Ontologically Significant Aggregation: Process Structural Realism (PSR)

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Introduction

Philosophical discussions of what sorts of things exist (ontology)[1] now recognize that many types of entities that played important roles in the science of earlier historical periods in fact *never existed*. This raises the troubling suggestion that some (perhaps many) of the entities invoked by present-day scientists may also be figments. John Worrall (1989) suggested that *structural* aspects of science persist even when *ontological* commitments change. He holds objects that scientists talk about *do* exist, but that they have unknowable natures — this has been called "epistemological structural realism" (ESR) (Ladyman 2001). Others (French and Ladyman 2003) hold that objects scientists discuss *do not* exist — but, paradoxically, their structures exist. This is "ontic structural realism" (OSR). This view seems consistent (Earley 2006) with Eddington's (1939) manifesto:

> What is sort of thing is it that I know? The answer is structure. To be quite precise, it is structure of the kind defined and investigated by the mathematical theory of groups.

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1 Ontological questions were out of fashion in American philosophy for several decades. That situation has changed. Hilary Putnam (2005) traces the revival of ontology (a mistake, in his opinion) to W. V. Quine's (1948) paper, "On What There Is."

Some scientists whose laboratory research deals with time-dependent phenomena (including Professor Stein and me) find Whitehead's cosmological scheme to be a useful approach to ontological questions. However, complications arise in constructing an applicable process ontology. This paper outlines some of these challenges, and sketches a neo-Whiteheadian ontological scheme — here called process structural realism (PSR)[2].

Navigating between the Sandbar and the Rock

Some philosophers adopt a relaxed ontology, exemplified by Justus Buchler's ([1966] 1990) notion of "natural complex."

> Whatever is discriminated in any way (whether it is "encountered" or produced or otherwise related to) is a natural complex, and no complex is more "real" or more "genuine" or more ultimate than any other.

The complex notion of "truth" that scientists commonly use (da Costa and French 2003) may foster this outlook — but ontological commitments, expressed or implied, seem necessary for serious philosophy. For instance, the notion that explanation must ultimately rest on a level of submicroscopic "elementary" (i.e., simple) constituents has been a presupposition (often unstated) of much of science and philosophy, at least until recently. Weyl (1949 86) gave a clear statement of this position:

> Only in the infinitely small may we expect to encounter the elementary and uniform laws, hence the world must be comprehended through its behavior in the infinitely small.

Arguably, the first half of the twentieth century was the golden age of this kind of explanation through reduction. Whitehead and Russell (1910) explored the foundations of mathematics in terms of elementary propositions. In the 1920s and 1930s, chemists and physicists produced adequate explanations of the chemical periodic table, of much organic chemistry, of the internal structure of atoms, and of aspects of the make-up of the

2 Elsewhere (Earley 2006), I used the more awkward name 'moderate ontological structural realism' (MOSR) for this approach.

atomic nucleus — using only a few kinds of "elementary particles." Russell's philosophical doctrine of "logical atomism" (1918) and its development by Wittgenstein (1922) achieved great success. Nevertheless, Wittgenstein ([1953] 1967 47) subsequently wrote:

> [B]ut what are the simple constituent parts of which reality is composed? … we use the word 'composite' (and therefore the word 'simple') in an enormous number of ways.

This calls the basis of logical atomism into question. So-called elementary entities encountered in experimental science have repeatedly turned out to be composite. Active areas of contemporary science require non-reductionist approaches. As Robert Laughlin (who won the Nobel Prize in Physics for 1998) writes (2005 208):

> Ironically, the very success of reductionism has helped pave the way for its eclipse. Over time, careful quantitative study of microscopic parts has revealed that at the primitive level at least, collective principles of organization are not just a quaint side show but everything — the true source of physical law, including perhaps the most fundamental laws we know. ….[N]ature is now revealed to an enormous tower of truths, each descending from its parent, and then transcending that parent as the scale of measurement increases. Like Columbus or Marco Polo, we set out to explore a new country but instead discovered a new world.

Is There an Ontological Criterion?

According to Whitehead ([1929] 1978 18)

> 'Actual entities' — also termed 'actual occasions'— are the final real things of which the world is made up.

