



HAL
open science

Phenotype divergence and cooperation in isogenic multicellularity and in cancer

Frank Alvarez, Jean Clairambault

► **To cite this version:**

Frank Alvarez, Jean Clairambault. Phenotype divergence and cooperation in isogenic multicellularity and in cancer. 2023. hal-04638544v1

HAL Id: hal-04638544

<https://hal.science/hal-04638544v1>

Preprint submitted on 29 Jun 2023 (v1), last revised 8 Jul 2024 (v3)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Phenotype divergence and cooperation in isogenic multicellularity and in cancer

Frank Ernesto Alvarez¹ & Jean Clairambault²

¹INSA Toulouse, France // orcid 0000-0002-6651-7374

²Inria and LJLL, Sorbonne Université, Paris, France // orcid 0000-0002-8336-9641

June 29, 2023

Abstract

We discuss the mathematical modelling of two of the main mechanisms which pushed forward the emergence of multicellularity: phenotype divergence in cell differentiation, and between-cell cooperation. In line with the atavistic theory of cancer, this disease being specific of multicellular animals, we set special emphasis on how both mechanisms appear to be reversed, however not totally impaired, rather hijacked, in tumour cell populations. Two settings are considered: the completely innovating, tinkering, situation of the emergence of multicellularity in the evolution of species, which we assume to be constrained by external pressure on the cell populations, and the completely planned - in the *body plan* - situation of the physiological construction of a developing multicellular animal from the zygote, or of bet hedging in tumours, assumed to be of clonal formation, although the body plan is largely - but not completely - lost in its constituting cells. We show how cancer impacts these two settings and we sketch mathematical models for them. We present here our contribution to the question at stake with a background from biology, from mathematics, and from philosophy of science.

Keywords. Differentiation, cooperation, multicellularity, cancer disease, structured population models, philosophy of science

1 Biological and evolutionary-developmental background

1.1 Being or not teleological: the two settings considered

Although this may seem completely trivial to state, let us emphasise that for us there is no such thing as teleology, i.e., orientation in a given direction or towards a given goal, in the general evolution of multicellular animals, which is constituted of a succession of haphazard strategic choices of adaptation to changing environments in existing evolutionary units, at one stage of evolution towards an identified next one. Such adaptations, often resulting in branchings of clades, as solutions to existential problems, imposed by external constraints as stresses [32, 43] induced by changes in the environment, are by no means unique, admitting that evolution proceeds by trials and errors, and by tinkering [22] from available material to solve such problems. We proposed in [2] a mathematical scheme to model the phenotypic divergence that may be a basis for such environmental stress-induced evolutionary steps.

Conversely, teleology is of course present in the embryonic development of multicellular animals, which, according to Haeckel's formula "Ontogeny recapitulates phylogeny" [16, 18], follows in each species the evolutionary choices made at each branching step of the evolution of species, leading from the fecundated egg (most frequent form of elementary material evolutionary unit in multicellular animals [47], those who are subject to cancer [1, 33]) to adult animals with their completely differentiated cell types, following the *body plan* [12, 30] characteristic of the species. From this holistic point of view, evolution of species is nothing but evolution of the body plan, evolution of genes and of gene regulatory networks being completely dependent upon this master regulator. We suggest here that understanding the cooperation principles that have been optimised (noting that an optimisation problem may have diverse solutions) at each developmental step may benefit from a close look at the mechanisms of the evolutionary steps that have determined the species body plan, and we sketch mathematical ways to achieve this task.

One of the main difficulties in understanding and representing the design of the body plan is how to introduce mechanisms of coherence (for signals) and cohesion (for tissues) that make a multicellular

organism stable and functional, with compatibility and cooperation between tissues and organs, and we are aware of the fact that such complete understanding still lies ahead of us. However, localised absence of coherence between tissues of an organism by lack of control on differentiations is precisely the main characteristic of cancer, the second and in our opinion resulting from the first one, being absence of control on proliferation [6]. We propose that evolution of cooperation between cells, that has been identified in tumours [11, 34, 38], is a reactivation of mechanisms present in the body plan that are still present, although chaotic, uncontrolled and doomed to fail at the level of the organism, in tumour cells, may rely on elementary evolutionary mechanisms that have been designed in the evolutionary past of their body plan, so that this point should be better understood to efficiently represent cooperation in tumours.

1.2 The atavistic theory of cancer

Recently popularised by physicists Paul Davies and Charles Lineweaver, together with oncologist Mark Vincent, the atavistic theory of cancer [13, 24, 25, 26, 44], had in fact been envisioned already in 1996 by oncologist Lucien Israel [21], and likely as early as 1914 by biologist Theodor Boveri [7], although none of these scientists seem to have been initially aware of the works of their predecessors. It helps us understand tumour progression and intratumoral organisation from a long-term evolutionary viewpoint. Briefly, it relies on the ideas that 1) all cancer cells are multicellular animal cells, results of a billion year-old evolution from unicellular organisms, and as such keep in their genomes powerful remnants of the organismic defence and construction mechanisms borne in their body plans (even if this term is not used by Davies and Lineweaver, they only mention their genomes); 2) tumours are results of a regression in the development of the organism, corresponding to early, incoherent versions of “*an ancient genetic toolkit of pre-programmed behaviors*”, which we may freely identify as an unachieved evolutionary version of the species body plan, and which they name “Metazoa 1.0”. The atavistic theory thus clearly states that a tumour is not just the result of some aberrant stochastic mutation in somatic cells (the somatic mutation theory, SMT, recently reviewed and compared to the atavistic theory in [25]), but that it rather follows predictable paths in such regression towards a poorly organised, incoherent population of cells, nevertheless constituted of animal cells that are highly plastic (and thus resistant to external therapeutic pressure by anticancer drugs), as they have the power to differentiate and de-differentiate, and also to loosely cooperate between them in tumours. The works of David Goode and colleagues [39, 40, 41, 42] have evidenced in cancer samples silencing of genes of multicellularity and compatibility between expression of genes of multicellularity and of unicellularity, resulting in escaping organismic control on cell differentiation (in other words, developing cell plasticity) and on proliferation, tending to a widely autonomic behaviour which is a characteristic of cells in tumour tissues.

The atavistic theory of cancer is little by little, as more evidence in the study of ancient genes becomes known and published [39, 40, 41, 42], gaining recognition among theorists of cancer biology, however still quite limited in the field of oncology, where people question its amenability to produce innovations in the therapeutics of cancer. Innovating theories may take a long time to reverse the argument of “authority of tradition” [5]. The present situation may remind us, *mutatis mutandis*, of the way geographers received in 1912 with much skepticism Alfred Wegener’s theory of continental drift [45], until it was completely justified fifty years later by the theory of plate tectonics and progressively admitted by all geophysicists. A limitation to a wider acceptance of the atavistic theory is the present lack of sufficient evidence susceptible to convince biologists and philosophers of cancer, who prefer to keep on the “safe” side of science under development and, at least temporarily, reject it as not sufficiently relying on facts. Indeed, when it is mentioned in recent texts of philosophy of science - by authors who nevertheless must be commended for at least mentioning it -, the atavistic theory of cancer is not always correctly summed up, sometimes even presented in an off-hand way with arguments against it that show but partial understanding, as in [37]. A mere hypothesis, really? At least a uniting one in understanding cancer, fully compatible with the holistic point of view on evolution that we have mentioned above.

1.3 Why and how does multicellularity fail in cancer?

Cancer is thus, taking the atavistic theory of cancer for granted - although it tells us nothing about the very origin of the disease -, the progressive result of a failed maintenance of the teleological (or teleonomical, if one wants to explicitly exclude any intentionality, which is our position) construction of an animal. It may be described as essentially “a deunification of the individual” [36]. In the perspective of evolved multicellularity, it is tempting to describe - an epistemological position we assume - such material construction at the level of genes and gene regulatory networks, initially not from the zygote, but from

nonclonal colonies of cells (i.e., before the invention of the egg [47] and of the *body plan* contained in it) in three successive steps.

