

# Non-Vertical Cultural Transmission, Assortment, and the Evolution of Cooperation

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## Abstract

We study the cultural evolution of cooperation under vertical, horizontal, and oblique transmission. Conditions are found for fixation and coexistence of cooperation and defection. We find that the evolution of cooperation is facilitated by horizontal transmission, especially when there is an association between cooperation and transmission, and that the effect of oblique transmission depends on the bias in horizontal transmission. Interestingly, stable coexistence of cooperation and defection can occur. A spatial model is constructed and compared to results from an unstructured model. Comparisons are drawn with Hamilton's rule and the concepts of relatedness and assortment.

# Introduction

Cooperative behavior can reduce an individual's fitness and increase the fitness of its conspecifics or competitors (Axelrod and Hamilton, 1981). Nevertheless, cooperative behavior appears to occur in many non-human animals (Dugatkin, 1997), including primates (Jaeggi and Gurven, 2013), rats (Rice and Gainer, 1962), birds (Stacey and Koenig, 1990; Krams et al., 2008), and lizards (Sinervo et al., 2006). Evolution of cooperative behavior remains an important conundrum in evolutionary biology.

Since the work of Hamilton (1964) and Axelrod and Hamilton (1981), theories for the evolution of cooperative and altruistic behaviors have been intertwined often under the rubric of *kin selection*. Kin selection theory posits that natural selection is more likely to favor cooperation between more closely related individuals. The importance of *relatedness* to the evolution of cooperation and altruism was demonstrated by Hamilton (1964), who showed that an allele that determines cooperative behavior will increase in frequency if the reproductive cost to the actor that cooperates,  $c$ , is less than the benefit to the recipient,  $b$ , times the relatedness,  $r$ , between the recipient and the actor. This condition is known as *Hamilton's rule*:

$$c < b \cdot r, \quad (1)$$

where the relatedness coefficient  $r$  measures the probability that an allele sampled from the cooperator is identical by descent to one at the same locus in the recipient.

Eshel and Cavalli-Sforza (1982) studied a related model for the evolution of cooperative behavior. Their model included *assortative meeting*, or non-random encounters, where a fraction  $m$  of individuals in the population each interact with an individual of the same phenotype, and a fraction  $1 - m$  interacts with a randomly chosen individual. Such assortative meeting may be due, for example, to population structure or active partner choice. In their model, cooperative behavior can evolve if<sup>1</sup> (Eshel and Cavalli-Sforza, 1982, eq. 3.2)

$$c < b \cdot m, \quad (2)$$

where  $b$  and  $c$  are the benefit and cost of cooperation. Here  $m$  in inequality 2 takes the role of the relatedness coefficient  $r$  in inequality 1.

The role of assortment in the evolution of altruism was emphasized by Fletcher and Doebeli (2009). They found that in a *public-goods* game, altruism will evolve if cooperative individuals experience more cooperation, on average, than defecting individuals, and “thus, the evolution of altruism requires (positive) assortment between focal *cooperative* players and cooperative acts in their interaction environment.” With some change in parameters, this condition is summarized by (Fletcher and Doebeli, 2009, eq. 2.3)

$$c < b \cdot (p_C - p_D), \quad (3)$$

where  $p_C$  is the probability that a cooperator receives help, and  $p_D$  is the probability that a defector receives help.<sup>2</sup> See Bijma and Aanen (2010) for treatment of non-public-goods games.

In this paper we study the evolution of a cooperative behavior that is subject to *cultural transmission*, which allows an individual to acquire attitudes or behavioral traits from other individuals in its social group through imitation, learning, or other modes of communication (Cavalli-Sforza and Feldman, 1981; Richerson and Boyd, 2008). Feldman et al. (1985) introduced the first model for the evolution of altruism by cultural transmission. They demonstrated that if the fidelity of cultural transmission of

<sup>1</sup>In an extended model, which allows an individual to encounter  $N$  individuals before choosing a partner, the righthand side is multiplied by  $E[N]$ , the expected number of encounters (Eshel and Cavalli-Sforza, 1982, eq. 4.6).

<sup>2</sup>inequality 3 generalizes inequality 1 and inequality 2 by substituting  $e_C = r + p$ ,  $e_D = p$  and  $e_C = m + (1 - m)p$ ,  $e_D = (1 - m)p$ , respectively, where  $p$  is the frequency of cooperators.