Whitehead did his main philosophical work during the golden age of explanation by reduction. Early interpreters reached a consensus that the fundamental units of Whitehead's philosophy of organism were necessarily submicroscopic. If (as current science strongly suggests) we abandon the notion of a submicroscopic, elementary-particle level of description as fundamental, could some other criterion differentiate

Whiteheadian actual occasions from Buchlerian natural complexes? Whitehead's discussion of the process of "concrescence" [3] — the coming to be of each actual occasion — suggests a possible way to make this distinction. Whitehead held that concrescence involves "ingression" of some "eternal object" — a "form of definiteness" that serves as a "subjective aim" to regulate whether "data" provided by the antecedent world are "prehended" positively (integrated into the concresent occasion) or negatively (excluded from the concrescence). A major distinction between Whiteheadian actual occasions and Buchlerian natural complexes might well be that a defining eternal object is necessary in the former case but not in the latter.

Neville (e.g., 2003) has pointed out that each existing thing has two aspects — distinguishable but related. These are the aspect of internal coherence and the aspect of external efficacy — called the "cosmological" and "epistemological" aspects, respectively. If an eternal object were necessary for each actual occasion, then that necessity would be a "cosmological" feature of each occasion. The "Eleatic Principle" (also known as "Alexander's Dictum") specifies what would be an *epistemological* difference between the two categories.

> …. everything that we postulate to exist should make some sort of contribution to the causal/nomic order of the world. (Armstrong 2004, 37).

Merricks (2001, 2003) proposed an important clarification of that principle:

> … every material object not only has causal powers, but has non-redundant causal powers. …For material objects to be is to have non-redundant causal powers.

The causal powers of a Buchlerian natural complex might well be redundant — just the aggregate of the causal powers of its components. The extended Eleatic Principle asserts that each ontologically significant entity must, somehow or other, exert causal influence

[3] Quotation marks enclose terms used in technical senses on their first use. Unless a different definition is given, the meaning intended is that used for that term elsewhere in this volume.

that is not simply reducible to the causality of the components. It is important that any adequate process ontology clarify the relationship between cosmological and epistemological aspects of whatever coherences have ontological significance. How could ingression of an eternal object connect with non-redundant causality?

Whitehead rejected the category of substance.[4] Whiteheadian actual occasions do not persist; they come to be and, as they do, they perish. However, Whitehead ([1933] 1967 206) recognized that some combinations of actual entities ("societies with personal order") do have careers through time.

> The Universe achieves its values by reason of its coordination into societies of societies, and societies of societies of societies.

Process ontology needs to deal with the question of how it is possible that many actual occasions could constitute a society that occupies time — though the constituent occasions do not persist.

In summary, any adequate application of Whiteheadian concepts to topics of interest to chemists, other scientists, and the world at large, should have three features. It must avoid the reductionist illusion (that there is some single privileged fundamental level of description). This requires an explicitly multi-level ontology. Process ontology also should reject Buchlerian ontological promiscuity by elucidating how eternal objects (forms of definiteness) ground entities at each ontological level. In addition, it ought to clarify the relationship of process and substance while elucidating ontic causality that fulfills the extended Eleatic Principle.

Parts, and Two Types of Wholes

Mereology is a branch of logic that sets out to deal with wholes and parts. As David Lewis (1999 1) puts it:

> Mereology is the theory of the relation of part to whole, and kindred notions. One of the kindred notions is that of a mereological fusion, or

[4] His rejection mainly concerns John Locke's understanding of the term.

> sum: the whole composed of some given parts. … The fusion of all cats is that large, scattered chunk of cat-stuff which is composed of all the cats there are and nothing else. It has all cats as parts.

Lewis routinely applies mereology to physical and biological systems (especially cats) but his main concern is with the foundations of mathematics. Some recent philosophical discussions of the constitution of material objects stand "in the tradition of Russell, Quine, and Lewis" (Barnett 2004, Wasserman 2004). Sider (2004) considered persistence through time from a related viewpoint.

When mereologists speak of "whole" they do not use the term in its usual English meaning, but rather in a specific technical sense with a meaning close to Buchler's natural complex. Wimstatt (2000) found that quite special conditions are necessary for the existence of the merely aggregative summation behavior that standard mereology assumes to be a general characteristic of what it calls wholes (fusions). Standard mereology considers that parts in fusions are the very same entities that existed prior to fusion. In contrast, chemical combination invariably causes significant changes in the entities that enter combination (Earley 2005). The notion of composition generally used by mereologists has little relevance for matters of interest to chemists or other scientists.

A quite different notion of a whole — one that is closer to the dictionary definition of that word — seems more relevant to chemistry, and to philosophical problems other than the basis of mathematics. Early papers by Rescher (1955) proposed three requirements for a composite individual to constitute a whole in this second sense.

