



What is an organism?

Description

Introduction

The question *What is an organism?*, formerly considered as essential in biology (e.g. Huxley 1852, Haeckel 1866, Loeb 1916, Goldstein 1939, Medawar 1957, Wolvekamp 1966, Lewontin 1983), has now been increasingly replaced by a larger question, *What is a biological individual?* (Hull 1978, 1992; Buss 1987; Wilson 1999; Sober 2000; Gould 2002; Wilson 2004). To understand why, we need to define what an individual in general is and then what a biological individual is. First, what is an individual from a general perspective? It is critical to understand that not every particular is an individual. A particular is everything that can be designated through a demonstrative reference (e.g. *this* F). An individual is a particular that is separable, countable, has acceptably clear-cut spatial boundaries and exhibits trans-temporal identity, that is, the capacity to remain the *same* while changing through time (Chauvier 2008). Two aspects of this definition are worth emphasising. First, "individual" can refer to natural objects (rocks, plants, etc.), as well as to artifacts (tables, cars, etc.). Second, individuality is a matter of degree: a car is better individuated than a cloud, which itself is better individuated than a nose. Of course, other definitions of the term 'individual' may be suggested, but the one given here is general enough to reflect the long history of the ontological questions dealing with individuality, at least since Aristotle.

What, now, is a *biological* individual? It is an individual that lives. There is no consensus on what the frontier between living and non-living individuals is but for the sake of the argument developed here we can consider that biochemical complexity, metabolism and reproduction are good candidates as characteristics of living individuals. Raising the question of biological individuality amounts to asking what living individuals are in our world. To this question the commonsensical answer is that they are organism. Common sense defines *organism* a functionally integrated living thing. The living world seems to be made of trees, flies, mice and men, all of which are considered as individuals - indeed, even paradigmatic individuals.

Yet, in the last three decades several philosophers of biology, most prominently David Hull (e.g. Hull 1992), have argued that: i) it is by no means self-evident to individuate organisms, ii) the notion of a *biological individual* is much larger than that of an *organism*: organisms might be biological individuals but all biological individuals are not necessarily organisms, iii) individuation is theory dependent, iv) the only biological theory sufficiently articulated to make biological individuation possible is the theory of evolution by natural selection, v) the organism is only one level in the hierarchy of biological individuals which may include genes, molecules, cells, organisms, groups and species (Hull1992).

I want to show here that the organism is not simply one level in the hierarchy of biological individuals but the most clearly individuated of all biological individuals. I accept points i, ii ((As the majority of philosophers involved in this discussion, I disagree with Buss (1987), who equates the individual and the organism and with Wilson and Sober (1989) who consider the individual as a special case of an organism.)) and iii but I reject iv and as a consequence v. I argue that at least one physiological field, namely immunology, offers a theory of biological individuality. I then articulate immunological individuation with evolutionary individuation. I conclude that among biological individuals the organism expresses the highest degree of individuality.

Phenomenal individuation

What are the biological individuals in our world? We can think of three ways to individuate biological entities: i) a phenomenal way, according to which we can easily see biological individuals, ii) a physiological way, according to which the biological world is made of a sub- class of biological individuals, that is, organisms, which are described as functionally integrated units, undergoing continuous change and made of causally interconnected elements, iii) an evolutionary way, according to which it is the theory of evolution by natural selection that tells us what a biological individual is.

Let us first examine the phenomenal way. According to this sort of individuation we can easily determine what the biological individuals are simply because we can see them. Biological individuals are organisms and organisms are easy to see in the world. In the same way a table is considered as a good example of an artificial individual; a horse or an ox will be considered as good examples of biological individuals. People who adopt this conception follow a common sense view of biological individuals. The

underlying idea is that we certainly do not have a very precise definition of the organism but we do not really need one because we can all recognise organisms when we see them. The problem is that phenomenal individuation simply does not work as soon as one considers living things other than higher vertebrates. Common sense cannot say where the individual is when the focus is on siphonophores, aspens, fungi or slime moulds – to take but few examples (see especially Hull 1988, Wilson 1999 and Wilson 2004 for several other examples). What is more, a cell, for instance, fulfils very well all our criteria of individuality raising the important question of whether a multicellular organism is better seen as one individual or a community of (cellular) individuals.