At the first step, the colony level, exist only genes of the cell division cycle and cell death, likely by quorum sensing. At the second step are introduced genes coding for transcription factors and (unregulated) differentiation. At the third step appear genes coding for epigenetic regulations, the top level of fine local regulations, that are themselves subject to central regulations in higher-level animals such as bilaterians. Such hierarchy is remarkably found, in a reverse order, in the evolution in malignancy found in fresh blood samples of patients with acute myelogenous leukaemia [20], which induces us to propose a scenario for cancer progression as relying firstly on epigenetic gene alterations (which includes differentiation control), secondly on alterations in differentiation, and only very late on alterations in cell cycle regulations, which are the strongest basis of proliferation. Unfortunately so far, with the remarkable and recent exception of the successes of immunotherapy, cancer therapies target mainly this strength [24].

1.4 A narrative of long-term evolution and cancer, freely exposed to the fire of philosophy of science

We need not justify any given evolutionary path that led to such and such animal, and rather see paths followed in evolution as diverse evolutionary strategies adapted to external constraints that imposed changes on the behaviour of the actors of the evolutionary paths at stake. Let us mention here that we hold, from our point of view, which resorts to functional, physiological and anatomical evolution, these actors, or evolutionary units, to be the *body plans* [12, 30] of multicellular animals, and not the individual genes, nor the gene regulatory networks that are mere effectors of evolutionary strategies, not determinants, and are only secondarily affected by them, as reflected in observations. A paleoanthropological analogy in evolution, *mutatis mutandis*, of such strategies at the level of divergence from a common ancestor in the Hominin lineage between Paranthropus and early Homo, relying on different dietary choices, may be found in [4]. Such haphazard strategical choices in long-term, Darwinian, evolution, that have become fixed in the body plan of animal species by genetic mutations and success in species fitness, may fail in cancer, as described in the previous section.

These firstly non determined (tinkered [22]) strategies led to epigenetic modifications (aka epimutations), later to fixed mutations of the genes coding for the epigenetic enzymes that determine these epigenetically defined strategies yielding functional body plans, that are the bases of physiology and anatomy construction in multicellular animals. Cancer cannot change the body plan of an animal in that of another animal, and it is certainly not a new form of life. However, by loss of organismic control on differentiations, it can reverse a cohesive body plan in a given species to some intermediate, poorly defined, unachieved form of the body plan of this species, yielding a collection of still very plastic cells, in other words a tumour, or a Metazoan 1.0 in the words of the atavistic theory of cancer [13]. The causes of such loss of control on differentiations are unknown, and the atavistic theory tells us nothing about them. However they may consist of an abrupt change in the environmental pressure on the tissue at stake, but also may be identified as due to a mutation in the genes responsible for epigenetic control [20].

2 Cell differentiation and phenotype divergence

2.1 Heterogeneity and plasticity with respect to what?

Cell populations, healthy and cancer, are heterogeneous w.r.t. various *continuous* traits under study, that are used to describe their biological variability, such as cell size, age in the cell division cycle, expression of genes of drug resistance, or more functional and abstract traits determining cell population fate such as viability, fecundity, motility, plasticity, according to the biological question at stake. Plasticity [9, 10] in a given trait is its capacity to change under the pressure of external constraints, such as drugs, and it has long been recognised as as relying on epigenetic factors [29]. Plasticity may be considered as a speed of evolution from one trait distribution to another one when the surrounding environment of the cell population changes, slowly or abruptly. Such evolution may be accelerated in equations by terms of advection (especially when abrupt changes in the environment force the cell population to adapt quickly) and diffusion (representing uncertainty in phenotype determination).

Differentiation in cell lineages, such as the ones constituting the paths of haematopoiesis, may consist either of simple maturation, following the same line towards a terminally differentiated cell type, such as the different granulocytes (neutrophils, eosinophils, and basophils) among white blood cells, or of branching, e.g., in haematopoiesis from pluripotent haematopoietic stem cells to myeloid versus

lymphoid progenitors. Phenotype divergence is the biological phenomenon by which branching occurs between precursors of terminally differentiated cell types. The first identified phenomenon relying on phenotype divergence in evolution from unicellularity towards multicellularity was likely the separation between germinal cells (the germen) and germen-supporting somatic cells (the soma), proposed in 1892 by August Weismann [46] and later mentioned by John Maynard Smith and Eörs Szathmáry as the first step from unicellularity towards multicellularity, one of the major transitions in evolution [28]. Basis of heterogeneity in cell populations within a cohesive multicellular individual, or within a tumour, phenotype divergence necessarily relies on phenotype plasticity, and it is the phenomenon we here tackle to represent in phenotype-structured equations.

2.2 Long-term evolution as genetic adaptation of the body plan in animals

As mentioned in the introduction, we consider that the fundamental evolutionary unit in the great Darwinian evolution of animals is the body plan [12, 30], which is virtually (as it is abstract, indeed as a plan, self-developing, written as a self-extracting archive in genetic code, its dynamic extraction occurring continuously during the process of animal development) present in every physiologically complete nucleated animal cell, starting from the zygote, i.e., the initial fecundated egg. The genes and gene regulatory networks that materially proceed from it and serve to design and cohesively maintain the construction of the animal when it is achieved, are its observable materialisation.

Anatomically in 3D observations, physiologically by the observation of the great functions of the organism, and genetically by investigation the genes that have been identified (e.g., by KO experiments) in different species to correspond to anatomic structures and physiological functions, and their expression, we may have access to material reflections of the body plan, and thus partially reconstitute its evolution across species. This is precisely what has been investigated about the genes at the origin of multicellularity and their correspondence with the genes that are altered in cancer by Domazet-Lošo and Tautz [14, 15], and later by Trigos *et al.* [39, 40, 41, 42] in David Goode's team, giving rise and genetic arguments to the atavistic theory of cancer [13, 24, 25].

2.3 A nonlocal phenotype-structured cell population model

The reaction-diffusion-advection model proposed in [2] to exemplify *bet hedging* as a 'tumour strategy' to diversify its phenotypes in response to deadly stress (e.g., by cytotoxic drugs), but also to represent phenotypic divergence in evolution towards multicellularity, runs as follows.

Let $D = \Omega \times [0, 1]$, where $\Omega := \{C(x, y) \leq K\}$ (a constraint between competing traits x and y) and $\theta \in [0, 1]$. The evolution with time t of a plastic cell population of density $n(z, t)$ structured in a 3D phenotype $z = (x, y, \theta)$, where x =viability, y =fecundity, θ =plasticity, with $r(z)$ and $d(z)$ growth and death rates, is given by

$$\partial_t n + \nabla \cdot (Vn - A(\theta)\nabla n) = (r(z) - d(z)\rho(t))n, \quad (1)$$

with $(Vn - A(\theta)\nabla n) \cdot \mathbf{n} = 0$ for all $z \in \partial D$ (\mathbf{n} is a normal vector to ∂D), $n(0, z) = n_0(z)$ for all $z \in D$,

where $\Omega = \{(x, y) \in [0, 1]^2 : (x - 1)^2 + (y - 1)^2 > 1\}$, and the diffusion matrix is

$$A(\theta) = \begin{pmatrix} a_{11}(\theta) & 0 & 0 \\ 0 & a_{22}(\theta) & 0 \\ 0 & 0 & a_{33} \end{pmatrix}, \text{ with } a_{11} \text{ and } a_{22} \text{ non-decreasing functions of } \theta, \text{ influencing the}$$

speed at which non-genetic epimutations occur, otherwise said, it is a representation of how the internal plasticity trait θ affects the non-genetic instability of traits x and y , by tuning the diffusion term $\nabla \cdot \{A(\theta)\nabla n\}$; the advection term

$$\nabla \cdot \{V(t, z)n\} = \nabla \cdot \{(V_1(t, z), V_2(t, z), V_3(t, z))n\}$$

represents the cellular stress exerted on the population by external evolutionary pressure, i.e., by changes in the cell population environment, here chosen as tearing apart the cell population between competing traits x (viability) and y (fecundity); and $\rho(t) = \int_D n(t, z)dz$ stands for the total mass of individuals in the cell population at time t .