> [1] … The whole must possess some attribute of its status as a whole — an attribute peculiar to it and characteristic of it as a whole. … [2] The parts must stand in some special and characteristic relationship of dependence with one another; they must satisfy some special condition in virtue of their status as parts of a whole….[3] The whole must posses some kind of structure, in virtue of which certain specifically structural characteristics pertain to it.

If the attribute of its status as a whole should be some sort of relationship with external entities, then the whole, as a unit, may satisfy the Eleatic Principle and have ontological significance. This notion of whole seems closely related to Millikan's (2000) notion of substance (Earley forthcoming).

Nature abounds in individual entities that qualify as wholes in this second sense. Biological individuals of many types immediately come to mind.[5] Clearly biological organisms are composed of parts, but individual biological organisms persist (in some sense) through many alterations of their components. This paper considers three examples of effective aggregation related to biology: virus capsids, swarms of organisms, and cyclical reaction networks.

Virus Capsids

Viruses are non-living aggregates of molecules (mostly proteins and nucleic acids). Viruses clearly have non-redundant causality. (The influenza virus *caused* the pandemic of 1918-1919.[6] None of the constituent molecules of the virus, nor any combination of them other than the virus itself, could have done this.) Viruses travel between individual organisms in particles of rod-like or (more usually) roughly spherical shape. These particles consist of an exterior shell (capsid) that contains and protects nucleic acids that provide information for replicating the virus when it infects a suitable host cell. Capsids of spheroidal viruses each consist of many copies of specific protein molecules. Each type of virus has a characteristic capsid protein. Figure 1 shows schematic representations of the structure of the well-studied chickpea chlorotic mottle virus (CCMV). This virus has the symmetry[7] of one of the five Platonic solids, the icosahedron (Zandi 2004). Remarkably, *all* of the many kinds of spheroidal viruses have the same symmetry. There

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[5] Merricks (2001), an "eliminativist" who denies the existence of middle-sized objects such as statues, insists on the existence of human persons (such as himself).

[6] That disease event killed more people than had died in the World War of 1914-1918.

[7] There are six five-fold axes of rotational symmetry, ten three-fold axes, and fifteen two-fold axes.

are 180 identical protein molecules[8] in the capsid of the CCNV. The numbers of protein molecules in the capsids of viruses are all multiples of sixty, consistent with geometric requirements for constructing icosahedral structures of various sizes. The capsid proteins of viruses differ among themselves: the mechanisms of aggregation of protein monomers to produce the capsid also vary greatly. Nevertheless, the final structures of the capsids are remarkably similar for all the many kinds of spheroidal viruses (Zlotnick 2004).

In aqueous solutions under appropriate conditions, molecules of the capsid protein[9] of the hepatitis B virus (HB) spontaneously organize to produce icosahedral aggregates of 240 molecules that are indistinguishable in most respects from the native HB virus capsid. The transition between the disaggregated (monomer) protein molecules and the 240-molecule aggregate is sharp. There are no detectable concentrations of aggregates of intermediate size. Experimental results and theoretical modeling indicate that aggregation depends on just two factors. Attraction (hydrophobic bonding) between protein molecules arises from shielding of parts of the protein molecules from solvent water in the interior of the capsid. This nonlocal attraction just balances the repulsion between the protein molecules due to electrical charges. These two forces are of only modest strength (Kegel 2004). The resulting structure is more flexible than structures that involve higher energies (e.g, most solids). Protein capsids constitute "soft condensed matter."

Swarms of Organisms

Biological individuals often coordinate their activities in large aggregations. This happens when many thousands of free-living *Dictyostelium discoideum* amoebas spontaneously coalesce to produce a single slug that moves (as a unit) to a favorable location and then becomes plant-like. Large animals (locusts, fish, birds, antelope[10] …)

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[8] These divide into groupings (capsomers) that are either pentagonal (twelve capsomers) or hexagonal (twenty capsomers).

[9] Experimenters deleted the part used to attach nucleic acid molecules from this protein before the experiment.

[10] It is not necessary to mention related human behaviors.

also spontaneously aggregate to produce swarms[11] that move and function in unified ways. Recent developments in mathematics and in dynamic-system modeling have produced significant understanding of these processes (e.g., Topaz 2004). A brief summary of the results of such studies is that, in each such case, just two factors[12] dominate — a force attracts members into the aggregation, and a countervailing interaction opposes crowding in the swarm. The attractive force falls off with distance but is otherwise "non-local" — it does not depend on the detailed arrangement of individuals. The repulsive force is "local" — it depends on the distance between each individual and its near neighbors. The properties of the swarm follow from the balance of these two forces. This situation is analogous to the balance of forces in the capsid of the viruses. However, the spatial structure of the swarm is generally less regular and is subject to larger variation than is the spatial structure of the capsid.

