavior (both necessary for an organism’s self maintenance). These last behaviors may be very complex and involve non-linear interactions with the environment. They may be further connected in complex non-linear ways with other aspects of an organism’s cohesion at different levels. We believe, however, that the central self-maintaining organization is primarily located within the organism, and this imbalance justifies deeming the organism autonomous. The organization called autonomy that constitutes the cohesion of an organism is like the organization that supposedly constitutes autopoiesis, however the gradations of cohesion allow us to consider interactions with the external world as part of total process closure, unlike Maturana and Varela.

In the case of *C. elegans*, some of the neural nets related to behavior form units that may be independent. The reducible sensory behavior mentioned above is one obvious case. This means that *C. elegans* may have a modular structure in which some subprocesses form natural processes. It is a matter of relative strengths of cohesion; if the modules are more cohesive with themselves than with other elements of the nematode, then they are individuated naturally. On the other hand, all of these modules serve the function of keeping the nematodes alive and reproducing. The organization involved in liver fluke development and stickleback mating cohesion also show both modular and holistic aspects. I am inclined to call the developmental
cycle cohesive, and also to call the mating coordination cohesive, although from an autopoietic point of view they are "leaky", with significant information guiding the behavior coming from outside. The variable nature of cohesion permits such leakiness, whereas the all or nothing nature of autopoiesis does not.

4. Autonomy

The notion of autonomy still needs clarification, but I am afraid that I will not give it completely here (Collier\textsuperscript{24} and Christensen, Collier and Hooke\textsuperscript{14,15} use autonomy in the present sense). Our basic idea is that a system is autonomous if there is an informational imbalance between the organization within the system and the environment with which it interacts. It is clear, for example, that organisms need food, but this food is actually broken down down into elementary parts before it can be used. The information required in the food is rather small. Certainly, it is smaller than in the digestion and respiration processes.

Autonomous systems have many functional properties that preserve system integrity by cycles of interaction, internally and with the environment. These cycles are typically complex and self-reinforcing. For example, the Cheetah’s capacity for the rapid chase is a complex neuro-optico-muscular property which is maintained both through its very exercise and through the food successful chases provide, as mediated by complex bodily processes. This illustrates a central feature of the constitutive processes of autonomous systems: they must achieve both process closure and interaction closure. Process closure concerns the fact that an overall process must achieve self-reinforcement by supporting system viability, and hence the continuing system capacity to carry out that process. If the system is to achieve overall process closure the elements of the system must interact with each other and with the environment in particular, circumscribed ways. This is interaction closure. This closure is the basis of system cohesion in autonomous systems. In the Cheetah example, it must be the case that (i) the multifarious biochemical reactions constituting hunting activity must interact so that effective hunting activity results, (ii) this activity must so interact with the environment that a sufficient supply of organic material results, and (iii) that material must lead, via eating and digestion, to the resulting components interacting with the body in a way that produces a sufficiently nutritive result, so that (iv) subsequent hunting activity (among other outcomes) is biochemically sustainable. None of these conditions is trivial.\textsuperscript{14} The hunting/eating example also makes the point that autonomous system processes will in general interact with many other such processes - e.g. eating and digesting, and so on supports not just hunting capacity, but every other system capacity. The logical limit of closure is the organism and all of its environment with which it interacts.

Things are even more complicated, however. It seems likely that self-organization plays a major role in biological processes. Schaffner\textsuperscript{17} cites Lewontin and others that phenotype is created by a non-linear combination of nature, nurture, and chance during development. We feel that the chance elements may play a central role in differentiation during development. For example, the original stem cells of animals and meristems of plants are totipotent, that is, they are not obliged to form a particular type of cell, but can form any type of cell in the organism. In fact, this is essential for development. What is the cause of differentiation of isomorphic cells? One possibility is some sort of preprogramming based on position or gradient, but neither answer is correct for all cases, and neither works for some cases. Collier, Banerjee and Dyck\textsuperscript{25} argue that the way meristems differentiate into two early types of cells is more similar to the formation of eddies in Bénard cells and other non-linear phenomena than to any other processes. Chance, in this case, has macroscopic consequences for development and phenotype. If self-organization plays a significant role in development (and perhaps higher order behavior\textsuperscript{21}), then we can expect that even if our rat could be reproduced by placing its molecules in the right locales, a non-isomorphic rat might develop. This sort of self-organization in development (and perhaps in cognition, especially creative thought) increases the individuality of organisms. It has no necessary effect on their autonomy, but if it enhances the capacity for adaptivity, then it is an important part of their autonomy. The capacity for self-organized responses to unusual stimuli allows for novel solutions to problems, unlike programmed reactions.
Returning to the examples above, fermentation and the Krebs cycle are not autonomous, and cannot survive on their own. The autonomy of the cell is variable, with bacteria, especially some varieties, quite autonomous, and others dependent on colonies. The nematode is autonomous, and has a number of modules as well. The liver fluke is autonomous, but the reproductive cycle I discussed has more to do with the maintenance of the lineage than of the individual fluke, and if anything is the subject of autonomy in this particular example, it is the lineage. Whether a lineage (or clade) has the sort of organization required to make it self-maintenant is not obvious, but I am inclined to think that does, and I find this easier to conclude in the case of social organisms. Ironically, social animals like humans depend heavily on their surrounding co-organisms, and thus lose some autonomy, but the autonomy of adult humans is so high that the loss can be circumvented. Finally, the mating behavior of two autonomous organisms, a male and female stickleback in breeding season is cohesive (the coordination implies cohesion), but applies again best to the lineage, not the individuals. Looking at closure conditions, especially of cohesion, can help to isolate the focus of explanation. The stickleback behavior was reported in the context of evolutionary explanation; this is no accident: that is the proper level on which to examine the processes involved in order to ensure the closure of the explanation (once it has been tested and accepted).