As Hull (1992) puts it, 'common sense is strongly biased by our relative size, duration and perceptual abilities' (see also Lewontin 2000). If we cannot trust our perception, how are we to determine what the biological individuals are? Following again Hull we can say that scientific theories constitute an excellent guide: scientific theories, in all natural sciences, offer an ontology, that is, they tell us what the entities of our world are (atoms, fields, genes, etc.)

In other words, individuation in science is always theory dependent (Hull 1992). Moreover, we have good reasons to trust scientific theories because they can explain and predict what happens in the world much better than common sense. Certainly, the philosopher should not trust blindly what science says about our world but she should see science as one excellent starting point with theories as the best of all starting points.

The next step in the reasoning is where I depart from Hull's thesis. Before explaining why I disagree with Hull, I would like to sum up his point. According to Hull the only true highly structured and well articulated biological theory is the theory of evolution by natural selection (TENS) (1992). Therefore, the TENS is our best guide or even our only guide when we seek to determine what biological individuals are. Hull emphasizes that physiology or morphology would be very useful to determine what a biological individual is, *if only* they were grounded in a theory. Unfortunately, the argument goes, there is no such thing as a physiological or morphological theory and therefore we are supposedly left only with the TENS to individuate biological entities:

The trouble with Haeckel's solution to the problem of biological individuals is that morphology and physiology do not provide sufficiently well articulated theoretical contexts. Biologists have been engaged in the study of anatomy and physiology for centuries, but no theories of morphology and physiology have materialised in the same sense that evolutionary theory is a theory. In order to see the dependence of individuality on theories, one must investigate more highly articulated areas such as evolutionary biology. (Hull 1992).

Let's now examine evolutionary individuation, then we will get back to physiological individuation.

Individuation by the theory of evolution by

natural selection

If individuation is always theory dependent and if TENS is the main, or sole, biological theory then the best way to individuate biological entities is to determine what an evolutionary individual is. Therefore, in the massive literature on this subject, determining what a biological individual is amounts, most of the time, to determining what an *evolutionary* individual is.

So, what is an evolutionary individual? The answer is given by the structure of the TENS. A biological individual is an evolutionary individual, that is, any entity on which natural selection acts. It is defined by the following characteristics, derived from the structure of the TENS: variation, heredity, differential fitness (Lewontin 1970). In this view, a gene, a genome, an organelle, a cell, an organism or even a group or a species can all, in appropriate circumstances, be defined as biological individuals. This is called the *hierarchical* conception of evolution (Lewontin 1970, Buss 1987, Gould and Lloyd 1999, Michod 1999, Gould 2002). According to this conception, the organism is only one biological individual among many others. ((A more radical view is that the living world is, from a scientific point of view, made of genes and not of organisms. This view, held by Dawkins (1982), may lead to the idea that 'there is no such thing as an organism', as discussed by Sterelny and Griffiths (1999). What follows will make clear why I think this view is utterly wrong.))

But the hierarchical view of biological individuality goes further. It leads to a revision of our ontology. We thought that the biological world was made of organisms as we see them but this is simply not true and it is individuation by natural selection that brings this to light. Janzen (1977) typically illustrates this attitude. He argues that while phenomenal individuation apparently tells us that a dandelion is that green thing in our garden, evolutionary individuation tells us that, in real fact, it is the extended, long-lived clone of dandelions that constitutes the biological individual because it exhibits *reproductive fitness*.

The consequence is that 'there may be as few as four individual dandelions competing with each other for the territory of the whole of North America' (Dawkins 1982). Equally, the aphid evolutionary individual is the set of insects originating from the same egg and *growing* by parthenogenesis. Because they share the same genome, they cannot be said to compete with each other and they constitute the *parts* of the same individual. Let us now examine the foundations and also the difficulties of physiological individuation.

Physiological individuation

Here physiology is broadly defined as all the biological fields which deal mainly with the *how* questions, in contrast with the *why* questions, which are raised by evolutionary biology. Physiology includes, in particular, anatomy, morphology, most of molecular biology (including molecular genetics) and most of developmental biology (Boron 2005).

What I call physiology here was referred to as 'functional biology' by Mayr (1961) but I prefer avoiding the phrase functional biology because the

aetiological conception of functions points towards evolutionary biology. Of course, physiology and evolutionary biology are complementary not conflicting but still most biologists acknowledge that they are more physiology oriented or alternatively more evolution oriented in their everyday work.

