

A Multi-level Selection Theory of Evolutionary Transitions in Individuality

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Introduction

The organization of the living world is hierarchical—lower level units group together and cooperate to form higher level units of organization (genes, chromosomes, bacteria-like cells, eukaryotic-like cells (cells in cells), multicellular organisms and societies). How this came about is far from clear. What is clear is that the major landmarks in the diversification of life have involved transitions between these hierarchical levels and that cooperation has been a dominant theme.

Throughout this paper, we illustrate our approach to evolutionary transitions using the transition from single cells to multicellular organisms. This transition has occurred multiple times in all major groups including bacteria, fungi, protists, plants and animals. Although we focus on the case of multicellularity, we believe the issues we discuss apply to the other major transitions including the origin of bacteria-like cells, eukaryotic-like cells (as discussed briefly at the end) and societies.

To be able to adapt to their environment, evolutionary individuals must be units of selection, and satisfy Darwin's conditions of heritability and variation in fitness. Using a multi-level selection framework¹⁻⁵, it is possible to understand how Darwin's properties emerge at a new level (for example, the multicellular organism) from the evolution of interactions in groups of lower level individuals (for example, cells). In this way, we may understand, in a general sense, the origin and maintenance of the biological hierarchy⁶. The properties of fitness, heritability and variation are all interrelated, although for purposes of discussion we consider each factor separately.

Multi-level Selection, Cooperation and Variation of Fitness

We take a multi-level selection approach to fitness variation and evolutionary transitions. The basic problem in creating new evolutionary individuals involves generating heritable variation in fitness at the group level, while reducing the variation in fitness and scope for evolutionary change within groups. Variation in fitness depends upon many processes and factors, including reproductive mode (asexual, sexual, fragmentation, etc.), reproductive

specialization of group members (germ versus soma), development and mutation. Understanding how reproductive modes and developmental programs are shaped during an evolutionary transition so as to effectively cope with mutation and shape heritable variation at the new level is a major concern of our work.

Cooperation is fundamental to the emergence of new levels of fitness in the biological hierarchy, because cooperation increases the fitness of the group, and new units of selection start out as groups of existing units. Thirty years ago, the study of cooperation received far less attention than the other forms of ecological interaction (competition, predation and parasitism). Scholars generally viewed cooperation to be of limited interest, of special relevance to certain groups of organisms to be sure, but not of general significance to life on earth. All that has changed with the study of evolutionary transitions in levels of organization. What began as the study of animal social behavior, has now embraced the study of interactions at all biological levels. Cooperation is now seen as the primary creative force behind ever greater levels of complexity and organization in all of biology.

Cell Behavior	Level of Selection	
	Cell	Group (organism)
Defection	(+) replicate faster	(-) less functional
Cooperation	(-) replicate slowly	(+) more functional

Table 1. Effect of cooperation on fitness at cell and organism level. The notation +/- means positive or negative effects on fitness at the cell or organism level.

We wish to understand how fitness emerges at a new higher level. Cooperation creates new levels of fitness by increasing the fitness of the group, and, if costly at the lower level, by trading fitness from a lower level (the costs of cooperation to group members) to a higher level (the benefits to the group)⁶. In Table 1, we illustrate this for the case of the transition between cells and multicellular organisms. As cooperation creates new levels of fitness, it creates the opportunity for conflict between levels as deleterious mutants arise and spread. As discussed further below, adaptations that restrict the opportunity for conflict between higher and lower levels (what we term "conflict modifiers") are instrumental in the conversion of the group to a new evolutionary individual, in the case studied here, conversion of the cell group to a multicellular organism.