60 altruism is  $\varphi$ , then the condition for evolution of altruism in the case of sib-to-sib altruism is (Feldman  
et al., 1985, Eq. 16)

$$62 \quad c < b \cdot \varphi - \frac{1 - \varphi}{\varphi}. \quad (4)$$

In inequality 4,  $\varphi$  takes the role of relatedness ( $r$  in inequality 1) or assortment ( $m$  in inequality 2),  
64 but the effective benefit  $b \cdot \varphi$  is further reduced by  $(1 - \varphi)/\varphi$ . This shows that under a combination  
of genetic and cultural transmission, the condition for the evolutionary success of altruism entails a  
66 modification of Hamilton's rule (inequality 1).

Cultural transmission may be either viewed as vertical, horizontal or oblique: vertical transmission  
68 occurs between parents and offspring, horizontal transmission occurs between individuals from the  
same generation, and oblique transmission occurs to offspring from the generation to which their  
70 parents belong (i.e. from non-parental adults). Evolution under either of these transmission models  
can be more rapid than under pure vertical transmission (Cavalli-Sforza and Feldman, 1981; Lycett  
72 and Gowlett, 2008; Ram et al., 2018). Both Woodcock (2006) and Lewin-Epstein et al. (2017)  
demonstrated that non-vertical transmission can help explain the evolution of cooperative behavior  
74 (the former using simulations with cultural transmission, the latter using a model where cooperation is  
mediated by microbes that manipulate their host's behavior.) Some of the analyses by Lewin-Epstein  
76 et al. (2017) can be applied to cultural transmission, because models of cultural transmission are  
mathematically similar to those for transmission of infectious diseases (Cavalli-Sforza and Feldman,  
78 1981).

Here, we study cultural-evolution models of cooperation that include both vertical and non-vertical  
80 transmission. We investigate these models using mathematical analysis and simulations. In our  
models behavioral changes are mediated by cultural transmission that can occur specifically during  
82 social interactions. For instance, there may be an association between the choice of partner for social  
interaction and the choice of partner for cultural transmission. As another example, when an individual  
84 interacts with an individual of a different phenotype, this exposure to a different phenotype may lead  
it to learn or convert its phenotype. Our results demonstrate that cultural transmission can enhance  
86 the evolution of cooperation even when genetic transmission cannot, partly because it facilitates the  
generation of assortment (Fletcher and Doebeli, 2009), and partly because non-vertical transmission  
88 can protect traits from the effect of natural selection (Ram et al., 2018). This further emphasizes that  
treatment of cooperation as a cultural trait, rather than a genetic one, can lead to a better understanding  
90 of its evolutionary dynamics.

## Models

92 Consider a very large population whose members are characterized by their phenotype  $\phi$ , which can  
be of two types,  $\phi = A$  for cooperators or  $\phi = B$  for defectors. An offspring inherits its phenotype  
94 from its parent via vertical transmission with probability  $v$  or from a random individual in the parental  
population via oblique transmission with probability  $(1 - v)$ . Following Ram et al. (2018), given that  
96 the parent phenotype is  $\phi$  and assuming uni-parental inheritance, the conditional probability that the  
phenotype  $\phi'$  of the offspring is  $A$  is

$$98 \quad P(\phi' = A \mid \phi) = \begin{cases} v + (1 - v)p, & \text{if } \phi = A \\ (1 - v)p, & \text{if } \phi = B \end{cases}, \quad (5)$$

where  $p = P(\phi = A)$  is the frequency of  $A$  among all adults in the parental generation.

100 Not all adults become parents due to natural selection, and we denote the frequency of phenotype  $A$   
among parents by  $\tilde{p}$ . Therefore, the frequency  $\hat{p}$  of phenotype  $A$  among juveniles (after selection and  
102 vertical and oblique transmission) is

$$\begin{aligned}\hat{p} &= \tilde{p}[v + (1 - v)p] + (1 - \tilde{p})[(1 - v)p] \\ &= v\tilde{p} + (1 - v)p.\end{aligned}\tag{6}$$

104 Individuals are assumed to interact according to a *prisoner's dilemma*. Specifically, individuals  
 106 interact in pairs; a cooperator suffers a fitness cost  $0 < c < 1$ , and its partner gains a fitness benefit  
 $b$ , where we assume  $c < b$ . Table 1 shows the payoff matrix, i.e. the fitness of an individual with  
 phenotype  $\phi_1$  when interacting with a partner of phenotype  $\phi_2$ .

