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The Architecture of the Life Cycle in Small Organisms

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The architecture of the life cycle in small organisms

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SUMMARY

The life cycle of eukaryotes has a dual nature, composed of a vegetative cycle of growth and reproduction, and a sexual cycle of fusion and reduction, linked by the spore. Large size is often favoured through interactions with other organisms, or as a means of exploiting locally or temporarily abundant resources, despite the metabolic penalty of size increase. Beyond a certain point, large organisms must be multicellular (or multinucleate) because of the requirement for more deoxyribonucleic acid (DNA) to service larger quantities of cytoplasm. Multicellularity evolves in some lineages but not in others because its evolution is constrained by the pattern of spore development, being favoured, for example, by the occurrence of multiple fission as the consequence of possessing a rigid cell wall. The separation of soma from germ is also the outcome of a developmental constraint, in this case the inability of cells to divide while flagellated, and also the necessity of remaining in motion. Once achieved, a general physiological advantage is realized through the specialization of soma as source and germ as sink. Large, complex multicellular organisms are fragile constructs that can only persist through deploying sophisticated devices for maintenance. Thus two crucial, and related, properties of life cycles are repair and repeatability. The dual life cycle achieves exogenous repair through spore production in the vegetative cycle and through outcrossing and recombination in the sexual cycle. Repeatability is enhanced by developmental mechanisms such as maternal control and germ-line sequestration, which by restricting the occurrence or the heritability of somatic mutations promote their own replication.

1. INTRODUCTION

(*a*) *Dual nature of the life cycle*

All organisms pass through a more or less stereotyped sequence of changes before returning to some initial state. This process is called the life cycle, to emphasize its cyclical, or repetitive, nature. The concept is closely related to those of the life history, development and ontogeny, but differs from them in stressing renewal. It expresses the wonder with which people have observed that old organisms give birth to young organisms, and continue to do so, generation after generation, apparently without limit.

Figure 1 shows a general representation of the life cycle, omitting many of the features of individual cases, but showing the relation between the most important processes. Our interpretation is based on two concepts. The first is the central position of the simple spore cycle: a unicellular spore which grows in size before dividing into two similar spores. Many protists actually possess such a cycle, but it can also be used to imagine what modifications are involved in producing more elaborate life cycles. The second is the dual nature of the life cycle, which we have divided into a vegetative cycle and a sexual cycle. The vegetative cycle involves growth and reproduction, and is responsible for change in the quantity of substance. The sexual cycle involves fusion and reconstitution, and produces change in quality. The two cycles are linked by the spore, which can be switched into either vegetative or sexual expression, knitting together the two cycles into a single life cycle. No aspect of the biology of life cycles is more striking than the fact that vegetative proliferation is very seldom, if ever, the sole mode of reproduction, the lineage instead being reduced at more or less frequent intervals to a single cell, whether produced sexually or asexually. One explanation of this remarkable pattern is that large mass of tissue will inevitably bear, in different cells, a variety of somatic mutations, which, as they cannot be eliminated, must continue to accumulate generation after generation. By producing many independent germ cells an individual ensures that any which bear somatic mutations are likely to be eliminated by selection. Adaptations of this sort, in which parental fitness is enhanced by competition among many cheap offspring, have been called 'selection arenas' by Kozlowski & Stearns

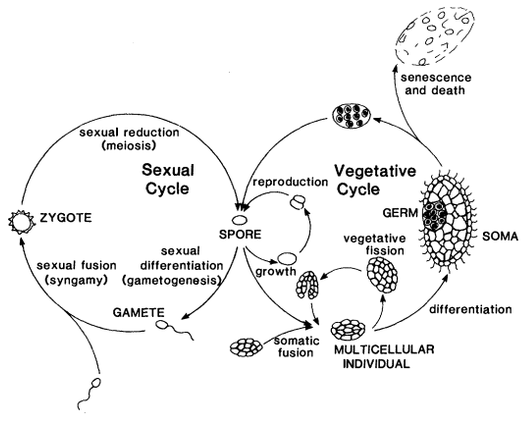

Figure 1. The life cycle.