Cycles of Chemical Reactions

Normally, chemical processes slow down as they proceed. Some chemical reactions (called autocatalytic) become more rapid as they go on. One way to achieve autocatalysis is through a molecule that generates copies of itself (for instance, by acting as a template). This type of autocatalytic reaction is common in biology — in nucleic acid replication, for instance. Providing a plausible basis for the evolution of this 'direct' autocatalysis has been a major focus of origin-of-life research. Regrettably, scenarios that emerge from such research require that significant evolutionary development necessarily requires events in which many independent factors have quite special properties. Such highly constrained transitions are improbable. Some cyclical chemical reaction networks are autocatalytic (the reactions continually get faster) although none of the individual reactions is autocatalytic. So long as the cycle of reactions remains closed, autocatalysis

[11] English has many collective nouns (e.g., school, herd, gaggle, mob, …) that apply to specific types of such aggregations. This paper uses the generic term swarm for all of them.

[12] The detailed nature of each of these two forces varies from species to species.

persists. Evolutionary development in such cases is less highly constrained than it is in cycles involving direct (e.g., template) autocatalysis.

The main features of biological metabolism[13] are common to all forms of life. The *citric acid cycle* (also known as the TCA cycle) is arguably the central feature of present-day chemical processing in aerobes — organisms that flourish in oxygenated environments. In the TCA cycle, a series of reactions (all catalyzed by specific protein catalysts) change the citric acid molecule (which contains six carbon atoms) into the oxaloacetic acid molecule (which contains only four carbon atoms) while also producing low-energy (unreactive) carbon dioxide and high-energy (reactive) adenosine triphosphate (ATP). This set of reactions reaches closure as a reaction cycle by production of citric acid from oxaloacetic acid. The overall cyclical process converts a two-carbon acetate group into two molecules of carbon dioxide with concomitant storage of chemical energy in reactive molecules.

$$\text{Acetate} \rightarrow 2\ CO_2 + \text{energetic molecules}$$

This reaction cycle transfers the chemical energy of food into molecules that then drive other reactions necessary for life. In a few types of organisms that flourish in the absence of oxygen (anaerobes), this sequence of reactions *runs in reverse* (the rTCA cycle) — using some source of energy to convert acetate and two moles of carbon dioxide into citric acid.

Several lines of evidence show that there was little free elemental oxygen (O_2) in the atmosphere of the primitive Earth. Living organisms produced the bulk of the oxygen that is now a major component of the Earth's atmosphere. Life must have evolved at low-oxygen (anaerobic) conditions. In certain locations in the deep ocean, hot springs provide abundant thermal energy and conditions conducive to the origin of life. Herbert Morowitz (Smith 2004) recently proposed that the reversed citric acid (rTCA) cycle could have functioned spontaneously at such locations, using available energy and carbon dioxide to

[13] Metabolism is the overall name for chemical changes that occur in biological organisms.

make citric acid. The overall process would be:

$$\text{energy} + \text{citric acid} + 4\,CO_2 + 5\,H_2 \rightarrow 2\,\text{citric acid} + 3\,H_2O$$

This cycle would be autocatalytic even though none of the component reactions is autocatalytic. Molecules involved in this cycle are starting materials for synthesis of all the necessary components of biological organisms. Spontaneous self-organization of such a cyclical reactions network would be a major step toward the origin what we would recognize as biological organisms. In the rTCA network of chemical process, factors that oppose autocatalysis control the autocatalytic reaction network and achieve a dynamic balance. Once such a cyclical process establishes itself, it could continue indefinitely if conditions remain favorable.

Process Structural Realism (PSR)

Everything that is ontologically significant must be definite — but nothing persists without change:

> One all-pervasive fact, inherent in the very character of what is real, is the transition of things, the passage one to another. This passage is not a mere linear procession of discrete entities. However we fix a determinate entity, there is always a narrower determination of something which is presupposed in our first choice. Also there is always a wider determination into which our first choice fades by transition beyond itself. The general aspect of nature is that of evolutionary expansiveness. These unities, which I call events, are the emergence into actuality of something. How are we to characterize the something which thus emerges? The name 'event' given to such a unity, draws attention to the inherent transitoriness, combined with the actual unity. …. 'Value' is the word I use for the intrinsic reality of an event. … Realization therefore is in itself the attainment of value. But there is no such thing as mere value. Value is the outcome of limitation. The definite finite entity is the selected mode which is the shaping of attainment; apart from such shaping into individual matter of fact there is no attainment. The mere fusion of all that there is would be

the nonentity of indefiniteness. (Whitehead [1925] 1967 93-94)