	$\phi_2 = A$	$\phi_2 = B$
$\phi_1 = A$	$1 + b - c$	$1 - c$
$\phi_1 = B$	$1 + b$	$1$

**Table 1: Payoff matrix for prisoner's dilemma.** The fitness of phenotype  $\phi_1$  when interacting with phenotype  $\phi_2$ .  $A$  is a cooperative phenotype,  $B$  is a defector phenotype,  $b$  is the benefit gained by an individual interacting with a cooperator, and  $c$  is the cost of cooperation.  $b > c > 0$ .

108 Social interactions occur randomly: two juvenile individuals with phenotype  $A$  interact with proba-  
 bility  $\hat{p}^2$ , two juveniles with phenotype  $B$  interact with probability  $(1 - \hat{p})^2$ , and two juveniles with  
 110 different phenotypes interact with probability  $2\hat{p}(1 - \hat{p})$ .

Horizontal cultural transmission occurs between pairs of individuals from the same generation. It  
 112 occurs between social interaction partners with probability  $\alpha$ , or between a random pair with proba-  
 bility  $1 - \alpha$  (see Figure 1). The social association  $\alpha$  is therefore the fraction of population that  
 114 receives (horizontal transmission) from the social interaction partner, and  $1 - \alpha$  receives randomly.  
 Horizontal transmission is not always successful, as one partner may reject the other's phenotype. The  
 116 probability for successful horizontal transmission of phenotypes  $A$  and  $B$  are  $T_A$  and  $T_B$ , respectively  
 (Table 2).

118 Therefore, the frequency  $p'$  of phenotype  $A$  among adults in the next generation, after horizontal  
 transmission, is

$$\begin{aligned}p' &= \hat{p}^2[\alpha + (1 - \alpha)(\hat{p} + (1 - \hat{p})(1 - T_B))] \\ &\quad + \hat{p}(1 - \hat{p})[\alpha(1 - T_B) + (1 - \alpha)(\hat{p} + (1 - \hat{p})(1 - T_B))] \\ &\quad + (1 - \hat{p})\hat{p}[\alpha T_A + (1 - \alpha)\hat{p}T_A] \\ &\quad + (1 - \hat{p})^2[(1 - \alpha)\hat{p}T_A],\end{aligned}\tag{7}$$

which simplifies to

$$p' = \hat{p}^2(T_B - T_A) + \hat{p}(1 + T_A - T_B).\tag{8}$$

Phenotype $\phi_1$	Phenotype $\phi_2$	Frequency	Fitness of $\phi_1$	$P(\phi_1 = A)$ via horizontal transmission:	
				from partner, $\alpha$	from population, $(1 - \alpha)$
$A$	$A$	$\hat{p}^2$	$1 + b - c$	$1$	$\hat{p} + (1 - \hat{p})(1 - T_B)$
$A$	$B$	$\hat{p}(1 - \hat{p})$	$1 - c$	$1 - T_B$	$\hat{p} + (1 - \hat{p})(1 - T_B)$
$B$	$A$	$\hat{p}(1 - \hat{p})$	$1 + b$	$T_A$	$\hat{p}T_A$
$B$	$B$	$(1 - \hat{p})^2$	$1$	$0$	$\hat{p}T_A$

**Table 2: Interaction frequency, fitness, and transmission probabilities.**

The frequency of  $A$  among parents (i.e. after selection) follows a similar dynamic, but also includes the effect of natural selection, and is therefore

$$\begin{aligned}\bar{w}\tilde{p}' &= \hat{p}^2(1+b-c)[\alpha + (1-\alpha)(\hat{p} + (1-\hat{p})(1-T_B))] \\ &+ \hat{p}(1-\hat{p})(1-c)[\alpha(1-T_B) + (1-\alpha)(\hat{p} + (1-\hat{p})(1-T_B))] \\ &+ (1-\hat{p})\hat{p}(1+b)[\alpha T_A + (1-\alpha)\hat{p}T_A] \\ &+ (1-\hat{p})^2[(1-\alpha)\hat{p}T_A] ,\end{aligned}\tag{9}$$