The existence and uniqueness of solutions is obtained in finite time in a constructive way by using the compactness of a sequence of numerical solutions, which are the result of the algorithms used to discretise the model. Simulations may be obtained with instances of the functions used in the equations. For instance, to obtain phenotypic divergence (which we take as the basis of both bet hedging in cancer and of emergence of multicellularity in evolution), we consider over the domain $D = \Omega \times [0, 1]$ an initial density given by

$$n_0(z) = a \mathbb{1}_{\{f(z) < 1\}} e^{-\frac{1}{1-f(z)}},$$

with $f(z) = \frac{\|z - z_0\|^2}{(0.025)^2}$, where $z_0 = (0.25, 0.25, 0.5)$ and $\|\cdot\|$ is the euclidean norm. We choose the value of a in such a way that $\rho_0 = \int_D n_0(z) = 1$.

We set the growth rate and the death rate as

$$r(x, y, \theta) = \mathbb{1}_{\{y > x\}} e^{-(0.1-x)^2 - (0.9-y)^2} + \mathbb{1}_{\{x \geq y\}} e^{-(0.1-y)^2 - (0.9-x)^2}, \quad d(x, y, \theta) = \frac{1}{2}.$$

We choose the diffusion matrix

$$A(\theta) = \begin{pmatrix} (\theta + 1)10^{-6} & 0 & 0 \\ 0 & (\theta + 1)10^{-6} & 0 \\ 0 & 0 & 10^{-6} \end{pmatrix},$$

and the advection term, tearing apart traits x and y , is chosen as $V(t, z) = 10^{-3}(-y, -x, -(x + y))$, or $10^{-3}\theta(-y, -x, -(x + y))$ if we want plasticity θ to impinge also on the advection term, representing in all cases the influence of the tumour ecosystem on the tumour cell population.

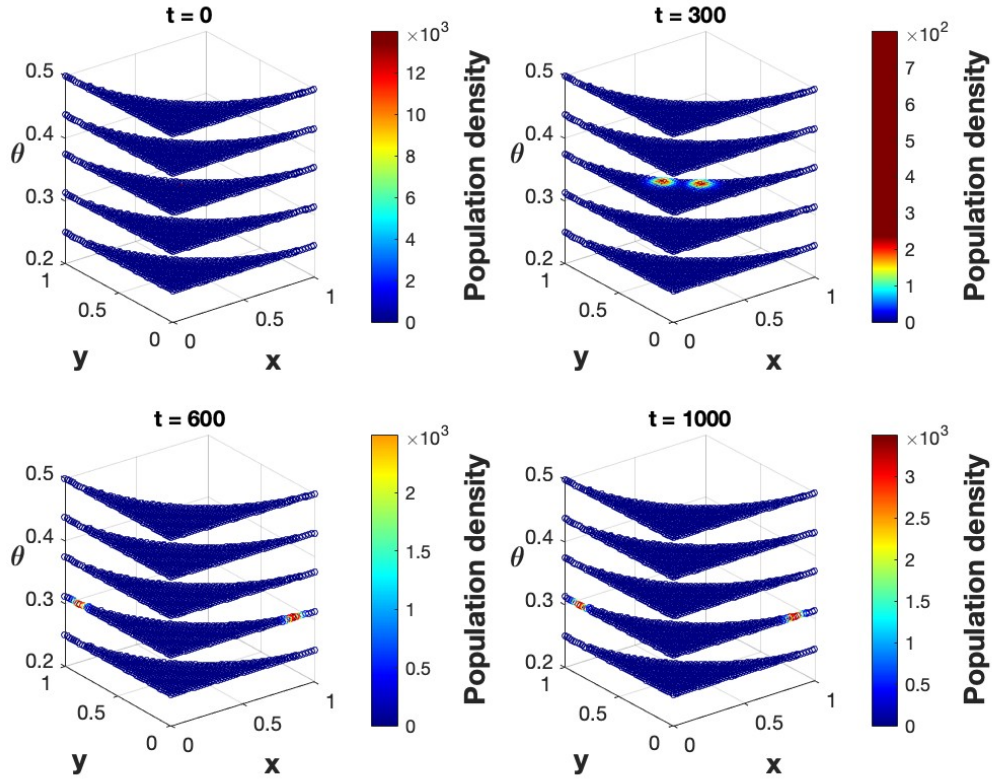


Figure 1: Phenotypic divergence and loss of plasticity. On these cartoon-like figures, one can follow the progressive distancing of an initial cell population arbitrarily set at $z = (0.25, 0.25, 0.5)$, submitted to an advection gradient that tends to split the cell population into two subpopulations migrating towards the two extreme points $(0, 1)$ and $(1, 0)$ of the domain Ω , while the plasticity variable θ decreases towards 0.

The reader is sent to [2] for more detailed explanations and illustrations.

2.4 What this model tackles and what it leaves unexplained

Our reaction-diffusion-advection equations give the most important part in modelling phenotype divergence to the drift (advection) term representing environmental pressure from the ecosystem towards separation of phenotypes. Plasticity is naturally already present in the reaction term of this continuous phenotype-structured cell population model of adaptive dynamics, and the diffusion term adds to phenotype adaptability by uncertainty in its determination. Nevertheless, the sensitivity of phenotype adaptation and the trade-off we set between the supposed contradictory 1D phenotypes is mainly represented by the advection term and the bounded region within which the phenotypes evolve, that together represent constraints and offer possibilities of trade-offs between the phenotypes.

This model is clearly a mathematical abstraction that may be applied as such to every possible branching situation in the physiological development of multicellular animals or in bet hedging of phenotypes in tumours. For instance, one could model more precisely in glioblastoma cells such branching situations as the “go-or-grow” alternative between enhancing a proliferation potential (fecundity) and a motion potential (motility) [19], which would need to represent in the same kind of model the biological mechanisms that account for them, and about the constraints (likely of energetic nature) between them. This would help us design more precisely the advection term and the domain in phenotype space within which phenotypes evolve. It would imply efficient transdisciplinary collaboration on this subject between mathematicians and biologists of cancer, which we hope to develop in the future.

3 Cooperation

3.1 Tinkered cooperation in the emergence of multicellularity vs. directed cooperation in constituted multicellular animals

Noting that the question of cooperation and of division of labour has been considered by many authors at different stages of associations between individuals, including animal societies [28]. To follow again the metaphor of the separation in evolution between Paranthropus and early Homo, the situation with respect to phenotype divergence between body plans of animals is as if, *mutatis mutandis*, in evolution from their common hominin ancestor, Paranthropus and early Homo, after their genetic separation starting by fixation of initial epigenetic haphazard strategic adaptive choices (since evolution under changes in environmental pressure proceeds by tinkering [22]), had found interest in developing mutualistic interactions, living in symbiosis, less and less independently of one another. However, since the Paranthropus species eventually became extinct, likely due to climate changes incompatible with his too specialised vegetarian diet, whereas Homo survived, having adapted his diet to meat eating, this was actually not the case, or not in a permanent way, in the evolution of hominins.

We are aware of the fact that this metaphor is by no means perfect, and that reversible development, of epigenetic nature, within an isogenic individual (or a tumour) is not the same process as evolution of species, which is based on fixed, irreversible, genetic separations by branchings. Nevertheless, hypothesising that genetic specialisation is likely to begin with reversible epigenetic phenotype divergence before being fixed by gene mutations, we hope that it sheds some light on the processes that are at work in elementary steps in the evolution towards multicellularity and in bet hedging in tumours.

Cooperation between populations of cells resulting from such phenotype divergence may be considered as the glue that holds together all cell subpopulations in an isogenic multicellular organism. It may occur when mutualistic interactions are beneficial for all the interacting cell populations, provided that none of them becomes extinct. And it may also not occur, in which case no trace of such missed mutualism is found in the evolution of body plans. It is indeed, in our representation, the body plan that has kept memory, in each species, in constitutive intercellular gene regulatory networks, of the proper strategic choices w.r.t. phenotype divergences that lead to the design of an anatomically and physiologically cohesive animal. No tinkering is present anymore in these programmed choices designed in the body plan, and this is what we would like to represent now.

We will present two different possible approaches to the study of evolution of cooperation. The first one takes the prisoner’s dilemma as a starting point, and considers reciprocity as a factor influencing the strategies of both players. The possible outcomes for a long running game are studied, and finally, a way to model a scenario with n players is described. The second modelling choice is through an integro-differential system structured according to the probability of cooperation. In this case, reciprocity is represented by an advective term. For a simple set of hypotheses we show that cooperation might mark the difference between extinction or proliferation for two interacting populations.