The three examples considered (aggregation of protein molecules into virus capsids, coalescence of biological individuals into swarms, closure of chemical reactions into cycles) all concern development of persistent coherences of individuals that are capable of independent existence ("societies," in Whitehead's vocabulary). However, those aggregations also are parts of more-inclusive coherences. The virus capsid is essential to the parasitic cycle of the virus, and depends on that cycle for its own reproduction. Particular virus particles do not generally persist long, but nearly indistinguishable units have recurred for millions of years. Although no coherence can persist indefinitely without change, in favorable circumstances particular structures may recur repeatedly.

Swarms of organisms consist of free-living individuals — but swarming behavior plays important roles in the life-strategies of the constituent individual organisms — often by providing protection from predators and opportunities for mate choice. In one sense, the genes of each organism determine and control swarming behavior — but in another sense, the swarming life-strategy determines what genes the organism carries. Individuals without genes consistent with swarming would rarely reproduce.

Each of the chemical processes in a closed reaction cycle can occur independently, but that reaction can continue indefinitely only while the cycle remains closed. Furthermore, the cycle persists only so long that cycle is in a suitable environment, usually as a feature of some living organism. As Whitehead observed, every effective unit entails both narrower and wider coherences. All of these examples require a multilevel ontology, featuring several levels of ontologically significant coherence.

The first of the three examples (the virus capsid) involves an easily recognizable form of definiteness, the icosahedral shape. Concrescence (aggregation) of protein molecules into a capsid (an effective unity) results from equilibration of attractive and repulsive interactions. In aggregation of the 240-molecule HB capsid, the icosahedral form develops[14] as the capsid coalesces. In contrast, swarms of organisms retain their

[14] This does not require 241 pre-existing entities, 240 protein molecules and one

integrity for extended periods but are relatively amorphous. However, for many such aggregations, average density tends to remain constant. The form of definiteness of a swarm does not show up as a geometric shape, as it does in the virus capsid, but rather in other properties, such as constant average density. The integrity both of the swarm and of the capsid depend on balance of nonlocal attraction and local repulsion. That balance of forces is the basis of definiteness in each case; it is the "structure" required to generate effective wholeness. Continuation of that balance through time constitutes the inheritance of defining form that marks each unit as a society with personal order. The behavior of individuals in swarms differs from the behavior of similar individuals outside those aggregations. The causal impact of the composite unit differs significantly from the mere sum of behaviors of a like number of individuals of the same type but absent the swarming interaction. Causal powers of swarms, when interacting with appropriate test entities, are non-redundant. (Earley 2003b, 2003c).

When a group of reactions achieves such closure that a set of states of affairs recurs continually (as in the hypothetical pre-biotic rTCA cycle) average values of each concentration differ from what would occur in the absence of that closure.[15] Such alteration of concentrations is an attribute of the system as a whole, and would have consequences. This indicates that the reaction network, as a unit, fulfills the extended

icosahedral "universal" (perhaps from some Platonic storehouse). On the basis of instance ontology characteristic of 'moderate realism' (Mertz 1991) what exist in this case are multiple disaggregated protein molecules (in the initial state) and individual aggregated icosahedral capsids (in the final state).

15 There is a major difference between the types of coherences exemplified by the virus capsid on the one hand, and by swarms and reaction cycles on the other hand. The hepatitis B virus capsid could persist indefinitely when cut off from interaction with the rest of the world – it is an "equilibrium structure". Neither swarms of organisms nor cycles of chemical reactions — "dissipative structures" (Kondepudi 1998)— could so persist. Such open-system dynamic coherences require connection with the rest of the world in order to exist.

Eleatic principle, and has ontological significance. Whenever a reaction network generates continual return to a limited set of concentration conditions, the reaction system may function as a 'whole'. Virus capsids and swarms of organisms result from balance of attractive and repulsive forces: reaction cycles result from a balance of factors that favor autocatalysis and those that decrease autocatalysis. (Earley 2000, 2003a) As in the other cases, that balance provides the form of definiteness of the cycle. For a society constituted by a closed cycle of reactions, each circuit of the cyclical path constitutes one actual occasion.[16] In homogeneous media, the cycle of reactions would not involve spatial structure.[17]

In one sense, the causal powers of each of the three aggregates considered here are indeed just the powers of the constituents "acting in concert" (Merricks 2001). Ontologically significant non-redundancy arises from the fact that the components act in concert *only because of* their inclusion in the coherence. In all three examples, the form of definiteness that provides the internal coherence (a cosmological aspect) also grounds the external efficacy (epistemological aspect) of the societal aggregation. This is a *structural* feature of each coherence — possibly, but not necessarily, apparent in spatial structuring.