where fitness values are taken from Table 1 and Table 2, and the population mean fitness is

$$\bar{w} = 1 + \hat{p}(b-c).\tag{10}$$

Eq. 9 can be simplified to

$$\begin{aligned}\bar{w}\tilde{p}' &= \hat{p}^2(1+b-c)(1 - (1-\hat{p})(1-\alpha)T_B) \\ &+ \hat{p}(1-\hat{p})(1-c)(\hat{p}(1-\alpha)T_B + 1 - T_B) \\ &+ (1-\hat{p})\hat{p}(1+b)(\hat{p}(1-\alpha) + \alpha)T_A \\ &+ (1-\hat{p})^2\hat{p}(1-\alpha)T_A .\end{aligned}\tag{11}$$

where  $\hat{p} = v\tilde{p} + (1-v)p$ . Table 3 summarized the model variables and parameters.

Symbol	Description	Values
$A$	Cooperator phenotype	
$B$	Defector phenotype	
$p$	Frequency of phenotype $A$ among adults	$[0, 1]$
$\tilde{p}$	Frequency of phenotype $A$ among parents	$[0, 1]$
$\hat{p}$	Frequency of phenotype $A$ among juveniles	$[0, 1]$
$v$	Vertical transmission rate	$[0, 1]$
$c$	Cost of cooperation	$(0, 1)$
$b$	Benefit of cooperation	$c < b$
$\alpha$	Social association	$[0, 1]$
$T_A, T_B$	Horizontal transmission rates of phenotype $A$ and $B$	$[0, 1]$

**Table 3: Model variables and parameters.**

## Results

### Oblique and Horizontal Transmission

With only oblique and horizontal transmission, i.e.  $v = 0$ , Eq. 6 becomes  $\hat{p} = p$  and Eq. 8 becomes

$$p' = p^2(T_B - T_A) + p(1 + T_A - T_B) .\tag{12}$$

Solving for  $p' > p$  we get the following result.

138 **Result 1** (Oblique and horizontal transmission of cooperation). *Without vertical transmission* ( $v = 0$ ),  
 140 *if there is a horizontal transmission bias in favor of cooperation, namely*

$$T_A > T_B , \quad (13)$$

*then the frequency of the cooperator phenotype among adults increases every generation,  $p' > p$ .*

142 That is, in the absence of vertical transmission, selection plays no role in the evolution of cooperation  
 (i.e.  $b$  and  $c$  are missing from Eq. 12). The dynamics are determined solely by differential horizontal  
 144 transmission of the two phenotypes, that is, the relative tendency of each phenotype to be horizontally  
 transmitted to peers (see Figure 6c). Note that without bias in horizontal transmission,  $T_A = T_B$ ,  
 146 phenotype frequencies are static,  $p' = p$ .

## Vertical and Horizontal Transmission

148 With only vertical and horizontal transmission, i.e.  $v = 1$ , Eq. 6 becomes  $\hat{p} = \tilde{p}$ , and Eq. 11 for  
 the frequency of the cooperative phenotype among parents in the next generation  $\tilde{p}'$  can be written  
 150 as

$$\begin{aligned} \bar{w}\tilde{p}' &= \tilde{p}^2(1+b-c)[1-(1-\tilde{p})(1-\alpha)T_B] \\ &\quad + \tilde{p}(1-\tilde{p})(1-c)[\tilde{p}(1-\alpha)T_B + 1 - T_B] \\ &\quad + \tilde{p}(1-\tilde{p})(1+b)[\tilde{p}(1-\alpha) + \alpha]T_A \\ &\quad + (1-\tilde{p})^2\tilde{p}(1-\alpha)T_A . \end{aligned} \quad (14)$$

152 Fixation of either cooperation,  $\tilde{p} = 1$ , or defection,  $\tilde{p} = 0$ , are equilibria of Eq. 14, that is, they solve  
 $\tilde{p}' = \tilde{p}$ . We therefore assume for the remainder of the analysis that  $0 < \tilde{p} < 1$ .