3.2 Prisoner's dilemma and reciprocity

According to [3], an initial intention for cooperation and the existence of reciprocity are crucial for the evolution of cooperation, even in an environment composed of egoistic individuals. However, one may wonder what are the conditions that guarantee this to be true; after all, it can be expected that, if reciprocity is stronger in the absence of cooperation, then cooperation becomes less usual. In other words: when is reciprocity a catalyst for cooperation? The following (very simple) model tackles this question.

Consider two players (that can range from cells to entire groups of individuals, such as governments) involved in the repeated prisoner's dilemma game. Player A will initially cooperate with probability $p_0 > 0$ while player B will do so with probability $q_0 > 0$. We assume both values to be strictly positive to account for the initial intention of cooperation described in [3]. Both players will modify their probabilities of cooperation at turn $k + 1$ (denoted as p_{k+1} and q_{k+1} respectively) by following the rule:

$$p_{k+1} = \begin{cases} p_k + \varepsilon_{11}(1 - p_k), & \text{if player B cooperated in turn k,} \\ p_k(1 - \varepsilon_{12}), & \text{if not,} \end{cases}$$

and

$$q_{k+1} = \begin{cases} q_k + \varepsilon_{21}(1 - q_k), & \text{if player A cooperated in turn k,} \\ q_k(1 - \varepsilon_{22}), & \text{if not,} \end{cases}$$

where $0 < \varepsilon_{ij} < 1$ for $i, j \in \{1, 2\}$. According to this model, both players modify their strategy by "learning" from each other. A different strategy was already studied in [31], where players could modify their strategy by imitation.

We recall that the payoff matrix of the prisoner's dilemma game is given by

$$\begin{pmatrix} b - c & -c \\ b & 0 \end{pmatrix},$$

where b is the benefit and c is the cost of cooperation ($b > c$). Hence, the expected gain for players A and B at turn k are given by

$$E_A^k = (b - c)p_k q_k + b(1 - p_k)q_k - cp_k(1 - q_k) = bq_k - cp_k \text{ and } E_B^k = bp_k - cq_k,$$

respectively. Therefore, the average expected gain at turn k is given by the relation

$$E_k = \frac{(b - c)}{2}(p_k + q_k).$$

Given that the probability of both players cooperating at turn k is equal to $p_k q_k$, our interest falls then on the question: What are the conditions over the values ε_{ij} , $i, j \in \{1, 2\}$, such that the sequence (p_k, q_k) converges towards a non trivial limit? In such cases, when does the average expected gain can be expected to increase?

In order to answer these questions we first explicitly give the values of p_{k+1} and q_{k+1} as functions of p_k and q_k . Thanks to the law of total probability, we get the relations

$$\begin{aligned} p_{k+1} &= q_k(p_k + \varepsilon_{11}(1 - p_k)) + (1 - q_k)p_k(1 - \varepsilon_{12}) \\ &= (1 - \varepsilon_{12})p_k + \varepsilon_{11}q_k + (\varepsilon_{12} - \varepsilon_{11})p_k q_k =: f_1(p_k, q_k), \\ q_{k+1} &= p_k(q_k + \varepsilon_{21}(1 - q_k)) + (1 - p_k)q_k(1 - \varepsilon_{22}) \\ &= (1 - \varepsilon_{22})q_k + \varepsilon_{21}p_k + (\varepsilon_{22} - \varepsilon_{21})p_k q_k =: f_2(p_k, q_k). \end{aligned}$$

If this sequence has a limit (p^*, q^*) , it must satisfy the relation

$$\begin{cases} p^* &= f_1(p^*, q^*), \\ q^* &= f_2(p^*, q^*). \end{cases} \quad (2)$$

In the following proposition we will identify the possible values for (p^*, q^*) and determine their stability.

Proposition 1. Consider a couple (p_0, q_0) and the value $e = \varepsilon_{11}\varepsilon_{21} - \varepsilon_{12}\varepsilon_{22}$.

i) If $e < 0$, then the only possible values for (p^*, q^*) are $(0, 0)$ and $(1, 1)$. The first one is a stable fixed point and the second one is an unstable fixed point.

ii) If $e > 0$, then the only possible values for (p^*, q^*) are $(0, 0)$ and $(1, 1)$. The first one is an unstable fixed point and the second one is a stable fixed point.

iii) If $e = 0$ then (p^*, q^*) is the unique solution of

$$\begin{aligned}\varepsilon_{22}p_0 + \varepsilon_{11}q_0 &= \varepsilon_{22}p^* + \varepsilon_{11}q^*, \\ q^* &= \frac{\varepsilon_{12}p^*}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*},\end{aligned}$$

and it is a stable fixed point.

Proof. Notice that the values $(0, 0)$ and $(1, 1)$ are always a solution of (2). The stability of said fixed points (and others we will determine) can be studied by means of the eigenvalues of the Jacobian matrix.

First case: The unbalanced scenario: ($\varepsilon_{11}\varepsilon_{21} \neq \varepsilon_{12}\varepsilon_{22}$) If this condition is satisfied, a simple computation shows that there are not non-trivial solutions for (2). Hence, if a limit exists, it has to be either the $(0, 0)$ or the $(1, 1)$. The Jacobian matrix of the system at each of these points is equal to

$$J_0 := J(0, 0) = \begin{pmatrix} 1 - \varepsilon_{12} & \varepsilon_{11} \\ \varepsilon_{21} & 1 - \varepsilon_{22} \end{pmatrix} \text{ and } J_1 := J(1, 1) = \begin{pmatrix} 1 - \varepsilon_{11} & \varepsilon_{12} \\ \varepsilon_{22} & 1 - \varepsilon_{21} \end{pmatrix}.$$

The eigenvalues of J_0 are then

$$\lambda_1^0 = \frac{2 - (\varepsilon_{12} + \varepsilon_{22}) - \sqrt{(\varepsilon_{12} + \varepsilon_{22})^2 + 4e}}{2} \text{ and } \lambda_2^0 = \frac{2 - (\varepsilon_{12} + \varepsilon_{22}) + \sqrt{(\varepsilon_{12} + \varepsilon_{22})^2 + 4e}}{2},$$

while those of J_1 are

$$\lambda_1^1 = \frac{2 - (\varepsilon_{11} + \varepsilon_{21}) - \sqrt{(\varepsilon_{11} + \varepsilon_{21})^2 - 4e}}{2} \text{ and } \lambda_2^1 = \frac{2 - (\varepsilon_{11} + \varepsilon_{21}) + \sqrt{(\varepsilon_{11} + \varepsilon_{21})^2 - 4e}}{2}.$$

If $e < 0$, then $-1 < 1 - (\varepsilon_{12} + \varepsilon_{22}) < \lambda_1^0 < \lambda_2^0 < 1$ and $\lambda_2^1 > 1$, hence $(0, 0)$ is stable and $(1, 1)$ is unstable. On the other hand, if $e > 0$, then $\lambda_2^0 > 1$ and $-1 < 1 - (\varepsilon_{11} + \varepsilon_{21}) < \lambda_1^1 < \lambda_2^1 < 1$, hence $(0, 0)$ is unstable and $(1, 1)$ is stable.