Physiology tries to make more solid and precise the common sense conception of what a biological individual is. It says that organisms are indeed the individuals of the living world but it offers an argument for this assertion. The argument is that the organism is a coherent functionally integrated whole undergoing continuous change and made of causally interconnected elements. This view, exemplified by Kant ([1790] 2007), dominates physiology. Many philosophers consider functional integration as a criterion for biological individuation (Wolvekamp 1977; Sober 1991; Sober 2000). I agree it is a very useful criterion but I think it needs to be made much more precise.

I consider that the concept of functional integration is too vague to offer an effective criterion for individuation because it is too close to the phenomenal individuation: we simply trust our impression that the organism is a coherent *whole* which we cut into functional pieces and to which we attribute *natural boundaries* (like the skin).

For example, what are the natural boundaries of the colonial organism *Botryllus schlosseri*? Each zooid has a membrane and is, at least to some extent, an integrated whole but one could say that the *true* functional integration happens at the level of the colony which has a common vascular network. What, then, is the proper physiological individual? In organisms like ourselves, a cell is spatio-temporally localised and functionally integrated: what are the criteria that lead us to say that the organism is the true biological individual in this case? Functional integration is certainly a good principle but it needs a more precise account based on a criterion of individuation.

Of course, one solution would be to say that the multicellular organism is an individual made of cells that are also individuals (Sober 1991). But the problem is that, if this were true, then we would have no reason to believe that the organism is better individuated than a cell - in other words, functional integration would not define *degrees* of biological individuality.

What is more, if it were true, physiology would not deal specifically with organisms but with any functional unit. I think physiology is really about organisms but needs a precise criterion to demonstrate so. I agree with Hull (1992) that a proper individuation needs a theory.

We must therefore figure out whether a criterion of individuality based on a physiological theory is possible. In the next section, I show that, if properly understood, one field of contemporary functional biology, immunology, offers a theory of biological individuality.

Individuation by a physiological theory: immunity and the biological individual

What is the relation between immunology and individuation?

Since its inception immunology has been considered as a key domain for the definition of biological individuality (Metchnikoff 1907; Loeb 1937; Medawar 1957; Burnet 1969; Tauber 1994). Yet what one should understand by this notion of individuality remains unclear. Here I use the notion of a *criterion of immunogenicity* to precisely define the contribution of immunology to the problem of biological individuation.

Immunology aims at finding a criterion of immunogenicity, that is, determining why and when an effective immune response is triggered. An immune reaction is a biochemical interaction between immune receptors and antigenic patterns. In certain conditions an immune reaction can lead to an immune response, that is, to immune activation which leads either to the destruction of the target (lytic activity) or to the prevention of such a destruction (down regulatory activity). The immune system in every organism exerts a permanent surveillance of the molecular patterns expressed by the entities present in this organism (Dunn et al. 2002). Any entity expressing strongly abnormal patterns will be rejected by the immune system.

A criterion of immunogenicity is precisely an attempt to say what exactly this *abnormality* is. Hence the immune system by its surveillance activity defines what will be accepted and what will be rejected by the organism and therefore a criterion of immunogenicity constitutes a criterion of inclusion for the organism: the distinction between the entities which will stick together as constituents of the organism and those which will be rejected from the organism is made by the immune system. ((Of course other biological activities lead to the *rejection* of some entities. We can think of metabolic activities: nutrition (rejection of faecal matter) and breathing (rejection of CO₂). Nevertheless, by these metabolic activities, the organism *assimilates* something and rejects the by-product of its own assimilation activity. By contrast, the immune system accepts or rejects living entities (organs, tissues, bacteria, parasites, even viruses which we consider as living entities) themselves as parts of its identity.))

As a consequence, the immune system is certainly not the same thing as the organism but it is a sub-system of the organism the activity of which leads to the discrimination between what is a part of the organism and what is not. This discrimination happens through time (i.e. it is diachronic): for instance, a proper criterion of immunogenicity must explain why an organism with one kidney at time 1 can have a second perfectly tolerated kidney coming from its twin brother at time 2.

Immunity offers a criterion of diachronic inclusion, that is, a criterion for what makes the organism a unit constituted of different entities through time. The idea that the immune system can explain what the constituents (parts) of the organism are has been intuitively expressed many times (see Gould and Lloyd 1999). What is needed now is a precise account of how this organismic individuation works.