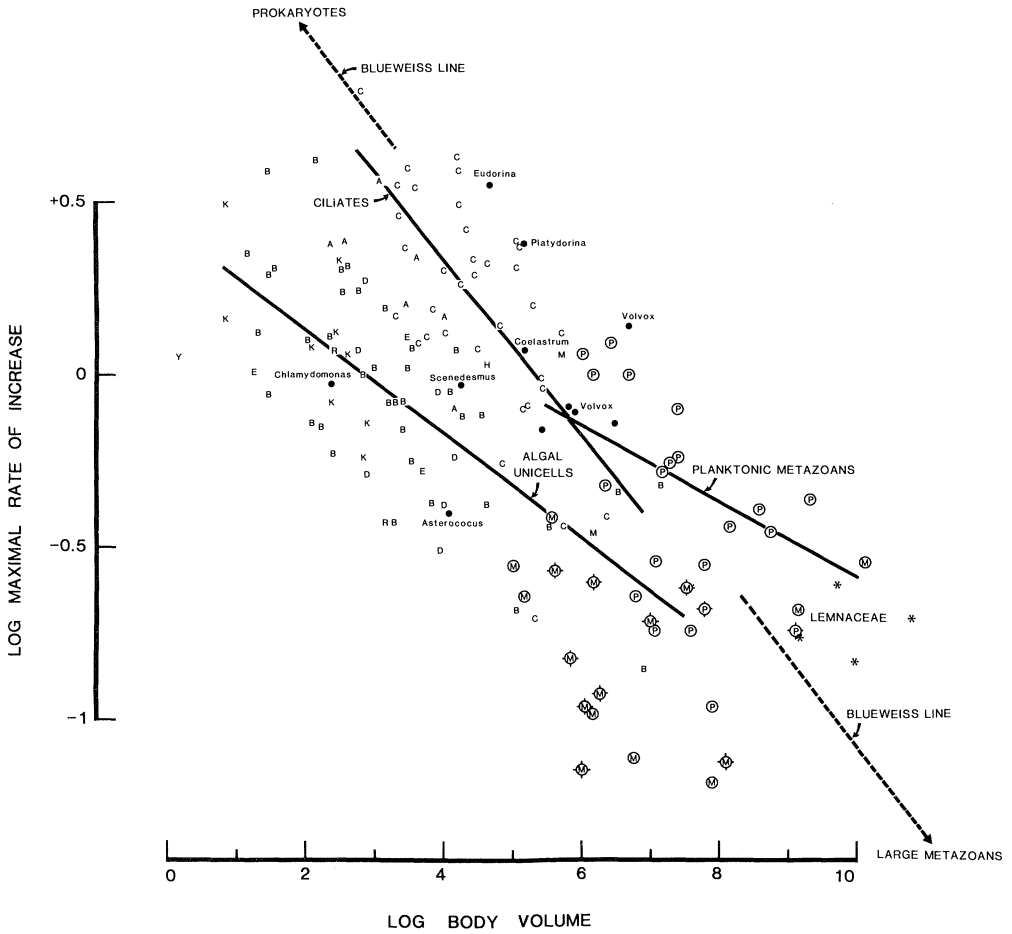

Figure 2. The relation between the limiting rate of increase r_{max} and body size among small organisms. The different taxa shown are: A, amoebas; B, Bacillariophyceae (diatoms); C, ciliates; D, Pyrrhophyceae; E, euglenids; H, Heliozoa; K, Chlorophyceae; M, benthic metazoans; P, planktonic metazoans; R, Cryptophyceae; Y, Myxophyceae. Metazoans are distinguished by a circle surrounding the letter; when the circle is pecked the organism is exclusively sexual, and r_{max} should be multiplied by two (add 0.3 on the log scale of the graph) to obtain values comparable with the remaining, asexual organisms. Solid lines are least-squares regressions for planktonic metazoans (P), ciliates (C) and algal unicells (B, D, E, K). The broken line is the regression obtained by Blueweiss *et al.* (1978), by using a smaller number of species over a wider size range. From Bell (1985).

(1989). A related idea is that somatic tissues become infected with pathogens, such as viruses, of which the lineage can be cleansed only through the production of numerous unicellular propagules, some of which will be uninfected. The notion that the life cycle facilitates exogenous repair by exposing offspring to natural selection will be developed in more detail below.

In this paper we have attempted to interpret the major features of life cycles shown in figure 1, by reference to small and simple organisms. The discussion is based on work done in our own laboratory on ciliates, *Chlamydomonas*, and multicellular green algae; it is not intended to be a review of protistan life cycles. Most of the theoretical issues that we address have been dealt with more extensively in recent books by Buss (1987), Bell (1989) and Bonner (1990).

2. THE VEGETATIVE CYCLE

(*a*) *Selection for small size*

The simplest life cycle comprises growth from initial size m to final size M, followed by complete fission into M/m propagules. The optimal values of m and M depend on the relation of fitness to size. If the environment is uniform and invariant, and if there are no interactions among individuals, then fitness can be equated with the rate of increase r in pure culture. This may take any value, depending on the physical conditions of culture; however, the maximum value of r which can be attained under nearly ideal conditions in the laboratory, r_{max}, is greatest for small organisms and declines with increasing size (Blueweiss *et al.* 1978). This generalization seems to hold at all scales; figure 2 shows the decline in rates of increase with size among small protists and metazoans. The optimal form of this cycle is thus to make m as small as possible, to grow to $M = 2m$, and then to divide by an equal binary fission. This is a common, but by no means a universal, pattern among prokaryotes and small unicellular eukaryotes.

The source of the disadvantage of increasing size seems to be related primarily to the smaller ratio of surface area to volume in larger cells, and thus to the lower specific rates of movement of materials and energy across surfaces. It is therefore rather surprising

that eukaryotic unicells are not always as small as possible, and do not always reproduce by binary fission. This introduces three questions that are fundamental to understanding the elaboration of the asexual cycle. First, what are the benefits of greater size that would cause it to be favoured by selection? Secondly, how are large organisms constructed so as to minimize the ineluctable penalty of size increase? And thirdly, why does large size evolve in some lineages and not in others?

(*b*) *Evolution of large size*

The benefits of large size and multiple fission arise from the failure of the assumptions that lead us to infer that small size is generally advantageous.

The environment may vary in space. If some sites are better than others then it will pay to exploit a favourable site by prolonged growth before producing dispersive propagules. Algal mats in sunny shallows and parasites that have found hosts are very familiar examples of this tendency. We have a strong although unquantified impression that continued growth and multiple fission are much more common among benthic, attached and parasitic protists than among free-living planktonic forms. Ciliates provide a good example of a group in which freeswimming forms are invariably unicellular whereas attached forms often develop into large colonies. Environmental heterogeneity provides a simple explanation of such patterns.