Second case: The balanced scenario ($\varepsilon_{11}\varepsilon_{21} = \varepsilon_{12}\varepsilon_{22}$) Under this condition, it is straightforward to notice the relation

$$\varepsilon_{22}p_{k+1} + \varepsilon_{11}q_{k+1} = \varepsilon_{22}p_k + \varepsilon_{11}q_k, \text{ for all } k \in \mathbb{N},$$

hence, if a limit (p^*, q^*) exists, it satisfies

$$r^* := \varepsilon_{22}p^* + \varepsilon_{11}q^* = \varepsilon_{22}p_0 + \varepsilon_{11}q_0 =: r_0.$$

Furthermore, directly from the relation $f_1(p^*, q^*) = p^*$ we get the equality

$$q^* = \frac{\varepsilon_{12}p^*}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*}.$$

Hence, the value of (p^*, q^*) is given by the unique solution of the system

$$\begin{cases} r_0 &= \varepsilon_{22}p^* + \varepsilon_{11}q^*, \\ q^* &= \frac{\varepsilon_{12}p^*}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*}. \end{cases} \quad (3)$$

Computing the Jacobian matrix at (p^*, q^*) gives

$$J_* := J(p^*, q^*) = \begin{pmatrix} 1 - \varepsilon_{11}\frac{q^*}{p^*} & \varepsilon_{12}\frac{p^*}{q^*} \\ \varepsilon_{22}\frac{q^*}{p^*} & 1 - \varepsilon_{21}\frac{p^*}{q^*} \end{pmatrix}.$$

The eigenvalues of J_* are

$$\lambda_1^* = 1 - \left(\varepsilon_{11} \frac{q^*}{p^*} + \varepsilon_{21} \frac{p^*}{q^*}\right) \text{ and } \lambda_2^* = 1.$$

Given that the second eigenvalue is equal to 1, we cannot immediately give a conclusion to the stability of (p^*, q^*) . However, we can proceed as follows: for a fixed (p_0, q_0) , p^* is solution of the equation

$$\begin{aligned} p^* &= f_1\left(p^*, \frac{r^* - \varepsilon_{22}p^*}{\varepsilon_{11}}\right) \\ &= (1 - \varepsilon_{12})p^* + (r^* - \varepsilon_{22}p^*) + (\varepsilon_{12} - \varepsilon_{11})p^* \frac{r^* - \varepsilon_{22}p^*}{\varepsilon_{11}} \\ &= r^* + (1 - (\varepsilon_{12} + \varepsilon_{22}) + (\varepsilon_{12} - \varepsilon_{11}) \frac{r^0}{\varepsilon_{11}})p^* + (\varepsilon_{22} - \varepsilon_{21})(p^*)^2 \\ &=: f(p^*). \end{aligned}$$

This is, p^* is a fixed point of $f(p)$. Therefore, in order to determine the stability of (p^*, q^*) , it suffices to study the value of

$$\begin{aligned} f'(p^*) &= (1 - (\varepsilon_{12} + \varepsilon_{22}) + (\varepsilon_{12} - \varepsilon_{11}) \frac{r^0}{\varepsilon_{11}}) + 2(\varepsilon_{22} - \varepsilon_{21})p^* \\ &= 1 - \left(\varepsilon_{11} \frac{q^*}{p^*} + \varepsilon_{21} \frac{p^*}{q^*}\right), \end{aligned}$$

which is precisely the first eigenvalue of J^* . Since $\lambda_1^* < 1$, (p^*, q^*) will be a stable fixed point if and only if $\lambda_1^* > -1$, or equivalently, if and only if

$$g(p^*) := \frac{\varepsilon_{11}\varepsilon_{12}}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*} + \frac{\varepsilon_{21}}{\varepsilon_{12}}(\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*) = \varepsilon_{11} \frac{q^*}{p^*} + \varepsilon_{21} \frac{p^*}{q^*} < 2.$$

Since $g(p)$ is a convex function over $[0, 1]$, which satisfies $g(0) = \varepsilon_{12} + \varepsilon_{22} < 2$ and $g(1) = \varepsilon_{11} + \varepsilon_{21} < 2$, we conclude $g(p^*) < 2$ for all possible values of p^* . Therefore (p^*, q^*) is a stable fixed point. \square

Let us discuss the results from Proposition 1. There are two scenarios for the unbalanced case. If the players reaction to the lack of cooperation is stronger than the reaction to the presence of it ($e < 0$), then both players will eventually adopt the no cooperation strategy, making the average expected gain equal to 0. On the other hand, two players that are highly responsive to cooperation, and not to the lack of it ($e > 0$), will eventually always cooperate, maximising this way the average expected gain.

We observe a far more complicated outcome when the responses of both players are balanced ($e = 0$). Given that (p^*, q^*) satisfies system (3), then the average expected gain will increase if $\varepsilon_{11} < \varepsilon_{22}$ and the initial values p_0 and q_0 satisfy

$$q_0 > \frac{\varepsilon_{12}p_0}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p_0},$$

or if $\varepsilon_{11} > \varepsilon_{22}$ and

$$q_0 < \frac{\varepsilon_{12}p_0}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p_0}.$$

Thanks to the balance condition, $\varepsilon_{11} < \varepsilon_{22}$ implies that $\varepsilon_{12} < \varepsilon_{21}$. This is, in a way, player A has more shy responses than player B . According to the previously established conditions, interactions between these two players will lead to an increase in the average expected gain only if the initial probability of cooperation for player B is sufficiently big. An analogous interpretation can be given when $\varepsilon_{11} > \varepsilon_{22}$. Figure 2 shows several initial configurations for (p_0, q_0) and their respective limiting values satisfying the relation.

$$q^* = \frac{\varepsilon_{12}p^*}{\varepsilon_{11} + (\varepsilon_{12} - \varepsilon_{11})p^*}.$$

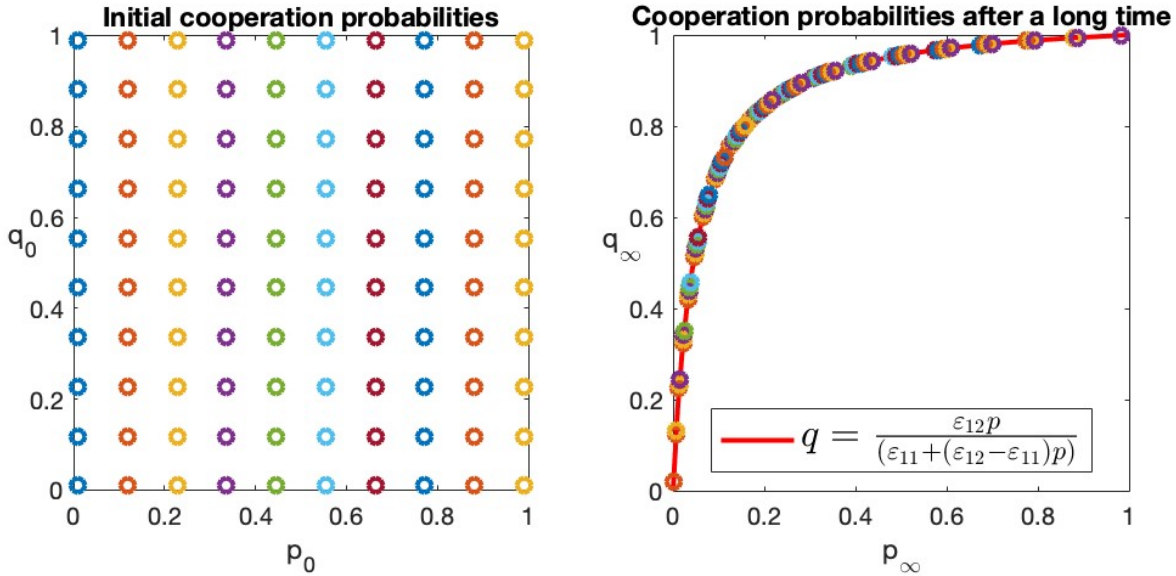


Figure 2: Left panel: Several initial configurations of cooperation probabilities. Right panel: Limiting values of the sequences (p_k, q_k) associated to initial values showcased on the previous figure.

Assume now the presence of n players, each one with an initial probability of cooperation p_0^i and reciprocity constants $(\varepsilon_{i1}, \varepsilon_{i2})$, for $i \in \{1, \dots, n\}$. The previous model can be adapted in such a way that each player modifies its strategy by taking into account the global cooperation level. This is, p_k^i satisfies the relation

$$\begin{aligned} p_{k+1}^i &= q_k^i(p_k + \varepsilon_{i1}(1 - p_k^i)) + (1 - q_k^i)p_k^i(1 - \varepsilon_{i2}) \\ &= (1 - \varepsilon_{i2})p_k^i + \varepsilon_{i1}q_k^i + (\varepsilon_{i2} - \varepsilon_{i1})p_k^i q_k^i, \end{aligned}$$

with

$$q_k^i := \frac{1}{n-1} \sum_{j \neq i} p_k^j,$$

being the average probability of cooperation from the co-players of player i . As in the previous case, it can be expected that the amount of fixed points for this recurrence, and its stability will depend on a family of conditions over the values of $(\varepsilon_{i1}, \varepsilon_{i2})$, however, for the moment being, we will not study this case any further.