Naturally, I am not saying that immunology is the only physiological field that can help to give a precise account of organismic individuality. I am saying that immunology is ready to answer Hull's challenge because it offers a criterion of individuality grounded in a physiological theory. It is very likely that developmental biology, studies of metabolism, studies

of phenotypic plasticity, among others, could also play an important role in defining organismic individuality but I leave to others the task of determining whether or not they can offer a proper theory and hence a proper criterion of individuality.

Before examining in details how immunological individuation works, I shall examine a possible objection: are there not very few organisms in nature that possess an immune system? If this is indeed the case then how can I claim to build on immunology a general physiological theory of biological individuation supposed to hold for all organisms?

The domain of an immunological theory of individuation

My answer is that this is simply not true that only very few organisms (i.e. higher vertebrates) have an immune system. For several decades, immunologists have believed that immunity was limited to jawed vertebrates because of an illegitimate focus on lymphocytes seen as the only true immune actors. Nevertheless, it is now clear to all immunologists that immunity is ubiquitous (Kurtz and Armitage 2006; Pradeu 2009): in all organisms in which immunologists have looked for an immune system, they have found one and most of the time a very complex one.

What, then, is immunity? One can talk of an immune system each time one finds specific interactions between receptors and ligands which can lead to the destruction (lysis) of the target. With such a definition in mind one finds immunity in all organisms. Let us examine two cases: the well-known insect *Drosophila* and plants. The *Drosophila* possesses an immune surveillance system especially thanks to its Toll receptors with which it can sense pathogens (Khush, Leulier and Lemaitre 2002). Interestingly, an equivalent of these receptors exists in mammals where they are called Toll-like receptors and play a key role in initiating immune responses.

Plants have several immune mechanisms which can be classified according to two lines of defence. The first one is the direct recognition of pathogen associated molecular patterns by plant transmembrane receptors. The second one, called the indirect pathway, is the recognition of specific effector molecules produced by the pathogen. It consists of, like mammalian adaptive immunity, a highly specific recognition of pathogen products. It is mostly triggered by NBS-LRR proteins, that is, proteins encoded by resistance (R) genes and containing a nucleotide-binding site (NBS) and leucine-rich repeats (LRR) (DeYoung and Innes 2006).

Here lies what is probably one of the most important immunological revolutions of the last decade. The clear-cut separation between adaptive immunity (sometimes equated with specific immunity) and innate immunity has vanished (Vivier and Malissen 2005). Adaptive immunity was attributed to jawed vertebrates only. Innate immunity was considered to be non-specific, but in fact, from a biochemical point of view, it is specific.

Organisms with innate immunity were also said to have no immune memory, that is, no capacity to mount a more rapid and more efficient immune response in case of a second contact with the same antigen. Yet, here again, many organisms with innate immunity have been found to have this capacity (Kurtz and Armitage 2006). The consequence is that today's immunologists admit that the old clear-cut boundary between innate and adaptive immunity is blurred or even non-existent.

According to an emerging consensus even unicellular organisms possess an immune system, that is, a system of receptors recognising abnormal patterns. It is a genome's immunity, which can be based on CRISPR (clustered regularly interspaced short palindromic repeats) (Barrangouet al. 2007), or on similar mechanisms, probably analogous to ARN interference, found in eukaryotes (Plasterk 2002).

Thus, we can conclude that immunity is ubiquitous both in multicellular and in unicellular organisms and hence that it can be the basis for a general physiological theory of organismic individuation. With these very important precisions in mind we can now go back to our main question: what criterion of immunogenicity should we adopt and how can it be the basis for a physiological theory of individuation?

Which criterion of immunogenicity should we adopt?

For sixty years now immunologists have suggested that the proper criterion of immunogenicity consists in the discrimination between self and non-self and that this discrimination tells us what a biological individual is (Burnet and Fenner 1949, Burnet 1969, Langman and Cohn 2000). I agree that immunology offers a physiological theory of individuation but I do not consider that this theory can be grounded in the discrimination between self and non-self. The self-non-self criterion is now increasingly regarded with suspicion (Tauber 1994; Anderson and Matzinger 2000; Pradeu and Carosella 2006a; Greenspan 2007). According to this criterion an organism does not trigger an immune response against its own constituents but it triggers an immune response against every foreign entity (except, of course, in cases defined as pathological). Nonetheless, recent discoveries in two critical areas, immune autoreactivity and immune tolerance, prove that this criterion is inadequate.