The environment may vary in time. If resources are often scarce, larger organisms will take longer to starve to death. This is simply the inverse of the argument that smaller organisms have higher specific metabolic rates. It is the foundation of the 'size-efficiency' hypothesis (Brooks & Dodson 1965), which states that larger organisms of given form have lower threshold concentrations of food for growth and reproduction.

Interactions among organisms are ubiquitous, and larger organisms may generally prevail in antagonistic interactions. It is obvious enough that larger organisms can eat smaller ones, and are themselves less likely to be eaten.

Spatial heterogeneity, temporal variation and antagonistic interaction provide three general theories of size increase. Whether or not such processes create a net benefit for increased size in some particular case will further depend on the structure of the organism concerned. Pre-existing design thus represents a further constraint on the evolution of large size. An example is the evolution of motile multicellular forms among walled but not among naked green algae, which is discussed at greater length below.

(*c*) *Body form of large organisms*

Starting from a small, essentially point-like unicell, larger organisms can be constructed in one of three ways. Extension in one dimension produces a filament, as in fungi and filamentous algae. This design maximizes contact with the local environment and is thus specialized for absorption. Extension in two dimensions produces a sheet, as in macroalgae, bryophytes and tracheophytes. This design maximizes the interception of fluxes, typically of light. Not all plants are simple sheets, but their assimilatory organs, such as leaves, are usually sheet-like, or else their structure or behaviour are modified so as to create an essentially two-dimensional form, such as the spiral chloroplast of gamophytes, or the rotation of large motile algae. Extension in three dimensions produces a massive body, as in ciliates and animals. This design permits the enclosure of other organisms and is thus specialized for ingestion.

(*d*) *Internal structure and the nucleoplasmic ratio*

All of these body plans incur the penalty of decreased specific rates of metabolism, although this will be least for filaments and greatest for massive bodies. In particular, a cell that is maintaining and increasing a large bulk of cytoplasm requires high rates of protein synthesis, which in turn requires large quantities of RNA and DNA. Because greater quantities of DNA are replicated more slowly, there is a tension between the demands of growth and those of reproduction.

The design of large cells and organisms is thus strongly influenced by the need to replicate large quantities of DNA as rapidly as possible. The simplest solution is polyploidy, as in large amoebas. This seems to be associated with low rates of replication: polyploid amoebas divide more slowly than other unicells of comparable size, perhaps because the nuclear surface area increases less rapidly than nuclear mass. A second solution is to become multinucleate. This is very common among large protists such as amoebas, ciliates and foraminiferans, and also occurs in fungi, and even in metazoans such as orthonectids. Without further refinement, however, the multinucleate habit makes it difficult to synchronize nuclear and cell division, and, more fundamentally, introduces the possibility of reproductive competition among nuclei that may result in the spread of selfish nuclei to the detriment of organismal function (Buss 1987). A final solution is to become multicellular. This can be achieved either by the failure of cells to separate after division, as in most multicellular algae, plants or animals, or by the reaggregation of separate cells, as in cellular slime moulds, sponge gemmules, or the capsular embryos of some turbellarians. A body comprising many similar quasi-autonomous cells is successful for the same reason that cells containing many similar quasi-autonomous organelles such as mitochondria are successful: the design ensures that each volume of cytoplasm is effectively served by a nearby centre of metabolism.

(*e*) *The division of labour within large organisms*

Multinucleate and multicellular organisms often further reduce the penalties of large size by a cooperative division of labour among dissimilar structures.

Large unicells must reconcile conflicting requirements for a large genome to support vegetative metabolism and a small genome to allow rapid replication. Most ciliates and forams have achieved this

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through the separation of somatic and germinal functions between macronucleus and micronucleus. The ciliate macronucleus is typically a large, highly polyploid nucleus capable of sustaining vegetative metabolism and dividing rapidly but imprecisely by amitosis. In large ciliates the macronucleus is often elaborately shaped so as to increase the surface area in contact with the cytoplasm. The micronucleus is a smaller diploid nucleus which does not participate in vegetative metabolism but is replicated with great precision by a regular mitosis. This division of labour between somatic and germinal nuclei explains why ciliates are able to sustain high rates of increase despite their large size (see figure 2).

In multicellular organisms, labour is divided among cells, the fundamental distinction again lying between somatic and germinal functions. The relation between soma and germ is the subject of the next section.

3. THE VEGETATIVE CYCLE IN THE VOLVOCALES

(*a*) *The evolution of motile multicellular algae*

The quantitative relations between soma and germ are best known in the Volvocales, a group of flagellated green algae which spans the entire range from unicells to differentiated multicellular individuals. The material on which the following sections are based is described more fully by Bell (1985) and Koufopanou (1991).