An element that was not considered in these models was the effect of the average expected gain on the relation between (p_k, q_k) and (p_{k+1}, q_{k+1}) . For example, considering variable reciprocity coefficients which directly depend on the average expected gain would create a mutual feedback between the cooperation probabilities and the gain, resulting this way in a far more complex, interesting and realistic model.

3.3 A continuously structured population model for the evolution of cooperation

Take $p \in [0, 1]$ to be a continuous structure variable representing a probability of cooperation. Consider two populations A and B , each one composed by individuals with different probabilities of cooperation with the elements on the other population. Let $n_A(t, p)$ and $n_B(t, p)$ be their respective population densities of individuals with probability of cooperation equal to p at time t . The total populations at time t are given by

$$\rho_A(t) := \int_0^1 n_A(t, p) dp \text{ and } \rho_B(t) := \int_0^1 n_B(t, p) dp,$$

and the mean cooperation probabilities by

$$\tilde{p}_A(t) := \frac{\int_0^1 pn_A(t,p)dp}{\rho_A(t)} \text{ and } \tilde{p}_B(t) := \frac{\int_0^1 pn_B(t,p)dp}{\rho_B(t)}.$$

These choices allow to define the global expected gain for each population. For the first population its global expected gain is defined then as

$$E_A(t) := (b - c)\tilde{p}_A(t)\tilde{p}_B(t) + b(1 - \tilde{p}_A(t))\tilde{p}_B(t) - c\tilde{p}_A(t)(1 - \tilde{p}_B(t)) = b\tilde{p}_B(t) - c\tilde{p}_A(t),$$

where b and c are the benefit and cost, respectively, of cooperation in the prisoner's dilemma setting¹. Similarly, the expected gain for population B is given by

$$E_B(t) := b\tilde{p}_A(t) - c\tilde{p}_B(t).$$

This way, we may consider that the population densities evolve following the system of equations

$$\begin{cases} \partial_t n_A(t,p) + \varepsilon_A \partial_p ((\tilde{p}_B(t) - p)n_A(t,p)) = g_A(p, E_A(t))n_A(t,p), \\ \partial_t n_B(t,p) + \varepsilon_B \partial_p ((\tilde{p}_A(t) - p)n_B(t,p)) = g_B(p, E_B(t))n_B(t,p), \\ n_A(0,p) = n_A^0(p), \quad n_B(0,p) = n_B^0(p), \end{cases} \quad (4)$$

where ε_A and ε_B are reciprocity coefficients and g_A, g_B are continuous and increasing functions of E_A and E_B respectively, while the elements of both populations modify their probabilities of cooperation, depending on the global probability of cooperation of their counterpart.

Cooperation or extinction, an easy choice From model (4), we will illustrate, for an specific choice of g_A and g_B , how cooperation may make a difference between extinction or persistence. Consider

$$\begin{aligned} g_A(p, E_A(t)) &:= r_A(p) + \gamma_A(p)E_A(t) = r_A(p) + \gamma_A(p)(b\tilde{p}_B(t) - c\tilde{p}_A(t)), \\ g_B(p, E_B(t)) &:= r_B(p) + \gamma_B(p)E_B(t) = r_B(p) + \gamma_B(p)(b\tilde{p}_A(t) - c\tilde{p}_B(t)), \end{aligned} \quad (5)$$

where $r_A(p), r_B(p)$ are the respective intrinsic growth rates of populations A and B and the non-negative functions $\gamma_A(p), \gamma_B(p)$ represent the effect of the expected gain on the growth rate of each population. This choice of g_A and g_B makes system (4) bear a striking resemblance to the model studied in [35], where conditions under which there is persistence of all species are given. Nevertheless, there are several differences: In our case the non local terms are given by the mean cooperation probabilities, the functions γ_A and γ_B are non-negative and we consider no restrictions over the signs of $r_A(p)$ and $r_B(p)$. Despite these differences, we do not rule out the fact that the tools and techniques used within the cited reference may be useful for the study of problem (4) as well. For specific choices of $\varepsilon_A, \varepsilon_B, \gamma_A$ and γ_B it is possible to identify the conditions over r_A, r_B, b and c which guarantee that one or both populations will either go extinct or proliferate. Such conditions are stated on the following proposition:

Proposition 2. *Consider $\varepsilon_A = \varepsilon_B = 0$, $\gamma_A(p) \equiv \gamma_A$ and $\gamma_B(p) \equiv \gamma_B$, with γ_A, γ_B non negative constants. Suppose $r_A(p), r_B(p), n_A^0(p)$ and $n_B^0(p)$ to be continuous functions such that the maximum value of $r_A(p)$ over the support of $n_A^0(p)$ is attained at a single point p_A^* , and the maximum value of $r_B(p)$ over the support of $n_B^0(p)$ is attained at a single point p_B^* . Then*

- i) *If $r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*) < 0$, population A will go extinct.*
- ii) *If $r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*) > 0$, there exists and interval I satisfying $p_A^* \in I \subset [0, 1]$ such that population A will blow up for all $p \in I$.*
- iii) *The same is true for population B , depending on the sign of $r_B(p_B^*) + \gamma_B(bp_A^* - cp_B^*)$.*

Proof. Under these hypotheses, the expression for $n_A(p)$ and $n_B(p)$ are implicitly given by the expressions

$$n_A(t,p) = n_A^0(p)e^{r_A(p)t + \gamma_A \int_0^t E_A(s)ds} \text{ and } n_B(t,p) = n_B^0(p)e^{r_B(p)t + \gamma_B \int_0^t E_B(s)ds},$$

¹For a more general model, the values of b and c could be dependent on p , this is, the cost and benefit of cooperation might depend on the probability of cooperation itself

respectively. This allows to explicitly compute the values of $\tilde{p}_A(t)$ and $\tilde{p}_B(t)$:

$$\tilde{p}_A(t) = \frac{\int_0^1 p n_A^0(p) e^{r_A(p)t} dp}{\int_0^1 n_A^0(p) e^{r_A(p)t} dp} \quad \text{and} \quad \tilde{p}_B(t) = \frac{\int_0^1 p n_A^0(p) e^{r_B(p)t} dp}{\int_0^1 n_A^0(p) e^{r_B(p)t} dp}.$$

From here, it is not hard to prove that, under the hypotheses of Proposition 2, $\tilde{p}_A(t)$ and $\tilde{p}_B(t)$ converge towards p_A^* and p_B^* respectively. This implies that, for all positive ε there exists $T > 0$ such that $r(p) + \gamma_A(b\tilde{p}_B(t) - c\tilde{p}_A(t)) \leq r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*) + \varepsilon$ for all $t > T$. If ε is chosen small enough, then $r(p) + \gamma_A(b\tilde{p}_B(t) - c\tilde{p}_A(t)) < 0$ for all $t > T$ which gives the convergence to 0 of the population. Conversely, if $r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*) > 0$, we set $\delta := \frac{r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*)}{2}$, and define

$$I = \{p \in [0, 1] : r_A(p) > r_A(p_A^*) - \delta\}.$$

Hence, for all $p \in I$ there exists $T > 0$ such that

$$r(p) + \gamma_A(b\tilde{p}_B(t) - c\tilde{p}_A(t)) \geq r_A(p_A^*) - \delta + \gamma_A(b\tilde{p}_B(t) - c\tilde{p}_A(t)) - \varepsilon = \delta - \varepsilon,$$

for all $t > T$. Once again, by choosing ε small enough we obtain the strictly positive growth rate for all values of $p \in I$, which implies the blow up of the population for all such values of p .