First, lymphocytes that do not react at all with *self* constituents of the body simply die. To be selected, both in primary organs and at the periphery, lymphocytes must be continuously stimulated by endogenous antigenic patterns. Furthermore, this normal autoreactivity concerns not only immune interactions but also immune effector mechanisms: for instance, macrophages react to dying *self* cells of the body and eat them (they are the scavengers of the body) (Taylor et al. 2005), and regulatory T cells are *self* cells which respond to other *self* cells by down-regulating their activity (Sakaguchi 2006).

Second, recent research has shown that immune tolerance is very common. Immune tolerance refers to the absence of immune response to foreign entities even if immune interactions with them occur. In particular, all known multicellular organisms are hosts of many bacteria, parasites and viruses. For instance, in a human being, commensal and symbiotic bacteria outnumber eukaryotic cells by at least one order of magnitude (Xu and Gordon 2003). Though these foreign entities are sometimes deleterious and

can even kill their host in many cases they are beneficial to the host and play a functional role.

Another example is that the mother does not reject the fetus though it is genetically different from her. Instead of the self-non-self criterion, I prefer the continuity criterion, (Pradeu and Carosella 2006b) according to which, every strong molecular discontinuity in the antigenic patterns (whether endogenous or exogenous) with which immune receptors interact induces an immune response. There is a discontinuity if there is a strong modification of molecular patterns with which immune cells interact: to put it very simply, the immune system responds to strongly unusual patterns. The criterion is molecular difference, as stated in the self-non-self theory but not the origin of the molecular pattern (i.e. endogenous or exogenous), contrary to what is stated in the self-non-self theory.

Immune habituation works both ways: when the immune system responds to an unusual antigen (whether endogenous or exogenous), the second response is usually more rapid and more efficient but according to the continuity criterion when the immune system reacts but does not respond to a usual antigen (whether endogenous or exogenous) the second response is likely to be weaker. This is called induction of tolerance by induction of continuity.

Therefore, the repeated presentation of an antigen in non-immunogenic conditions leads to a subsequent tolerance of this antigen. Non-immunogenic conditions are: small quantities of antigen, antigen introduced progressively and with no pro-inflammatory signals. Tolerance of microorganisms, feto-maternal tolerance, chimerism and some cases of graft tolerance could all be examples of induction of tolerance by induction of continuity.

The continuity criterion accounts for immune auto-reactivity because it states that immune receptors interact with normal constituents of the body with a medium strength (which is measurable very precisely by its specificity, affinity and avidity). Interactions are very strong when immune receptors meet unusual patterns. The continuity criterion also accounts for immune tolerance with the concept of induction of continuity.

Thus, the criterion of immunogenicity we are looking for cannot be the self-non-self criterion, which is grounded in a wrong idea: the preservation of endogenous elements by the immune system of the organism. By contrast, the continuity criterion integrates auto-reactivity and tolerance, it offers an experimentally adequate account of immune phenomena and therefore it can be the criterion of inclusion we are looking for.

This criterion of inclusion is derived from a true physiological theory of individuation, because i) it is composed of several, hierarchically organised, hypotheses, ii) it applies to all organisms, iii) it explains current data and iv) it makes new predictions. The next question is: what does this physiological theory of individuation tell us about the definition of the organism?

The organism: a set of interconnected heterogeneous constituents interacting with immune receptors

Definition of an organism

Let us start with the usual physiological definition of an organism: the organism is a functionally integrated whole which undergoes continuous change and which is made of interconnected elements characterised by causal dependence (e.g. Sober 2000). The constituents of John may causally interact with the constituents of Tim but not with the same intensity, timing and scale as John's constituents interact with each other. This definition is certainly correct but it is too general. Biochemistry can help us to make it more precise.

Indeed, although functional integration can be observed at many levels in the organism, the finest level is that of proteins: the parts of an organism (organs, tissues, cells, and even constituents with cells) are indeed interconnected by strong biochemical interactions involving mainly proteins-proteins interactions (Lesk 2004). In plants regulation and coordination of metabolism, growth and morphogenesis often depend on a network of chemical signals (Taiz and Zeiger 2006). In many instances, in multicellular organisms, a cell which does not receive signals from its local environment and which does not send signals to it rapidly dies. The elucidation of protein-protein interactions is a very active field in contemporary biology. It will probably be in the near future the best level to understand functional integration within an organism, because, again, the strength, timing and extension of inner biochemical interactions are very different from those occurring between two distinct organisms (Lesk 2004).