The volume of motile green unicells ranges over three orders of magnitude, from about 10^1 to about 10^4 μm^3. Larger forms are colonial, and extend the size range up to about 10^6–10^7 μm^3 in algae comprising several thousand cells. For comparison, the largest immotile green unicells, the desmids, have volumes of up to 10^7 μm^3, whereas large attached forms such as *Ulva* have protoplast volumes of roughly 10^{13} μm^3; motile forms are thus relatively small. The multicellular habit has arisen at least six times in the Volvocales. The simplest colonies, found in Dunaliellaceae and Polyblepharidaceae, are loose aggregations of an indeterminate number of cells; such colonies reproduce by fragmentation, subsequently increasing in bulk through the binary fission of each of their members. Being associated with other cells in a colony probably offers some protection against filter-feeders such as rotifers. The more profound shift in design to regular multicellular individuals ('coenobia') is associated with the presence of a cell wall. Naked and scaly unicells invariably reproduce by binary fission and form loose colonies that reproduce by fragmentation. Unicells that have a rigid cell wall (such as *Chlamydomonas*) form 2–16 spores, which are liberated when the parental cell wall breaks down. Multiple fission presumably represents an economy of scale associated with the fixed overhead cost of discarding the cell wall. Colonies of such forms comprise a fixed number of cells arranged in a characteristic manner, and each cell in the colony divides so as to create the appropriate number of cells, constituting a miniature colony after which liberation enlarges by the equal growth of all its cells ('autocolony formation'). The evolution of regular multicellular individuals is thus contingent on the prior possession of a particular mode of development ('eleutheroschisis') involving repeated division within a rigid cell wall.

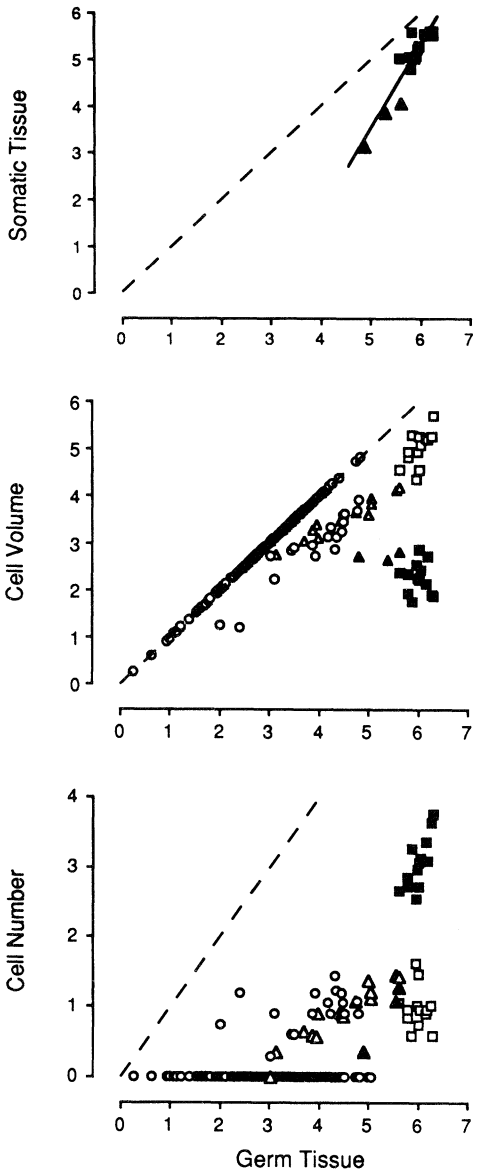

Figure 3. The quantitative relation between somatic and germinal tissue in flagellated green algae. From Koufopanou (1991). Solid symbols represent soma (triangles, *Pleodorina*; squares, *Volvox*) and open symbols germ tissue (circles, unicells and non-Volvocacean colonies; triangles, Volvocaceae except *Volvox*; squares, *Volvox*).

Colonies of this sort comprise 4–64 identical cells, arranged as a plate, ball or hollow sphere, and usually embedded in a common matrix. Among unicells, there is a steep regression of daughter cell volume on parental cell volume: larger forms divide to give larger daughters. Among coenobia there is no relation between the sizes of daughter and parental cells: larger colonies develop because larger parents undergo more divisions to form more daughters and thus a coenobium with more cells (figure 3). The evolution of larger multicellular individuals among the Volvocales thus proceeds by heterochronic shifts in the timing of the initiation of cell division.

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(*b*) *Soma and the flagellation constraint*

In coenobia with 64–128 cells, in *Eudorina* and more distinctly in *Pleodorina*, there first appears a distinction between two cell lineages, a sterile soma and a fertile germ. The soma is first manifested as a tier of small anterior cells, and is thus associated with directional movement, in a manner reminiscent of metazoan amphiblastulae. The emergence of a separate caste of sterile cells appears to follow from a constraint on flagellation, as suggested by Buss (1987; see also Margulis & Sagan 1986). Naked green unicells retain the parental flagella during cell division, and so remain motile throughout their life cycle. Walled unicells, however, must discard their flagellum when dividing, being constrained mechanically by the presence of the cell wall and physiologically by possessing only a single centre of developmental activity, responsible both for cell division and for flagellation. Volvocacean colonies follow the same mode of development as their ancestral walled unicells: the basal bodies move away from the flagellar bases during cell division, and the flagella would consequently be unable to keep the large colonies from sinking during the long period of their development.

In larger forms such as *Volvox*, with many hundreds or thousands of cells, the distinction between soma and germ becomes steadily more exaggerated. The evolution of such forms does not proceed by heterochrony, but by shifts in the allocation to soma and germ caused by unequal cell divisions during development (see Kirk & Harper 1986).