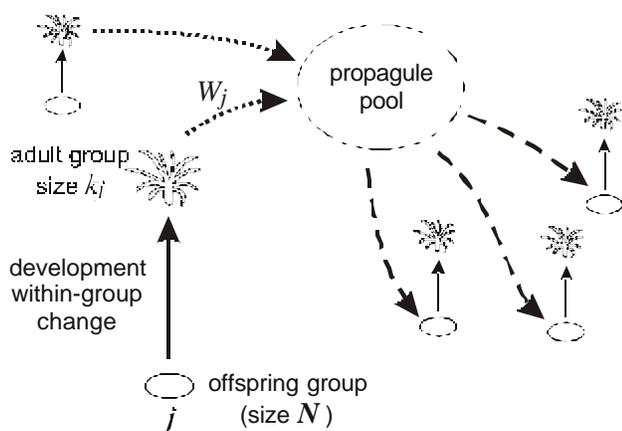


Figure 1. Model life cycle. The offspring group may be formed by different reproductive processes. In the case of zygote reproduction the offspring “group” is a single cell that may or may not be formed sexually. In the case of aggregation, the offspring group is formed by aggregation of cells. The subscript j refers to the number of non-mutant cells in the offspring group; $j = 0, 1, 2, \dots, N$, where N is the total number of cells in the offspring group, termed propagule size ($N = 1$ for zygote reproduction). The fitness of group j , defined as the expected number of offspring produced by the group is indicated by the dotted lines. Two components of group fitness are considered: size of the adult group and its functionality (or level of cooperation among its component cells represented by parameter ϕ in the models). The propagules are single cells in the cases of zygote and aggregation reproduction and small groups of cells in the case of fragmentation. The propagules then form offspring groups of the next generation (dashed arrows). The dashed arrows involve different processes depending on reproduction and may involve aggregation or fusion (in the case of sexual reproduction) or may simply refer to the direct entry of the propagule into the next generation in the case of fragmentation.

Synergistic forms of cooperation benefit both the cell and the cell group. In the case of synergistic cooperation, there is no obvious conflict between levels in terms of how cooperation is defined, but if disrupting cooperation harms the higher level more than the lower level, modifiers may also evolve that increase the heritability of fitness of the higher level.

The basic framework we have used to study the transition between single cells and multicellular organisms is given in Figure 1. In addition to studying the focal levels of cells and cell groups (the emerging organism), we consider the “surrounding” levels of genes within cells and populations of cell groups. Cell groups start out as offspring groups composed of N cells. During development cells proliferate and die (possibly at different rates) to create the adult cell group. Deleterious mutation may occur during cell division. The adult groups produce offspring groups of the next generation, either by producing propagules (which

may fuse with other propagules as in the case of sex or other forms of aggregation) or by direct fragmentation. The functioning of the groups and their group fitness (number of propagules or offspring groups produced) depends upon their composition of mutant and non-mutant cells at the end of development. The total change in gene frequency results from both within and between group change. We have been especially interested in the features of organisms that affect the opportunity for within and between group change for they shape the variation and heritability at the new level. For the group to become a new individual, the organism, the opportunity for between group change must be enhanced while the opportunity for within group change must be restricted. How and why does this occur?

The proliferation of cells during development is indicated by the vertical arrows in Figure 1. Because of mutation during development and different rates of replication and survival of different cell types, there will be a change in gene and genotype frequency of cells within the cell groups in Figure 1. There will also be a change in gene frequency in the global population due to differences in fitness between the adult groups (dotted arrows). The propagules produced by the adult form offspring groups of the next generation (dashed arrows). The dashed arrows involve different processes depending on reproductive mode; they may represent aggregation or fusion (in the case of sexual reproduction) or they may simply represent the direct entry of the propagule into the next generation as in the case of fragmentation. The two components of frequency change, within organisms and between organisms give rise to the total change in gene frequency in the global population.

During the proliferation of cells throughout development, deleterious mutation can lead to the loss of cooperative cell functions. We represent cell function in terms of a single cooperative strategy determined by genetic variation at a single genetic locus with two alleles: non-mutant and mutant. We assume non-mutant cells are cooperative and benefit the group. We have studied two different kinds of cooperation, depending upon whether the cooperative phenotype is costly or beneficial at the cell level. If costly, cooperation is assumed to lower the cell’s replication or survival rate. When cooperation benefits the cell as well as the cell group, cooperation is always synergistic, as defined in terms of a payoff matrix. Costly forms of cooperation may be synergistic in our model or not, depending on the magnitude of the costs and other parameters⁵.

Mutant cells do not display the cooperative phenotype. In the case of costly cooperation, mutants are selfish in that they replicate faster and harm the group. In the case of cell beneficial forms of cooperation, mutants are uniformly deleterious at both the group and cell level. We believe that both kinds of mutations, selfish and uniformly deleterious, are important for understanding the evolution of cooperation and fitness heritability during evolutionary transitions. We have studied deleterious mutations using a variety of deterministic and stochastic techniques that allow us to study a distribution of mutational effects (from

uniformly deleterious to selfish). In general, we have found that even a small proportion of selfish mutations (that is, most mutations being uniformly deleterious with a small fraction of selfish mutations) has significant effects on the evolution of genetic modifiers of the life cycle.