The problem is that, even at a biochemical level, functional integration is local. In other words, two sub-systems in an organism can be quasi-independent (Lewontin 2000). It is at this point that the contribution of immunology is critical: immune interactions are fundamentally organismic (i.e. they concern the whole organism) because they are systemic for the lymphatic system (or its equivalent) is an extensive system collecting extracellular fluid (lymph) from all tissues of the organism. All the tissues and cells of the organism are therefore under the influence and control of the immune system.

Thus, immune interactions are a sub-set of biochemical interactions but i) they are systemic (as opposed to local) and ii) they offer a criterion of inclusion because they are responsible for the acceptance or rejection of constituents in the organism. Now we reach the heart of the argument. When we link together the general biochemical point of view and the specific but systemic immunological point of view, we obtain the following definition of an organism:

An organism is a functionally integrated whole made up of heterogeneous constituents that are locally interconnected by strong biochemical interactions and controlled by systemic immune

interactions that repeat constantly at the same medium intensity.

It should be clear that the immune interactions are critical in this conception and that they constitute the basis of our physiological individuation of the organism. First, whereas biochemical interactions are most of the time local, immune interactions are systemic. Second, while the strength of biochemical interactions is not always easy to define (because of their diversity), immune interactions are receptor-ligand interactions the strength of which is very clearly defined in terms of specificity, affinity and avidity.

Immune cells interact in a medium, but not too strong, way with the antigenic patterns of the organism's constituents: if these interactions are very weak the target (whether endogenous or exogenous) dies; if they are very strong, it means that an immune response, leading to a possible rejection of the target, has been triggered. It is only if they remain at the same intermediate intensity that we observe a normal homeostatic state in the organism. These interactions must also be repeated continuously (constantly), which means regularly, and not, of course, without any interruption.

My definition does not imply that everything which does not trigger an immune response from an organism belongs to this organism: for instance, two identical twins can tolerate each other's organs in case of transplantation but it does not entail that they are one and the same organism.

Instead, my criterion requires both presence and inclusion (absence of rejection). I also believe that my definition sheds some light on the frequently made assertion that every organism is heterogeneous (Lewontin 2000).

The heterogeneity of an organism

According to my definition, the constituents of an organism are heterogeneous. The word heterogeneous is not synonymous with different. Etymologically it means coming from the other, that is, in this context, coming from what is initially the outside of the organism. My discussion of immune tolerance has shown the importance of this heterogeneity: an organism is made of constituents that do not need to have originated in it.

In other words, an organism is made of many foreign things, it is never endogenously constructed. I can illustrate this heterogeneity by an examination of the functional role of indigenous symbiotic bacteria in mammals (Hooper and Gordon 2001).

For example, each human being is constituted of indigenous symbiotic bacteria that clearly outnumber his or her own cells originating from the egg cell. The majority of these bacteria live in our intestine. Most of them are obligatory symbionts, meaning that they cannot survive outside the host and the host cannot survive in their absence.

They play indispensable physiological (functional) roles: in particular, gut bacteria are needed for digestion. Strikingly, these symbiotic bacteria, far from being foreign enemies that our immune system should fight, also play an indispensable immune role in our bodies (Noverr and Huffnagle 2004). These bacteria have permanent and constitutive biochemical

interactions with other parts of the host. There is no fundamental difference between interactions of the host's immune receptors with these symbiotic bacteria and interactions of the host's immune receptors with endogenous constituents. In both cases, what we observe is a regulated immune reactivity.

Consequently, these endosymbiotic bacteria are not just here in the organism, they are parts of the organism (O'Hara and Shanahan 2006; Xu et al. 2007). An objection could be that the gut is an interface of the organism, not a true internal part of it. Nevertheless, of the ten mammalian organ systems, eight (integumentary, digestive, respiratory, excretory, reproductive, immune, endocrine, circulatory) have persistent associations with normal bacteria (the exceptions being, so far, the musculoskeletal and nervous systems) (McFall-Ngai 2002). The organism is a 'local concentration of interfaces' (Patrick Blandin, pers. comm.).