(*c*) *Soma and germ as source and sink*

The separation of soma from germ realizes an important physiological advantage, which is shown by the fact that large coenobia have a greater maximal rate of increase than do unicells of comparable size (figure 2). Bell (1985) has suggested that the cause of this advantage is the specialization of the soma as a source and the germ as a sink of metabolites. The rate of chemical reactions, including photosynthesis, is generally reduced by the accumulation of end-products. In unicells, the intracellular concentration of products such as starch is reduced by their localization in structures such as the pyrenoid. Differentiated multicellular individuals can go further by translocating substances from the somatic cells in which they are produced to the germ cells where they will be used for reproduction and embryogenesis. In this way the rate of synthesis is increased by steepening the concentration gradient between the external medium and the cytoplasm of the soma. We have attempted to test this theory by the following experiment, which is described in more detail by Koufopanou & Bell (1991*a*).

The asexual germ cells, or gonidia, of *Volvox* will develop normally if isolated from the parental coenobium and cultured in an appropriate medium. We can make three predictions about the effect of the culture medium on the rate of growth of gonidia. First, if growth is limited by the supply of nutrients then the rate of growth, both of isolated gonidia and of those within intact parental coenobia, will increase with the concentration of the medium. Secondly, if the soma supplies resources to the developing gonidia, then those in intact coenobia will grow more rapidly than those which are cultured as isolated cells. Finally, if the source-and-sink hypothesis is correct, then the difference in growth rate between isolated gonidia and those in intact coenobia will be least at low nutrient concentrations, where feedback inhibition will be minimal, and greatest at high nutrient concentrations, where the advantage of a differentiated body should be expressed most clearly. The result of the experiment was consistent with all three predictions. In more natural circumstances, the eutrophication of ponds is associated with an increase in the frequency of colonial forms (Koufopanou & Bell 1991*a*).

The evolution of multicellularity in the Volvocales thus illustrates the interplay between general adaptive trends and specific developmental constraints. Multicellularity evolves readily because the possession of a rigid cell wall favours multiple fission, which permits the reproduction of regular multicellular individuals by autocolony formation. Large coenobia must remain motile while dividing, but because they possess only a single microtubule-organizing centre can do so only by setting aside a lineage of sterile flagellated somatic cells. The specialization of somatic cells as source and of germ cells as sink realizes an important physiological advantage in some ecological conditions, explaining why differentiated coenobia can reproduce faster than unicells of comparable size.

(*d*) *The allometry of soma and germ*

The quantitative relation between soma and germ is shown in figure 3. The total quantity of somatic tissue rises steeply with the quantity of germ. This may set an upper limit to the size of organisms with this body-plan, and the figure seems to show why forms larger than *Volvox* have not evolved. Larger colonies have more soma and more germ, but the two tissues increase in quite different ways: the increase in the quantity of germ tissue is caused by the greater size of a more or less constant number of germ cells, while the increase in somatic tissue is due to a greater number of smaller cells. This is how the exaggerated division of labour among cells in the larger Volvocales is produced.

The relation between the number and size of gonidia is complex (figure 4). Among undifferentiated forms arising through heterochrony, larger colonies have more and larger cells, all of which are reproductive. Overall size increase thus creates positive correlation between the number and size of germ cells. Among differentiated forms evolving by shifts in allocation, the correlation between the number and size of gonidia is negative, implying a fixed upper limit to the quantity of germ tissue. The tendency for overall size increase to generate positive covariance among fitness components while shifts in the allocation of a fixed quantity of material generate negative covariance is a central principle in the quantitative theory of life histories (Bell & Koufopanou 1986).

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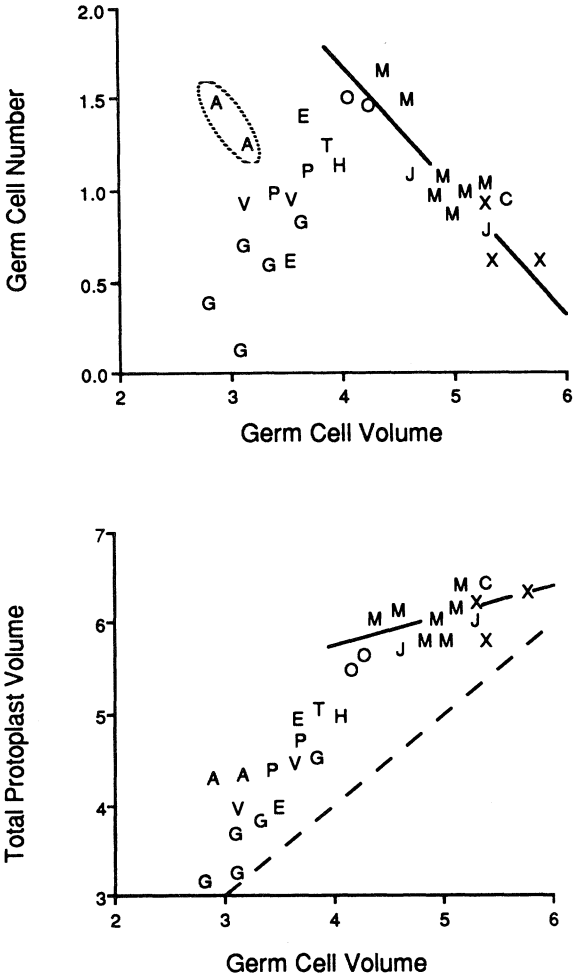

Figure 4. The number and size of germ cells in volvocacean algae of different overall size and degree of differentiation. Letters indicate taxa: A, *Astrephomene*; G, *Gonium*; T, *Platydorina*; V, *Volvulina*; P, *Pandorina*; E, *Eudorina*; P, *Pleodorina*; M, *Volvox*, sect. Merillosphaera; J, *Volvox*, sect. Janetosphaera; C *Volvox*, sect. Copelandosphaera; X *Volvox*, sect. *Euvolvox*. From Koufopanou (1991).