154 If  $\alpha = 1$ , then  $\tilde{p}' = \tilde{p}$  is reduced to

$$\tilde{p}(1-\tilde{p})[(1+b)T_A + (1-c)(1-T_B) - 1] = 0 , \quad (15)$$

156 and there are no additional equilibria. For cooperation to take over the population (for  $\tilde{p} = 1$  to be  
 globally stable) we require  $\tilde{p}' > \tilde{p}$ ; that is,

$$\tilde{p}^2(1+b-c) + \tilde{p}(1-\tilde{p})[(1-c)(1-T_B) + (1+b)T_A] > \bar{w}\tilde{p} . \quad (16)$$

Factoring out  $\tilde{p}(1-\tilde{p})$  and setting  $\bar{w} = 1 + \tilde{p}(b-c)$ , we find that  $\tilde{p}' > \tilde{p}$  if

$$(1-c)(1-T_B) + (1+b)T_A > 1 . \quad (17)$$

162

If  $\alpha < 1$ , divide both sides of Eq. 14 by  $\tilde{p}$  and set  $\bar{w} = 1 + \tilde{p}(b-c)$ . Then  $\tilde{p}' > \tilde{p}$  if

$$\begin{aligned} 1 + \tilde{p}(b-c) &< \tilde{p}(1+b-c)(1-(1-\tilde{p})(1-\alpha)T_B) \\ &\quad + (1-\tilde{p})(1-c)(\tilde{p}(1-\alpha)T_B + 1 - T_B) \\ &\quad + (1-\tilde{p})(1+b)(\tilde{p}(1-\alpha) + \alpha)T_A \\ &\quad + (1-\tilde{p})^2(1-\alpha)T_A . \end{aligned} \quad (18)$$

Simplifying, we find that  $\tilde{p}' > \tilde{p}$  if and only if

$$c(1-T_B) - b\alpha T_A - (T_A - T_B) < \tilde{p} \cdot b(1-\alpha)(T_A - T_B) . \quad (19)$$

In addition to the the fixation states  $\tilde{p} = 0$  and  $\tilde{p} = 1$ , there may be an actual polymorphic equilibrium of  $\tilde{p}' = \tilde{p}$  in Eq. 14, namely

$$\tilde{p}^* = \frac{c(1 - T_B) - b\alpha T_A - (T_A - T_B)}{b(1 - \alpha)(T_A - T_B)}, \quad (20)$$

which is legitimate if  $0 < \tilde{p}^* < 1$ .

Since all parameters are positive, we can apply inequality 19 and see that a requirement for  $\tilde{p}' > \tilde{p}$  is that either

$$T_A > T_B \quad \text{and} \quad \tilde{p} > \tilde{p}^*, \quad \text{or} \quad (21)$$

$$T_A < T_B \quad \text{and} \quad \tilde{p} < \tilde{p}^*. \quad (22)$$

We define the *cost boundaries*,

$$\gamma_1 = \frac{b\alpha T_A + (T_A - T_B)}{1 - T_B}, \quad \gamma_2 = \frac{b\alpha T_B + (1 + b)(T_A - T_B)}{1 - T_B}. \quad (23)$$

Then, applying Eqs. 20, 21, and 22, we summarize the possible outcomes in the following result and corollaries.

**Result 2** (Vertical and horizontal transmission of cooperation). *With vertical and horizontal but without oblique transmission ( $v = 1$ ), the cultural evolution of cooperation will follow one of the following scenarios, depending on the cost boundaries  $\gamma_1$  and  $\gamma_2$  (Eq. 23):*

1. Fixation of cooperation: if (i)  $T_A \geq T_B$  and  $c < \gamma_1$ ; or if (ii)  $T_A < T_B$  and  $c < \gamma_2$ .
2. Fixation of defection: if (iii)  $T_A \geq T_B$  and  $\gamma_2 < c$ ; or if (iv)  $T_A < T_B$  and  $\gamma_1 < c$ .
3. Stable coexistence: if (v)  $T_A < T_B$  and  $\gamma_2 < c < \gamma_1$ .
4. Unstable coexistence: if (vi)  $T_A > T_B$  and  $\gamma_1 < c < \gamma_2$ .

These conditions are illustrated in Figure 3.