Heritability of Fitness

We wish to understand how heritability of fitness, the defining characteristic of a unit of selection, may increase at the group level, so that the group may become an evolutionary individual or unit of selection. Using the multilevel selection framework outlined in previous sections, we estimate the levels of cooperation maintained in cell groups, the mutation load, and the fitness variation at the two levels (cell and cell group) as a function of the reproductive system and the basic parameters of the model (including the offspring group or propagule size, mutation rate, development time, benefit of cooperation to the group, and parameters of selection at the cell level)^{1,2,4,5}. Fitness variation at the cell and group levels translates directly into the opportunity for within and between group change. Under what conditions, can evolution select for modifiers of development and the parameters of within group change so as to increase the opportunity for between group change and restrict the opportunity for within group change? Such conditions promote heritability of fitness at the group level and change the cell group into an individual organism. Under these conditions, an evolutionary transition will occur.

In our view an organism is more than a group of cooperating cells, more even than a group of cooperating cells related through common descent, say from a single cell. An organism must have functions that maintain its integrity and individuality. We are interested in understanding these first true emergent level functions during the origin of the multicellular organism. To understand the conditions under which an evolutionary transition occurs, we posit a second modifier locus that modifies the assumptions and parameters representing the biological processes described above. All models make assumptions about the processes they study, in the present case, these assumptions involve development, the reproductive system, within-organism mutation and selection, and cell-cell interactions such as cooperation. The purpose of the modifier model is to study how evolution may modify these assumptions and parameter values, and further how these modifications affect the transition to a higher level of selection. Unlike the classical use of modifier models, say in the evolution of dominance and recombination, the modifiers studied in the present paper are not neutral. Instead, they have direct effects on fitness at the cell and organism level by changing the parameters of within-organism change. By molding the ways in which the levels interact so as to reduce conflict among cells, for example by segregating a germ line early or by policing the selfish tendencies of cells, the modifiers

construct the first true emergent organism level functions.

The modifier allele can affect virtually any aspect of the model, in particular we have studied modifiers that create a germ line, that police other cells, or that cause cell death of renegade dividing cells. We have been most interested in modifiers that shape the variation and opportunity for selection at the organism and cell level. A *germ line modifier* affects the way in which cells are chosen to be propagules and is assumed to sequester a group of cells which have a shorter development time and possibly a lower mutation rate than the soma, and, consequently, less selection at the cell level. A *self-policing modifier* causes cells in the group to spend time and energy monitoring other cells and reducing the advantages of defection possibly at some cost to the group. An *apoptotic modifier* is more direct and is expressed by the mutant renegade cells themselves and lowers the rate of proliferation (or probability of survival) of the mutated cell. When these modifiers of development and within organism change increase in the population, the level of cooperation increases as does the heritability of fitness at the group level.

Overview of the Origin of Organisms

The evolution of modifiers of within-organism change leads to increased levels of cooperation within the organism and increased heritability of fitness at the organism level. The evolution of these modifiers are the first new functions at the organism level. An organism is more than a group of cooperating cells related by common descent; organisms require adaptations that regulate conflict within. Otherwise their continued evolution is frustrated by the creation of within-organism variation and conflict. The evolution of modifiers of within-organism change are a necessary prerequisite to the emergence of individuality and the continued well being of the organism.

What happens during an evolutionary transition to a new higher level unit of individuality, in this case the multicellular organism? Cooperation increases the fitness of the new higher level unit, and, in this way, cooperation may create new levels of selection. However, the evolution of cooperation sets the stage for conflict, represented here by the increase of deleterious mutants within the emerging organism that tilt the balance of selection in favor of the lower level, cells in our case. The evolution of modifiers restricting the effective mutation rate are the first higher level functions at the organism level. Before the evolution of a means to reduce conflict between levels of selection, the evolution of new group adaptations (such as the underlying traits leading to increased cooperation among cells) is frustrated by the deleterious mutation. Individuality requires more than just cooperation among a group of genetically related cells, whether the cooperation is altruistic or synergistic; individuality depends upon the emergence of higher level functions that restrict the opportunity for conflict within and ensure the continued

cooperation of the lower level units. Conflict leads—through the evolution of adaptations that reduce it—to greater individuality and harmony for the organism.