Whitehead vigorously attacked the notion that basic entities have "simple location" – unique, precise, and unambiguous situations in what we now call four-dimensional space-time (Whitehead [1925] 1967 passim). Taking this attack seriously implies recognition that the idea that actual occasions have no temporal duration is a high abstraction (Earley 1995). Early interpreters may or may not have been correct in their conclusion that Whitehead himself intended to hold that the "final real things" are all submicroscopic. Whether or not Whitehead held it, the doctrine a submicroscopic level of unique significance is quite inconsistent with the science of the twenty-first century. We now recognize that what is fundamental is achievement of effective coherence. The level of

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[16] Inquiry as to a specific beginning or end of such a cycle would be misplaced concreteness of high order (Earley 1993).

[17] If diffusion were important, spatial structure could result.

size on which that achievement occurs may have little importance.

Combinations of molecules, of biological individuals, or of chemical processes can produce effects that are not simply attributable to the constituents. Such non-redundant causality warrants recognition of those coherences as ontologically significant whenever that efficacy is relevant.[18] With respect to such interaction, the effective coherence is *more real* than are the components. This ontological view is, I submit, a variety of structural realism and is also a kind of process philosophy. The designation 'process structural realism' (PSR) seems appropriate.

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[18] In all cases, whether or not a specific coherence is ontologically significant depends on the detailed characteristics of entities with which that coherence interacts (Earley 2003c).

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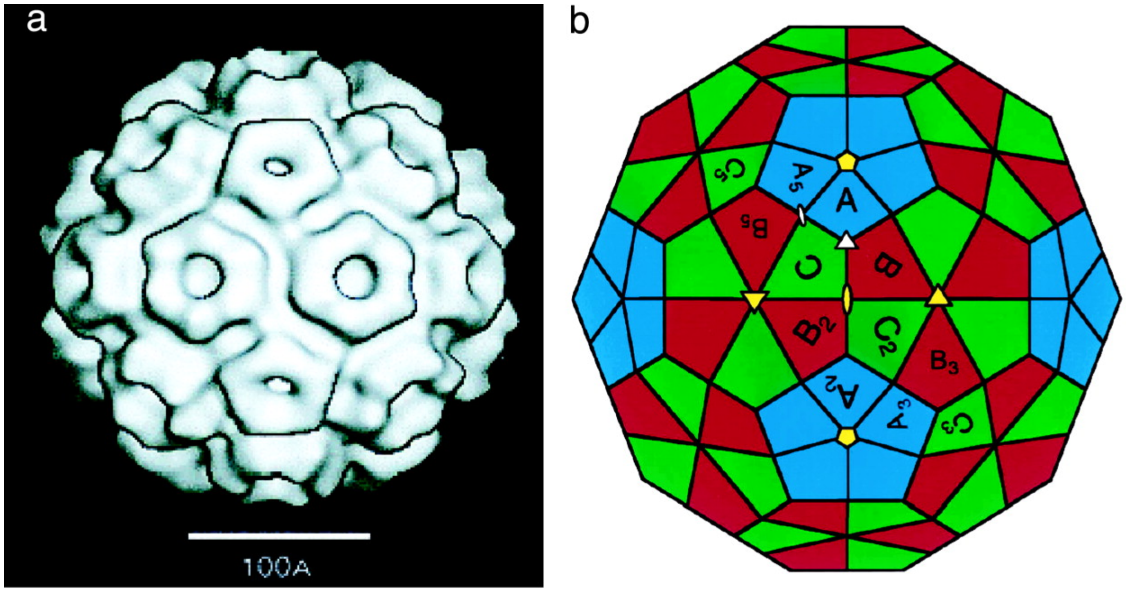

Fig. 1. Icosahedral symmetry of a viral capsid. (*a*) Reconstruction of CCMV. (*b*) Arrangement of subunits on a truncated icosahedron; A, B, and C denote three symmetry-nonequivalent sites. [Reproduced with permission from Fox 1998. (Copyright 1998, Elsevier)].

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