Cooperation and defection can coexist stably at frequencies  $\tilde{p}^*$  and  $1 - \tilde{p}^*$  (Eq. 20) if there is horizontal transmission bias for defection,  $T_A < T_B$ , and the cost of cooperation is intermediate,  $\gamma_2 < c < \gamma_1$ ; see yellow area in Figure 3b. When unstable coexistence occurs, phenotype A will fix if initially at a frequency  $p > \tilde{p}^*$ , and phenotype B will fix if initially at a frequency  $1 - p > 1 - \tilde{p}^*$ ; this occurs when there is horizontal transmission bias for cooperation,  $T_A > T_B$ , and the cost is intermediate,  $\gamma_1 < c < \gamma_2$ . Figure 2 shows the mapping  $\tilde{p} \rightarrow \tilde{p}'$ ; see blue areas in Figure 3a and Figure 3b.

**Corollary 1** (Symmetric horizontal transmission). *If  $T = T_A = T_B$ , then cooperation will take over the population if*

$$c < b \cdot \alpha \frac{T}{1 - T}. \quad (24)$$

Note that the right-hand side equals  $\gamma_1$  when  $T = T_A = T_B$ . This condition is obtained by setting  $T = T_A = T_B$  in inequality 19 and can be interpreted as a version of Hamilton's rule ( $c < b \cdot r$ , inequality 1) or as a version of inequality 3, where  $\alpha T / (1 - T)$  can be regarded as the *effective relatedness* or *effective assortment*, respectively. Figure 6a illustrates this condition.

The condition in inequality 24 demonstrates the importance of the social association  $\alpha$ . The following corollaries provide additional demonstrations.

200 **Corollary 2** (Perfect social association of transmission and cooperation). *With perfect social associ-*  
 202 *ation ( $\alpha = 1$ ), the only equilibria are the fixation states,  $\tilde{p} = 0$  and  $\tilde{p} = 1$ , and cooperation will evolve*  
*from any initial frequency,  $\tilde{p}' > \tilde{p}$ , if*

$$c < \frac{b \cdot T_A + (T_A - T_B)}{1 - T_B}. \quad (25)$$

204 This condition is obtained from inequality 17, and the right-hand side equals  $\gamma_1$  when  $\alpha = 1$  (Eq. 23).  
 Perfect social association (horizontal transmission always occurs during the cooperative interaction)  
 206 is also assumed in the model studied by Lewin-Epstein et al. (2017), and therefore this corollary is  
 equivalent to their result (see their eq. 1).

208 Inequality 25 can also be written as  $1 - (1 - c)(1 - T_B) < (1 + b)T_A$ , which provides an interesting  
 interpretation for the success of cooperation. In the interaction between a cooperator and a defector,  
 210  $(1 - c)(1 - T_B)$  is the probability that the cooperator remains cooperative and also reproduces. There-  
 fore,  $1 - (1 - c)(1 - T_B)$  is the probability that either the cooperator becomes a defector, or that it fails  
 212 to reproduce. This is the *effective cost of cooperation* from this interaction. Similarly,  $(1 + b)T_A$  is  
 the probability that during an interaction between a cooperator and a defector, the defector becomes  
 214 cooperative and reproduces, which is the *effective benefit of cooperation* from this interaction. Thus,  
 inequality 25 entails that cooperation can evolve if the effective cost of cooperation is less than the  
 216 effective benefit during an interaction between a cooperator and a defector.

218 **Corollary 3** (No social association of transmission and cooperation). *Without social association ( $\alpha =$*   
*0) cooperation can take over the population if there is horizontal transmission bias for cooperation,*  
 220  *$T_A > T_B$ , and if either*

$$c < \frac{T_A - T_B}{1 - T_B} \quad \text{or} \quad \tilde{p}_0 > \tilde{p}^* = \frac{c(1 - T_B) - (T_A - T_B)}{b(T_A - T_B)}. \quad (26)$$

222 Figure 3a illustrates these conditions, which are obtained by setting  $\alpha = 0$  in Eq. 20 and Eq. 23. If  
 there is horizontal transmission bias for cooperation ( $T_A > T_B$ ) then cooperation can evolve from any  
 224 initial frequency if the cost is low enough,  $c < \gamma_1$  (green area below solid line). If the cost is not  
 low enough, cooperation can also evolve if starting from high frequency and the cost is not too high,  
 226  $c < \gamma_2$  (blue area between solid and dashed lines).