Origin of the Eukaryotic Cell

In multi-level selection, individuals associate in groups, within which interactions occur that affect the fitnesses of both the individuals and the group. For example, under certain conditions some bacteria associate to form a fruiting body, some amoebae associate to form a slug, some solitary cells form a colonial group, some normally solitary wasps breed cooperatively, some birds associate to form a colony, and some mammals form societies. And about 2 billion years ago, archaeobacteria-like cells (destined to be the ancestors of all eukaryotes) began alliances with other bacteria to form the first eukaryotic like cell.

The basic problem in an evolutionary transition is how and under what conditions a group becomes a new kind of individual. Initially, group fitness is taken to be the average of the component lower level units, but as the evolutionary transition proceeds, group fitness becomes decoupled from the fitness of its members. Indeed, the essence of an evolutionary transition is that the lower level units must in some sense “relinquish” their “claim” to fitness, that is to flourish and multiply, in favor of the new higher level. This transfer of fitness from lower to higher levels occurs through the evolution of cooperation and conflict modifiers that restrict the opportunity for within group change and enhance the opportunity for between group change. Until eventually, the group becomes an evolutionary individual in the sense of having heritable variation in fitness at its level of organization and in the sense of being protected from the ravages of within group change by adaptations that restrict the opportunity for non-cooperative behaviors

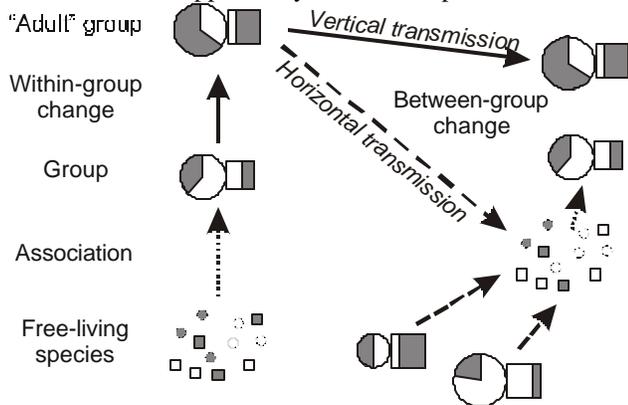


Figure 2. Multilevel selection framework for symbiotic species groups. Two species are indicated by squares and circles. Within each species there are two phenotypes indicated by open and shaded shapes. A two species group is indicated by touching shapes; the size of each touching shape indicating the relative proportions of each species within the group and the shading of each shape indicating the relative proportion of the two phenotypes within each species in the group.

such as defection⁶. Of course, no evolutionary individual ever rids itself from the threat of change within, as evidenced by the increasingly numerous examples of evolutionary conflict.

The multi-level selection approach to evolutionary transitions begins by partitioning the total change in frequency of phenotypes and their underlying genes at the lower level into within and between group components. Groups are defined by a group property, usually the within group frequency of a phenotype (or some other property reflecting group composition). In the transition from single cells to multicellular organisms, the cells form cell groups belonging to the same species⁶. The multi-level selection framework presented for the origin of multicellular organisms (Figure 1) can be extended to the case of cell groups composed of different phenotypes belonging to different species (Figure 2).

In Figure 2, the two different species (host and symbiont, predator and prey, two different syntrophic feeders, etc.), are indicated by squares and circles. Within each species there are two phenotypes (cooperate or defect, cultivate or exploit, etc.) indicated by open and shaded shapes. A two species group formed by association of members from different species is indicated by the larger touching shapes; the size of each touching shape indicating the relative proportions of each species within the group and the shading of each shape indicating the relative proportion of the two phenotypes within each species in the group. After group formation, members may reproduce or survive at different rates leading to within group change. An additional factor leading to within group change is mutation leading to loss of cooperative cell phenotypes. The total change in frequency of different phenotypes within species and the relative proportions of different species is also affected by the between group change that occurs during horizontal and/or vertical transmission of group properties. Groups may breakup and reform as in the case of horizontal transmission, or reproduce as groups in the case of vertical transmission.

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