The proof for population B is analogous. \square

Let us illustrate the result of Proposition 2 with an example. Consider

$$r_A(p) = r_B(p) = p(1-p) - \frac{1}{2} < 0.$$

It is straightforward to conclude that, if there is no cooperation ($\gamma_A(p) = \gamma_B(p) = 0$ or $n_0^A(p) = n_0^B(p) = \rho_0 \delta_0(p)$) then both populations will go extinct, at an exponential rate. On the other hand, consider $\gamma_A(p) = \gamma_B(p) = 1$, $n_0^A(p) \equiv n_0^A$ and $n_0^B(p) \equiv n_0^B$. Under these assumptions, we have

$$n_A(t, p) = n_0^A e^{r_A(p)t + \int_0^t E_A(s) ds} \quad \text{and} \quad n_B(t, p) = n_0^B e^{r_B(p)t + \int_0^t E_B(s) ds},$$

and consequently we get

$$\tilde{p}_A(t) = \frac{\int_0^1 p e^{r_A(p)t} dp}{\int_0^1 e^{r_A(p)t} dp} = \frac{1}{2} \quad \text{and} \quad \tilde{p}_B(t) = \frac{\int_0^1 p e^{r_B(p)t} dp}{\int_0^1 e^{r_B(p)t} dp} = \frac{1}{2},$$

after integrating by means of a substitution. This way, the equations for $n_A(t, p)$ and $n_B(t, p)$ are reduced to

$$\begin{cases} \partial_t n_A(t, p) = (r_A(p) + \frac{(b-c)}{2}) n_A(t, p), \\ \partial_t n_B(t, p) = (r_B(p) + \frac{(b-c)}{2}) n_B(t, p), \\ n_A(0, p) = n_0^A, \quad n_B(0, p) = n_0^B. \end{cases}$$

It is then evident that, as long as $(b-c) > 1$ there will be values of p for which $r_A(p) + \frac{(b-c)}{2} > 0$ and $r_B(p) + \frac{(b-c)}{2} > 0$, hence, the population densities $n_A(t, p)$ and $n_B(t, p)$ will be proliferating exponentially. An interesting question left unanswered is the case $r_A(p_A^*) + \gamma_A(bp_B^* - cp_A^*) = 0$. In this scenario, additional conditions over the parameters of the problem might be needed in the general case in order to determine the behaviour of the solution. For the previous illustrative example, this condition is equivalent to choosing $b-c = \frac{1}{2}$, which leads to a solution which decreases for all $p \neq 1/2$ and that remains constant for $p = 1/2$. It is also of interest to identify whether the effect of cooperation on the populations dynamics proved in Proposition 2 can be observed for a more general family of conditions, and choices of g_A and g_B . As mentioned before, the tools presented in [35] might be of use in order to better understand the long time dynamics of both populations, and identify concentration phenomena, stable steady states and rates of convergence or explosion.

The study of the effect of the advection term, representing reciprocity adds a layer of complexity to the study of the problem. We refer to [17] and the references therein, where similar non local advection-reaction problems have been studied, but for a single population. A diffusion term can be considered as well in both equations of system (4) in order to model random instabilities of the probabilities of

cooperation. This term may be a second order differential operator and suitable boundary conditions, or an integral term with a mutation kernel. A similar model, for only one population, excluding the advection term and depending on the population size as the non-local term was already studied in [27]. Finally, if all three terms are considered, the resulting model will follow the same principles as in model (1), where the diffusion term represents the non-genetic instability of trait p , the advection term represents the external stress exerted over each population as in [2] or the existence of a bias in the direction of epimutations, as in [8] (in our case such stress or bias is prompted by the global cooperation probability of the other population) and the reaction term accounts for selection mechanisms.

4 Conclusion

We have sketched in this short essay, relying on concepts of philosophy of science and on mathematical models under development, the two settings of evolution in which phenotype divergence and cooperation between phenotypes in the constitution of animal multicellularity should be considered from our point of view. They are the billion-year Darwinian evolution of species - which we assimilate with the evolution of body plans - and the short-term construction, in embryogenesis and development, of an isogenic animal from the zygote to the constituted, terminally differentiated multicellular organism.

In the first case, phenotype divergence is considered to be determined by changes in the environment, and it is represented by an advection term in a PDE, yielding different optimal adaptive strategies that are chosen randomly in the initial body plan and resulting in (at least) two different body plans, that in the first place should be reversible, before being fixed by stabilising mutations.

In the second case, the body plan of a given coherent multicellular animal, that has been established in Darwinian evolution in a deterministic machinery of embryogenesis and organism maintenance, governs the process of development from the zygote of the animal individual on principles of compatibility and cooperativity between physiological functions, organs and tissues, that relies on cell differentiations. Of note, cellular stress-induced genes might evolve into developmental organisers, according to a mechanism proposed in the *Chlamydomonas/Volvox* lineage [23]. Such differentiations are by nature theoretically reversible, relying on epigenetic enzyme activities which graft methyl or acetyl radicals on the DNA or on the histones that constitute the genome on animal, and dedifferentiations indeed have been shown to be experimentally possible in 2006 by Takahashi and Yamanaka [48]. However, they are physiologically excluded, except in particular situations such as wound healing, by a strict control of the expression of these epigenetic enzymes. Plasticity in cancer cells alters such normal organismic control.

In cancer, which is a disease characteristic of multicellular animals, differentiations are (locally, in the tissue from which it originates) out of organismic control, so that tumours, as poorly organised cell colonies that nevertheless are made of cells bearing in each one of them the body plan of a multicellular organism, can reactivate a process of phenotype divergence in response to a deadly insult (such as a chemotherapy at high doses), resulting in cancer bet hedging, i.e., developing diverse transient (reversible) phenotypes without organised control, with the goal to preserve the proliferation potential of their cells.

We are aware that the mathematical models presented here are sketches that need refinement, and that in particular the cooperativity part should be oriented towards defining a compulsory common gain (likely represented by, again, an advection term in a PDE) that determines the precise construction of an individual animal organism designed by its body plan. Much still remains to be done towards this goal, and in particular the body plan - whose effects are patent in embryogenesis and development, but is still not properly defined as a programme - needs to be better defined in a mathematical representation. It is likely made of an organised ensemble of gene regulatory networks, as evidenced in the works of Eric Davidson [12] and his colleagues, and systematically described in the diversity of its functions in hypothetical *Urmetazoa* by W.E.G. Müller and his colleagues [30]. A mathematical representation of the body plan, as a programme of construction of the individual and as the evolutionary unit on which relies Darwinian evolution and the design of animal anatomy and physiology, is a challenge that awaits philosophers, evolutionary biologists, and mathematical modellers and analysts, a challenge we have merely sketched in this short essay.

References

- [1] Aktipis, C.A., Boddy, A.M., Jansen, G., Hibner, U., Hochberg, M.E., Maley, C.C., & Wilkinson, G.S. (2015). Cancer across the tree of life: cooperation and cheating in multicellularity. *Phil. Trans. Roy. Soc. B*, 370: 20140219.