Obligate indigenous bacteria are in no way limited to mammals, we find them in arthropods, plants, colonial organisms, etc. For example, *Wolbachia* bacteria, which are present in many multicellular organisms, have been proved to be indispensable for the development of a parasitic wasp *Asobara tabida* (Dedeine et al. 2001). In many plants, too, some bacteria are indispensable for nutrition, as illustrated by the symbiosis between the host plant and the bacteria *Rhizobium* (Kiers et al. 2003).

Thus, every organism is a heterogeneous entity, made of different constituents from different origins but unified by common interactions with immune receptors. As a consequence, a proper criterion of immunogenicity tells us first that the organism is a unified whole (its unity is grounded in biochemical and above all in immunological interactions) and second that it is heterogeneous. It offers therefore a dialectical understanding of the inside of the organism (Lewontin 1994): some entities usually considered as parts of the environment are in fact constituents of the organism's identity.

Biological genidentity defined thanks to immune interactions

The definition of the organism suggested here gives a precise content to the notion of genidentity as applied to biological entities (Locke ([1975] 1690); Lewin 1922; Reichenbach 1956; Hull 1992). The genidentity thesis asserts that individuality through time is ensured by the spatiotemporally continuous interactions among the constituents of a being. A classical objection is that it is impossible to speak of interactions among constituents without saying to what these interactions must be attributed and hence without considering that a core (substratum) underlying these interactions must exist.

Nevertheless, this objection can now be rejected: the immunogenicity criterion allows us to single out the biochemical interactions that are constitutive of the organism as a whole. The (constantly repeating at the same medium intensity) immune interactions single out continuous biochemical interactions, which themselves single out the organism.

My definition does not start with the constituents of an organism and then asks what the interactions between them are. It states that every entity bearing molecular patterns that continuously trigger immune interactions of medium intensity is a constituent of the organism. What is fundamental,

therefore, is the strength of the immune interactions which tells us what the constituents of the organism are (e.g. endobacteria).

Difference with other physiological way to individuate entities

The immunological-physiological individuation I suggest differs from both common-sense physiological individuation and endogenous physiological individuation. First, my conception is grounded in the usual physiological definition of the organism (functional integration) but it certainly does not amount to the common-sense physiological individuation which states that the organism is what is behind the skin (or any membrane).

Let us go back, for instance, to the colonial organism *Botryllus schlosseri*. In this case, as we saw, common-sense individuation cannot say what the proper biological individual is, between the zooid and the colony. My criterion of individuality tells us that the organism in this case is not each zooid but the colony characterised both by strong biochemical interactions and by one and the same immune system based on one histocompatibility system (maintained from the larva stage to the colony stage) (De Tomaso et al. 2005).

Sometimes, my criterion gives the same result as the common sense view but it offers a scientific ground for this result: for instance, my criterion tells us that a mouse as we see it is indeed an individual organism but contrary to the common sense view it also states precisely what counts as a part of the mouse. Counter-intuitively, gut bacteria, bacteria situated on the skin, long-tolerated parasites, etc., are part of the mouse. Thus, again, I offer a proper theory, leading to ontological revisions or confirmations.

Second, my criterion shows that the usual conception of the organism as an endogenous entity is wrong. The idea that the organism is the set of constituents originating from the egg cell, that is, a genetically homogeneous entity, is often put forward (e.g. Hull 1978). Immunological individuation shows, however, that every organism is heterogeneous - made of entities of different origins. In the last section, I try to articulate the two theoretical criteria (the immunological-physiological and the evolutionary) and to show what are the consequences of this articulation.

Articulating the physiological and the evolutionary individuations

We now have two theories with which to individuate biological entities. According to the evolutionary criterion there exists a hierarchy of individuals, the organism being simply one of them. By contrast, my physiological criterion shows that the organism expresses the highest level of individuality among biological individuals for the three following reasons.

The boundaries of the heterogeneous organisms are clearly defined

Part of Hull's argument is that the organism does not possess clear-cut boundaries (1992). It is true with the phenomenal definition of an organism but not with the one given here. The immunological criterion of

individuation allows us to take decisions, as in the case of *Botryllus*. I do not pretend that this criterion eliminates all contentious cases but I do claim that the organism as I define it has more clear-cut boundaries than the other levels in the evolutionary hierarchy, in particular a gene (Griffiths and Stotz 2006) or a group.