We can interpret these condition as follows. First, when cooperators are rare, they will mostly inter-  
 228 act with defectors. Therefore, for cooperation to increase in frequency and fix, the *effective cost of*  
*cooperation* must be lower than the horizontal transmission of cooperation,  $1 - (1 - c)(1 - T_B) < T_A$ ,  
 230 which is equivalent to the left condition in Eq. 26. Second, if  $T_A$  is not large enough, cooperation  
 will fix if the initial frequency is higher than the threshold  $\tilde{p}^*$ ; thus, this threshold must be below one,  
 232 which entails  $1 - (1 - c)(1 - T_B) < T_A + b(T_A - T_B)$ . That is, the effective cost of cooperation must  
 be lower than the combined effect of horizontal transmission of cooperation,  $T_A$ , and the benefit of  
 234 cooperation multiplied by the transmission bias,  $b(T_A - T_B)$ .

236 Given the previous two corollaries for no association and perfect association ( $\alpha = 0$  and  $\alpha = 1$ ), it  
 is interesting to examine the general effect of social association on the evolution of cooperation. We  
 238 denote the social association boundaries by

$$a_1 = \frac{c(1 - T_B) - (1 + b)(T_A - T_B)}{b \cdot T_B}, \quad a_2 = \frac{c(1 - T_B) - (T_A - T_B)}{b \cdot T_A}. \quad (27)$$

240 Applying Eqs. 20, 21, and 22, we have the following corollary.



242 **Corollary 4** (Intermediate association of transmission and cooperation). *Cooperation will increase*  
*from rarity if social association is high enough, or specifically if*

$$244 \quad \begin{aligned} &T_A > T_B \text{ and } a_2 < \alpha, \quad \text{or} \\ &T_A < T_B \text{ and } a_1 < \alpha. \end{aligned} \quad (28)$$

Figure 3c demonstrates these conditions. With horizontal transmission bias for cooperation ( $T_A > T_B$ ),  
 246 cooperation can fix from any initial frequency if  $a_2 < \alpha$  (green area in positive x-axis). Otherwise,  
 cooperation can also fix if the horizontal bias is strong, the initial frequency is high, and social  
 248 association is high,  $a_1 < \alpha$  (blue area). With horizontal bias for defection ( $T_A < T_B$ ), cooperation  
 can fix from any frequency if social association is high,  $a_1 < \alpha$  (green area in negative x-axis), and  
 250 can also increase in rarity and maintain a stable coexistence with defection if social association is  
 intermediate,  $a_2 < \alpha$  (yellow area). Without horizontal bias ( $T_A = T_B$ ) fixation of cooperation occurs  
 252 if social association is high enough,  $\frac{c}{b} \cdot \frac{1-T}{T} < \alpha$  (inequality 24; in this case  $a_1 = a_2$ ).

### With Vertical and Oblique Transmission

254 With both vertical and oblique transmission,  $0 < v < 1$ , the recursion system is more complex, and we  
 focus on local rather than on global stability. To proceed, we note that Eq. 6 can give  $\hat{p}'$  as a function  
 256 of both  $p'$  and  $\tilde{p}'$ . Eq. 8 gives  $p'$  as a function of  $\tilde{p}$ , since  $\hat{p}$  is given in Eq. 6 as a function of  $\tilde{p}$  and Eq.  
 11 gives  $\tilde{p}'$  as a function of  $\hat{p}$ . Combining these equations, we find an equation for  $\hat{p}'$  as a function of  
 258  $\hat{p}$  (shown in Appendix Appendix A). We then determine the equilibria, namely, solutions of  $\hat{p}' = \hat{p}$ ,  
 and analyse their local stability.