A typical organism interacts with its environment as well as having more complex internal behavior that together contribute to its viability. I mentioned before that autopoiesis requires that the self-maintenant aspects of organization can be separated from the interactive aspects. Given the existence of high level interactions involving the most complex systems in organisms, their nervous systems and brains, it is hard to see where this cut is supposed to be made.

5. Functionality: Adaptivity and adaptability

Autonomy is a form of cohesion, thus it is essential to preservation. Like other forms of cohesion, it comes in degrees. However it also requires a complex organization and an imbalance between the complexity of internal processes and the complexity of resources. This sort of relative independence of resources is possible with closure alone if the environment presents simple raw resources (a chemical soup), but if the environment is more complex, the organism must be correspondingly even more complex to deal effectively with the complexity of its environment. Thus autonomy in many realistic cases implies adaptivity, which adds even further complexity to the organism.

Since autonomy and the processes supporting autonomy contribute to the survival of the organism (or whatever entity we are trying to explain), relative differences in autonomy or things that contribute to autonomy will be subject to selection. It is not selection that makes selected traits functional, but it is because the traits contribute to autonomy that they are functional, and they are selected only if (in combination) they are more functional. Complete explanation of biological function requires not only a history of selection, but also an account of relative functionality in terms of autonomy (or something equivalent in each particular case). Otherwise, explanatory closure is violated, since the organisms are treated as "black boxes", and there will almost certainly be open (or incomplete) process closure.

In the short space remaining, I will just mention adaptability. It requires an even more refined organization, but leads to even more autonomy from the environment, since the environmental conditions that matter crucially are simplified at a high level to general responses to types of environments, permitting more detailed responses to particular environments without coding for each individually. All other things being equal, adaptive creatures will show more autonomy than nonadaptive ones, and adaptable ones will show even more autonomy.

6. Conclusions

On the Newcastle view, function ultimately serves autonomy. Even a less adapted creature might be autonomous, but autonomy can vary in degree (as well as strength). In biological creatures, their robustness, or the robustness of their lineage, depends more on the
degree of autonomy than on the strength of their cohesion, since all biological creatures exist in shallow energy wells (they are clever rather than strong). More autonomous creatures are more likely to be selected, so differences in autonomy can explain selection (with the possible exception of cases in which highly specialized adaptations to peculiar conditions are not the cause of selection).

Function is a product of the interlocking processes that underlie the organization that constitutes autonomy, and selected traits are functional because of their contribution to autonomy. More functional traits are more likely to be selected, all other things being equal. Consequently, the full story of selection involves, or should involve, considerations of contributions to autonomy. Function can be determined by examining these contributions, irrespective of selection. As mentioned in the Introduction, selection is just a consequence. A purely selectionist story leaves out the causes.

Because autonomy is a matter of degree, like cohesion, its determinable cognate, complete closure is not required. What is required is a significant difference between the internal and external parts of the complete organization, with the greater balance being internal. Unlike autopoiesis, autonomy is "leaky", and it may be bothersome that it is not a clear-cut concept. Clear cut distinctions, however, are not typical in the biological world.

A complete explanation of behavior (or adaptation, for that matter) will include environmental interaction, which is usually essential for self-maintenance. Interaction closure will be part of any full story just as much as autonomy. Autonomy, however, is focussed on the self-maintenant aspects of the organism (or perhaps lineage or some autonomous module), and an understanding of autonomy could help to understand the environmental range of an organism or population.

Glossary

**Autonomy**: An autonomous system is independent and self-maintaining, and is so organized that the greater balance of organization producing self-maintenance is internal to the system.

**Cohesion**: Cohesion is an equivalence relation that is the logical closure the dynamical relations between the dynamical parts of a thing that make it resistant to both external and internal fluctuations.

**Complexity**: Complexity is the minimal amount of information required to define something from simple parts.

**Dynamical**: A dynamical system is one can be defined in terms of concepts like energy, force and work. An abstract, degenerate version of this used by mathematicians is a system with a time parameter.

**Function**: Mathematically, a many one mapping, but in biology and more generally a trait is functional if and only if it contributes to the autonomy of something.

**Information**: The information content of something is the minimum number of binary distinctions required to individuate it. Equivalently, the length of the shortest truth table row that implies everything true of it.

**Organization**: Both ordered and complex, but is not maximally either; shows subtle redundancies.

References