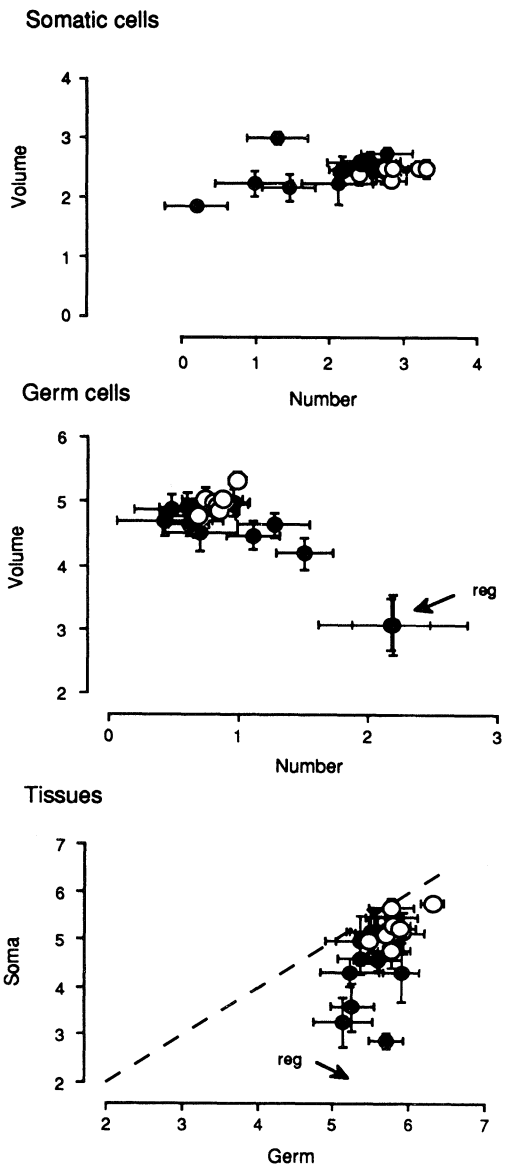

Figure 5. The number and size of cells among mutants of *Volvox carteri*. Wild-type strains are shown as open circles and mutant strains as solid circles; 'reg' is the Regenerator mutant described by Kirk & Harper (1986), in which somatic cells regenerate as gonidia. The bars are ± 2 standard errors. From Koufopanou & Bell (1991).

(*e*) *Developmental mutants of* Volvox

The developmental genetics of *Volvox carteri* are relatively well known and provide an opportunity of looking more closely at the relation between soma and germ. It is possible that somatic differentiation and even multicellularity can be abolished through lesions in only three genes, or closely linked groups of genes (Kirk & Harper 1986). This need not imply that the evolution of differentiated multicellular individuals from unicells requires only three genes, but does make it feasible to obtain by mutation a range of forms which span that found in all the rest of the Volvocales.

We measured the numbers and sizes of cells in a series of such developmental mutants (Koufopanou & Bell 1991*b*). As expected, the mean values of characters thought to enhance fitness, such as the numbers and sizes of cells, are lower among mutants than among wild-type strains. The total quantity of soma increases steeply with the total quantity of germ, as it does among species; it comprises a highly variable number of cells of rather uniform size. There is a striking negative correlation between the number and size of germ cells, attributable largely to a class of mutants in which somatic cells are able to redifferentiate as gonidia. This again recalls the pattern shown by different species.

The allometry of tissues among species of the Volvocaceae and among mutants of the single species *Volvox carteri* is shown more explicitly in figure 5. The total quantity of somatic tissue varies widely among the mutants, with no relation between the number and size of somatic cells. The negative correlation between number and size found among species might therefore reasonably be attributed to selection. One possible selective agent is the requirement for large numbers of flagella to keep big colonies in motion. The negative correlation between the number and size of germ cells among mutants parallels the pattern among species, suggesting a constraint on the total quantity of germ

tissue. The correlation found among species could thus be produced by mutation without the intervention of selection.

4. THE SEXUAL CYCLE

(*a*) *Origins of sexuality*

Sexual cycles in protists are exceedingly diverse; although unfortunately no recent review of the whole group is available. Some large taxa appear to lack sex altogether. Since sex is facultative in most (if not all) protists, it may be that the environmental conditions that induce sex have not yet been discovered in the less well-studied groups. Nevertheless, some very well-studied taxa, such as the euglenids, seem genuinely to lack any conventional sexual process.

A quantitative comparative account of the sexual cycle of Volvocales, complementing the account of the asexual cycle given above, was published by Bell (1985). The discussion here is restricted to experiments with ciliates which emphasize the importance of exogeneous repair in the evolution of the sexual cycle.