- [2] Alvarez, F.E., Carrillo, J.A., & Clairambault, J. (2022). Evolution of a structured cell population endowed with plasticity of traits under constraints on and between the traits. *J. Math. Biol.* 85:64.
- [3] Axelrod, R. & Hamilton, W. D. (1981). The evolution of cooperation. *Science*, 211(4489), 1390–1396. <https://doi.org/10.1007/s00285-022-01820-5>
- [4] Balter, V., Braga, J., Télouk, P., & Thackeray, J.F. (2012). Evidence for dietary change but not landscape use in South African early hominins. *Nature Lett.* 558:489, 558–560.
- [5] Bayle, P. (1682). *Pensées diverses sur la comète*. Ch. VII, Paris.
- [6] Bertolaso, M. (2016). *Philosophy of Cancer. A Dynamic and Relational View*. Springer Science+Business Media B.V., Dordrecht.
- [7] Boveri, T. (1914). *Zur Frage der Entstehung maligner Tumoren*. Gustav Fischer Verlag, Jena. Re-translated and annotated in 2008 by H. Harris as “Concerning the Origin of Malignant Tumours by Theodor Boveri”, *J. Cell Sci.* (2008) 121 (Supplement 1):1–84. <https://doi.org/10.1242/jcs.025742>
- [8] Chisholm, R.H., Lorenzi, T., Desvillettes, L. & Hughes, B.D. (2016). Evolutionary dynamics of phenotype-structured populations: from individual-level mechanisms to population-level consequences. *Z. Angew. Math. Phys.* 67, 100. <https://doi.org/10.1007/s00033-016-0690-7>
- [9] Clairambault, J. (2020). Plasticity in cancer cell populations: biology, mathematics and philosophy of cancer. In: G. Bebis, M. Alekseyev, H. Cho, J. Gevertz, M. Rodriguez Martinez (Eds.), Springer LNBI 12508, pp. 3-9, October 2020. <https://hal.science/hal-03066491>
- [10] Clairambault, J. (2023). Mathematical modelling of cancer growth and drug treatments: taking into account cell population heterogeneity and plasticity. Paper #427 in Proceedings of ECC 2023 European conference on control, Bucharest, June 2023. <https://hal.science/hal-03938411>
- [11] Cleary, A.S., *et al.* (2014). Tumour cell heterogeneity maintained by cooperating subclones in Wnt-driven mammary cancers. *Nature Lett.* 508:113–117.
- [12] Davidson, E.H., Peterson, K.J., & Cameron, R.A. (1995). Origin of Bilaterian Body Plans: Evolution of Developmental Regulatory Mechanisms. *Science*, 270(5240):1319-1325.
- [13] Davies, P.C.W. & Lineweaver, C.H. (2011). Cancer tumors as Metazoa 1.0: tapping genes of ancient ancestors. *Phys. Biol.* 8:015001 (7pp).
- [14] Domazet-Lošo, T. & Tautz, D. (2008). An ancient evolutionary origin of genes associated with human genetic diseases, *Mol. Biol. Evol.*, 25(12):2699-2707.
- [15] Domazet-Lošo, T. & Tautz, D. (2010). Phylostratigraphic tracking of cancer genes suggests a link to the emergence of multicellularity in metazoa, *BMC Biol.* , 8(1):66.
- [16] Gould, S.J. (1977). *Ontogeny and Phylogeny*. Harvard University Press.
- [17] Guilberteau, J., Pouchol C., & Pouradier Duteil, P (2023). “Long-time behaviour of an advection-selection equation”. Preprint arXiv:2301.02470.
- [18] Haeckel, E. (1866). *Generelle morphologie der organismen*. G. Reimer Verlag, Berlin, 1866
- [19] Hatzikirou, H., Basanta, D., Simon, M., Schaller, K., & Deutsch, A. (2010). ‘Go or Grow’: the key to the emergence of invasion in tumour progression? *Mathematical Medicine and Biology*, 29(1):49-65.
- [20] Hirsch, P., Zhang, Y., Tang, R., Joulin, V., Boutroux, H., Pronier, E., *et al.* (2016). Genetic hierarchy and temporal variegation in the clonal history of acute myeloid leukemia. *Nature Comm.* 7:12475
- [21] Israel, L. (1996). Tumour Progression: Random Mutations or an Integrated Survival Response to Cellular Stress Conserved from Unicellular Organisms? *J. Theor. Biol.* 178, 375–380
- [22] Jacob, F. (1977). Evolution and tinkering. *Science*, 196:4295, 1161–1166.
- [23] König, S.G. & Nedelcu, A.M. (2020). The genetic basis for the evolution of soma: mechanistic evidence for the co-option of a stress-induced gene into a developmental master regulator. *Proc. R. Soc. B* 287:20201414.

- [24] Lineweaver, C.H., Davies, P.C.W., & Vincent, M. (2014). Targeting cancer’s weaknesses (not its strengths): therapeutic strategies suggested by the atavistic model. *Bioessays* 36(9):827–835.
- [25] Lineweaver, C.H. & Davies, P.C.W. (2020). Comparison of the atavistic model of cancer to somatic mutation theory: phylostratigraphic analyses support the atavistic model. Ch. 12 in *The physics of cancer*, B.E. Gerstman Ed., World Scientific, Singapore.
- [26] Lineweaver, C. H., Bussey, K. J., Blackburn, A. C., & Davies, P. C. W. (2021). Cancer progression as a sequence of atavistic reversions. *BioEssays* 43, 2000305.
- [27] Lorenzi, T. & Pouchol, C. (2020). Asymptotic analysis of selection-mutation models in the presence of multiple fitness peaks. *Nonlinearity* 33 5791. doi: 10.1088/1361-6544/ab9bad
- [28] Maynard Smith, J. & Szathmáry, E. (1995). *The major transitions in evolution*. W.H. Freeman, Oxford.
- [29] McCullough, K.D., Coleman, W.B., Ricketts, S.L., Wilson, J.W., Smith, G.J., & Grisham, J.W. (1998). Plasticity of the neoplastic phenotype in vivo is regulated by epigenetic factors. *Proc. Natl. Acad. Sci. USA*, 95(26):15333-15338.
- [30] Müller, W.E.G., Wiens, M., Adell, T., Gamulin, V., Schröder, H.C., & Müller, I.M. (2004). Bauplan of Urmetazoa: Basis for Genetic Complexity of Metazoa. *Int. Rev. Cytol.* 235:53-92
- [31] Murase, Y., Hilbe, C., & Baek, S.K. (2022). Evolution of direct reciprocity in group-structured populations. *Sci Rep* 12, 18645. <https://doi.org/10.1038/s41598-022-23467-4>
- [32] Nedelcu, A.M. & Michod, R.E. (2020). Stress Responses Co-Opted for Specialized Cell Types During the Early Evolution of Multicellularity. : The Role of Stress in the Evolution of Cell Types Can Be Traced Back to the Early Evolution of Multicellularity. *Bioessays* 42(5):e2000029.
- [33] Nedelcu, A.M. (2020). The evolution of multicellularity and cancer: views and paradigms. *Biochem. Soc. Trans.*, 48(4):1505–1518.
- [34] Polyak, K. & Marusyk, A. (2014). Clonal cooperation. *Nature* 508:53–54.
- [35] Pouchol, C. & Trélat, E. (2018). Global stability with selection in integro-differential Lotka-Volterra systems modelling trait-structured populations. *Journal of Biological Dynamics*. Vol. 12, No. 1, 872–893. doi: 10.1080/17513758.2018.1515994
- [36] Pradeu T. (2019). *Philosophy of immunology*. Cambridge University Press.
- [37] Pradeu, T., *et al.* (2023). Reuniting philosophy and science to advance cancer research. *Biol. Rev.*, pp. 000–000. doi: 10.1111/brv.12971
- [38] Tabassum, D.P. & Polyak, K. (2015). Tumorigenesis: it takes a village. *Nature Rev. Cancer* 15:473–483.
- [39] Trigos, A.S., Pearson, R.B., Papenfuss, A.T., & Goode, D.L. (2017). Altered interactions between unicellular and multicellular genes drive hallmarks of transformation in a diverse range of solid tumors. *Proc. Natl. Acad. Sci. USA* 114 (24):6406-6411.
- [40] Trigos, A.S., Pearson, R.B., Papenfuss, A.T., & Goode, D.L. (2018). How the evolution of multicellularity set the stage for cancer, *Br. J. Cancer* 118:145-152.
- [41] Trigos, A.S., Pearson, R.B., Papenfuss, A.T., & Goode, D.L. (2019). Somatic mutations in early metazoan genes disrupt regulatory links between unicellular and multicellular genes in cancer. *eLIFE* 8:e40947, 28 pages.
- [42] Trigos, A.S., Bongiovanni, S., Zethoven, M., Tothill, R., Pearson, R., Papenfuss, T., & Goode D.L. (2023). Disruption of metazoan gene regulatory networks in cancer alters the balance of co-expression between genes of unicellular and multicellular origins. *bioRxiv* <https://www.biorxiv.org/content/10.1101/2023.04.20.537744>
- [43] Wagner, G.P., Erkenbrack, E.M., & Love, A.C. (2019). Stress-Induced Evolutionary Innovation: A mechanism for the origin of cell types. *Bioessays* 41(4): e1800188.

- [44] Vincent, M. (2011). Cancer: a de-repression of a default survival program common to all cells?: a life-history perspective on the nature of cancer, *Bioessays*, 34(1):72-82.
- [45] Wegener, A. (1912). Die Entstehung der Kontinente. *Geologische Rundschau*, 3:276-292.
- [46] Weismann, F.L.A. (1892) *Das Keimplasma. Eine Theorie der Vererbung*, Gustav Fischer, Jena.
- [47] Wolpert, L. & Szathmáry, E. (2002). Evolution and the egg. *Nature* 420:745.
- [48] Takahashi, K. & Yamanaka, S. (2006). Induction of Pluripotent Stem Cells from Mouse Embryonic and Adult Fibroblast Cultures by Defined Factors. *Cell* 126:663–676.