The heterogeneous organism is sometimes the proper evolutionary individual

Let us go back to clonal organisms and especially to Janzen's aphids (1977). His point is that, during the parthenogenesis phase the aphid organism (the observable insect) is not an evolutionary individual. Instead, the evolutionary individual is the set of all the insects originating from the same egg, because they all have the same genome, and cannot be said to compete with each other. The underlying idea, more or less inherited from Weismann, is that genetic homogeneity is the key to evolutionary individuality.

The immunological-physiological criterion, however, suggests something else. Each immunological-physiological aphid ((Following our definition, an immunological-physiological aphid is a small aphid insect, including its indigenous bacteria, fungi, etc.)) contains intracellular symbionts, whose presence is required for the survival of the host. These symbionts are vertically transmitted (each aphid transmits its symbionts to its offspring). They are different in different aphids. They can mutate during the aphid lifetime, modify its fitness and that of its offspring (O'Neill et al. 1997).

For example, Dunbar et al. (2007) show that a point mutation in *Buchnera aphidicola*, hosted by *Acyrtosiphon pisum* aphid, modifies the host response to heat stress, 'dramatically affecting host fitness in a manner dependent on thermal environment'. It means that physiological aphids born by parthenogenesis do in fact compete with each other: they contain endosymbionts which vary, whose variation is inheritable, and modify host fitness.

The aphid case shows that the argument of genetic homogeneity can lead to wrong conclusions about what the evolutionary individual is. I defend an extended replicator view, stating that genes are not the only replicators in nature (Sterelny et al. 1996). Indeed, vertically transmitted bacteria can be excellent replicators, too.

My argument concerning aphids probably holds for most clonal organisms, especially plants, which massively host obligate symbiotic bacteria (Kiers et al. 2003) or fungi (Heijden et al. 1998), though the mode of transmission (vertical or horizontal) makes a difference. For instance, it is likely that my argument can be made for dandelions.

If this is true, it will revise Janzen's revision of the ontology of living entities: in many clonal organisms, the evolutionary individual would not be the clone but the immunological-physiological organism. Hence, what counts as an evolutionary individual should not be determined by resorting to the sole criterion of genetic homogeneity.

A precise observation of physiological and especially immunological, mechanisms is needed. I do not claim that the organism as I define it is

always the proper evolutionary individual but that it is often necessary to start with the heterogeneous organism to determine what the evolutionary individual is, especially in all cases where endobacteria are vertically transmitted.

I think that this conclusion extends the ideas of Leo Buss. Buss (1987) used a physiological domain, developmental biology, to show that the conception of the organism as a genetically homogeneous entity was (approximately) correct only in a very limited number of species. He showed that many organisms are heterogeneous in the sense that, contrary to Weismann's main idea, their somatic cells can mutate and subsequently give rise to germ cells.

Here I use another physiological domain, immunology, to show that many organisms are heterogeneous in the sense that some of their constituents do not come from the egg cell and can be transmitted to their offspring and influence their fitness. Even organisms Buss considers as homogeneous, that is, arthropods, are in fact heterogeneous because they are constituted of entities of different origins, which can influence their evolution.

The heterogeneous organism controls the variations of lower level constituents, especially cell lineages

The emergence of the pluricellular organism in evolution presupposed the existence of mechanisms controlling the appearance of lower level variants, especially at the level of cell lineages (Buss 1987). The immune system plays a critical role in this control (Buss 1987; Michod 1999) which is exerted on cell lineages but also on endobacteria (Frank 1996). As we saw, immune surveillance is exerted towards all the constituents of the organism. The immune system constantly eliminates *selfish* cell lineages (in the case of tumours in particular). The immune system constantly maintains the individuality of the organism by eliminating the replication of lower level individuals.

Naturally, it is possible that natural selection at a higher level (e.g. group or species) presupposes that variations at the organismic level should be restricted but this control is not as regular and as efficient as in the case of the organism controlling its lower level constituents.

Conclusion

Immunology makes a physiological theory of individuality possible. A proper criterion of immunogenicity offers an account of what the parts of an organism throughout its life are. An organism can be defined as a functionally integrated whole made up of heterogeneous constituents that are locally interconnected by strong biochemical interactions and controlled by systemic immune interactions that repeat constantly at the same medium intensity.

When articulated with the evolutionary criterion of individuation this physiological criterion shows that the heterogeneous organism is not simply one level in a rich hierarchy of biological individuals but expresses the highest level of individuality among all living things.

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