(*b*) *Sex and death in ciliates*

The fission-rate of isolate lines of ciliates, maintained as far as possible by single-cell descent, generally declines through time, until the lines eventually become extinct. A sexual episode reverses the decline and restores the previous level of vigour. This phenomenon has recently been discussed at length by Bell (1989). It is thought to be caused by the irreversible accumulation of slightly deleterious mutations at many different loci in asexual lineages (Muller 1964). The ciliate macronucleus is typically highly polyploid and divides amitotically. If a mutation occurs in one of the n copies of a gene, $\frac{1}{n}$ of the descendant macronuclei will bear only the mutant allele, as a result of somatic assortment, and cannot thereafter recover their original non-mutated state. Continued amitosis therefore leads to a monotonic increase in mutational load, causing a steady decline in performance. This can be reversed by the dissolution of the old macronucleus and the formation of a new structure specified by the mitotically replicated micronucleus. However, because the micronuclear genome is not expressed vegetatively, micronuclear mutations are essentially neutral, and will accumulate rapidly, even though they are deleterious when expressed as macromolecular genes. The micronuclear genome can be cleansed of such mutations only by outcrossing followed by recombination. This creates variance in the load of mutations among sexual products and thus enables many deleterious mutations to be eliminated at once through the death of cells bearing heavily loaded genomes, allowing unloaded or lightly loaded genomes to persist, and preventing the irreversible accumulation of mutational damage. The fate of isolate lines of ciliates provides convincing evidence both for the necessity and for the effectiveness of sex as an exogenous repair device. Experimental work has been confined almost exclusively to ciliates, although there is some evidence for similar phenomena in other protists, and even in asexual metazoans.

(*c*) *Sex and natural environments*

The most plausible accounts of short-term selection for the maintenance of sexuality involve the concept that the environment as perceived by the organism continually deteriorates, either through the accumulation of mutations, or through the adaptation of antagonistic organisms, necessitating a continual evolutionary response through sexual outcrossing and meiotic recombination (Jaenike 1978; Hamilton 1980). There is as yet no convincing direct evidence for this theory, although it is consistent with the major ecological correlates of sexuality (Bell 1982), and with the observation that biological control is often more effective against asexual than against sexual pests (Burdon 1987). There is no relevant work on protists. However, it is a commonplace observation that sex is induced by unfavourable conditions of culture. The routine technique for crossing *Chlamydomonas* involves transferring cultures to nitrogen-free medium, which causes the cells to differentiate as gametes and fuse with compatible partners. It would be interesting to know the range of stresses effective in inducing sexuality; whether auxotrophic mutants can be induced sexually by genotype-specific stresses; and whether the rate of recombination as well as the occurrence of sexuality can be environmentally induced. Elucidating the relation of sex and recombination to host–pathogen coevolution awaits the development of a model system using a protistan host.

5. GENERAL DISCUSSION: REPAIR AND REPEATABILITY

A central place in the life cycle is occupied by that single cell or nucleus, which goes by many names in different groups of organisms, but which we have called the spore. Most major taxa of multicellular organisms – the main exceptions are metazoans such as rotifers, nematodes and insects – can reproduce without spores, forming new individuals from large masses of parental tissue by budding or fragmentation. Offspring that are produced vegetatively in this way will inevitably bear a load of somatic mutations. These are transmitted in a non-Mendelian fashion, with some progeny receiving by chance more mutant cells and others fewer, and will therefore show somatic assortment. Any given lineage will therefore tend to become fixed for a succession of somatic mutations. The particular loci that are affected will be different in different lineages, but all will acquire a gradually increasing load of somatic mutations. The process is irreversible because once all cells bear a mutation at a given locus, the original state of the locus cannot be recovered. Using very many cells to form new individuals offers no protection: the assortment of previously acquired mutations will be slowed down, but a greater number of new mutations will arise. Selection will oppose the accumulation of somatic mutations by eliminating heavily loaded individuals, but it will not be very effective because it can act only through the variation among individuals in the mean

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number of mutations per cell. Lineages which proliferate vegetatively will in the course of time reproduce more slowly, show a greater incidence and frequency of congenital abnormalities of development, and at last become extinct.

This argument introduces the concept of repair, and in particular exogenous repair, as a central organizing principle of life cycles. Exogenous repair is the appropriate exposure of propagules to natural selection. It is related to the concept of 'selection arenas' (Kozlowski & Stearns 1989). Here, we suggest that the spore is an instrument of exogenous repair. When spores are produced, each cell is independently exposed to the action of selection. Genetic variance for effects caused by somatic mutations will be greater among spores than among offspring produced by budding or fission, because the variance of items is greater than the variance of means, and spore production therefore enhances the effect of selection in reducing mutational load. Spores will nevertheless bear a certain number of new mutations, which will increase with the length of time or the number of replications separating spore from spore. Several authors have reported that asexual lineages propagated exclusively through the late offspring of old parents tend to deteriorate and eventually become extinct, whereas those propagated through the early offspring of young mothers flourish (the 'Lansing effect', discussed by Bell (1989), pp. 93–95), and such results, although they remain controversial, may reflect the greater mutational load of older spores. More generally, the details of spore production may be arranged so as to minimize mutational damage. In some organisms the germ line is sequestered early in development and so passes through relatively few replications. This should reduce the necessity for exogenous repair. Consequently, we are led to predict that the overproduction of asexual spores should be greatest among organisms which develop by somatic embryogenesis (multicellular fungi, plants, sponges and a few metazoan phyla), less in organisms with epigenetic development (some molluscs, annelids and echinoderms), and least in organisms with preformistic development (such as gastrotrichs, rotifers, nematodes, tardigrades and vertebrates).

The spore is not the only state to which most or all vegetative cycles are regularly reduced; it is also the switch-point between the vegetative and sexual cycles. What controls this switch? The unequivocal answer is that spores are switched into the sexual cycle when the environment deteriorates, by nutrient depletion, crowding or starvation. The vegetative cycle is the means by which the spore takes advantage of temporarily or locally favourable conditions to grow and reproduce; the sexual cycle is the response of the spore to the eventual failure of these conditions. The reason for being so confident about this statement is that making the environment worse is the routine laboratory procedure for switching spores from vegetative to sexual expression in a very wide variety of protists and other organisms. In a very broad sense, then, the sexual cycle is also a repair mechanism, whose primary function is to overcome the failure of vegetative expression. The sense is so broad, however, that the statement has little substance unless the meaning of 'environment' is made more explicit.

The environment as perceived by an organism might be said to deteriorate in either of two ways. First, the external conditions of growth might change so that current genotypes are poorly adapted, in the sense that fitness would be increased by the appropriate genetic changes. We have already argued that the only way in which the external environment can be expected consistently and continually to deteriorate is through the evolution of antagonistic species. By becoming well-adapted to antagonists, a species causes environmental stress through the selection that it imposes on its antagonists for counter-adaptation, thereby ensuring that further genetic change will be required in the future to maintain adaptation. In some cases, such as the immune system of vertebrates or the antigenic surface proteins of trypanosomes, this change can be achieved endogenously. For the most part, however, it seems possible that some exogenous mechanism such as sexuality is necessary to break up and rearrange currently well-adapted genotypes before they fall victim to their own success. Secondly, if the external conditions of growth were to remain unchanged, organisms might nevertheless perceive them as having got worse if they have received genetic damage such as mutation. Although the production of asexual spores reduces mutational load by exposing individual genotypes to selection, it cannot entirely prevent the irreversible accumulation of deleterious mutations. The sexual cycle arrests this accumulation by generating non-mutant genotypes from mutant gametes through meiotic recombination. For the purposes of this essay, we have drastically simplified the diversity of opinions regarding the effect of sex on adaptation, opinions which are discussed at greater length by Williams (1975), Maynard Smith (1978), Bell (1982, 1989), Hamilton (1980), Kondrashov (1984), and many others. Our main point is that the primary function of the sexual cycle may be to maintain adaptation despite the fact that the external environment or the genotype's ability to deal with the environment are tending continually to deteriorate, and that in this sense it acts as a mechanism of exogenous repair.

The success of the quantitative theory of life histories makes it natural to think that the same principles will be equally successful in the interpretation of life cycles, and in particular to think that the most successful life cycles will be those which have the greatest fitness, in the conventional sense of generating the greatest rate of producing offspring. However, this is not necessarily the case. Life cycles that displace alternative cycles may do so, not only because they are more prolific, but also because they are more precisely repeatable. A theory of this sort has been strongly advocated by Buss (1987), but its intellectual precursors also include C. H. Waddington's concept of epigenetic canalization (Waddington 1957) and R. Dawkins' general theory of replicators (Dawkins 1985). Consider two genes which direct the same sequence of development, leading to the same allocation to germ cells and the same

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reproductive output; but while one gene invariably directs this life cycle, the other produces the same result only as an average, the actual course of development varying more or less widely among individuals. The former gene is thus associated with a more stable and highly canalized life cycle, and if this life cycle is nearly optimal then its lack of variability will be advantageous. Nevertheless, individuals bearing the latter gene, although their phenotypes may be far from optimal, will produce offspring that will again express the optimal phenotype as an average. Instability of development has more profound consequences when the phenotype of offspring is related to the phenotype of their parent. Any variation in the sequence of development will then increase through time, obliterating the initial sequence completely. If all life cycles were, in a conventional sense, neutral, having the same rate of production of offspring, then the more stable would increase in frequency, not because of their greater reproductive fitness, but because of their greater repeatability. Life cycles will behave in this Markovian manner only if the variation in life cycles among the progeny of a single spore is heritable. Somatic mutations that direct the entry of somatic cells into the germ line will create heritable variation, in the sense that the different life cycle found among the asexual products of a single spore will each tend to be transmitted to the next generation of spores, causing a Markovian disintegration of the original cycle. It is important to distinguish this phenomenon from the effect of 'selfish' somatic mutations in disrupting an orderly and prolific sequence of development. This may often be the case; but the distinctive property of the evolution of life cycles is that heritable stability of development (or the lack of heritable instability) will be favoured on its own account, independently of any effects on the reproductive success of individuals. Stable development will thus be ensured if either the occurrence or the transmission of somatic mutations can be minimized. Buss points out two ways in which this can be achieved: the control of early development by maternal transcripts in the spore cytoplasm prevents the occurrence of expressible somatic mutations, because development is under the control of the nuclear genome of the parent; and the early sequestration of the germ line, besides minimizing germ-line mutations, also reduces the heritability of somatic mutations by denying them access to the germ line. Genes borne by the spore which promote maternal control or germline sequestration will be favoured because they will thereby promote their own precise replication; genes that do not have this property will tend to be replaced by a host of somatic mutations. The phenotypic consequence will be the evolution of highly repeatable life cycles. It is very likely, of course, that, once a stable sequence of development has evolved, selection will favour modifiers that shift the life cycle towards an optimal pattern of allocation which maximizes spore production. Our point is to distinguish between selection for the rate of reproduction and selection for repeatability, and to argue that repeatability, independently of reproductive rate, may be crucial to understanding how life cycles evolve.

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