260 We apply Eqs. 6, 8, and 11 to obtain the function  $f(\hat{p})$  (see Appendix Appendix A):

$$f(\hat{p}) = \bar{w}(\hat{p}' - \hat{p}) = \beta_1 \hat{p}^3 + \beta_2 \hat{p}^2 + \beta_3 \hat{p}, \quad (29)$$

262 where

$$\begin{aligned} \beta_1 &= [c(1-v) - b(1-\alpha v)](T_A - T_B), \\ \beta_2 &= -\beta_1 - \beta_3, \\ \beta_3 &= \alpha b v T_A - c v(1 - T_B) + (T_A - T_B). \end{aligned} \quad (30)$$

264 If  $T = T_A = T_B$  then  $\beta_1 = 0$  and  $\beta_3 = -\beta_2 = \alpha b v T - c v(1 - T)$ , and  $f(\hat{p})$  becomes a quadratic  
 polynomial:

$$266 \quad f(\hat{p}) = \hat{p}(1 - \hat{p})[\alpha b v T - c v(1 - T)]. \quad (31)$$

Clearly the only two equilibria are the fixations  $\hat{p} = 0$  and  $\hat{p} = 1$ . These equilibria are locally stable if  
 268  $f'(\hat{p}) < 0$  near the equilibrium (Appendix Appendix B), and

$$f'(\hat{p}) = (1 - 2\hat{p})[\alpha b v T - c v(1 - T)], \quad (32)$$

270 with

$$\begin{aligned} f'(0) &= \alpha b v T - c v(1 - T), \\ f'(1) &= -\alpha b v T + c v(1 - T). \end{aligned} \quad (33)$$

272 Therefore with symmetric horizontal transmission, fixation of the cooperative phenotype ( $\hat{p} = 1$ )  
 occurs under the same condition as Corollary 1.1, namely Eq. 24.

274 In the general case where  $T_A \neq T_B$ , the coefficient  $\beta_1$  is not necessarily zero, and  $f(\hat{p})$  is a cubic  
 polynomial. Therefore, three equilibria may exist, two of which are  $\hat{p} = 0$  and  $\hat{p} = 1$ , and the third  
 276 is

$$\hat{p}^* = \frac{\beta_3}{\beta_1}. \quad (34)$$

278 Note that the sign of the cubic (Eq. 29) at positive (negative) infinity is equal (opposite) to the sign of  $\beta_1$ . If  $T_A > T_B$ , then

$$280 \quad \beta_1 < [c(1 - \alpha v) - b(1 - \alpha v)](T_A - T_B) = (1 - \alpha v)(c - b)(T_A - T_B) < 0, \quad (35)$$

since  $c < b$  and  $\alpha v < 1$ . Hence the signs of the cubic at positive and negative infinity are negative and positive, respectively. First, if  $\beta_3 < \beta_1$  then  $1 < \hat{p}^*$  and therefore  $f'(0) < 0$  and  $f'(1) > 0$ ; that is, fixation of the defector phenotype  $B$  is the only locally stable legitimate (i.e. between 0 and 1) equilibrium. Second, if  $\beta_1 < \beta_3 < 0$  then  $0 < \hat{p}^* < 1$  and therefore  $f'(0) < 0$  and  $f'(1) < 0$ , that is, both fixations are locally stable and  $\hat{p}^*$  separates the domains of attraction. Third, if  $0 < \beta_3$  then  $\hat{p}^* < 0$  and therefore  $f'(0) > 0$  and  $f'(1) < 0$ ; that is, fixation of the cooperator phenotype  $A$  is the only locally stable legitimate equilibrium.

288 Similarly, if  $T_A < T_B$ , then

$$\beta_1 > [c(1 - \alpha v) - b(1 - \alpha v)](T_A - T_B) = (1 - \alpha v)(c - b)(T_A - T_B) > 0, \quad (36)$$

290 since  $c < b$  and  $\alpha v < 1$ , and the signs of the cubic at positive and negative infinity are positive and negative, respectively. First, if  $\beta_3 < 0$  then  $\hat{p}^* < 0$  and therefore  $f'(0) < 0$  and  $f'(1) > 0$ ; that is, fixation of the defector phenotype  $A$  is the only locally stable legitimate equilibrium. Second, if  $0 < \beta_3 < \beta_1$  then  $0 < \hat{p}^* < 1$  and therefore  $f'(0) > 0$  and  $f'(1) > 0$ ; that is, both fixations are locally unstable and  $\hat{p}^*$  is a stable polymorphic equilibrium. Third, if  $\beta_1 < \beta_3$  then  $\hat{p}^* > 1$  and therefore  $f'(0) > 0$  and  $f'(1) < 0$ , and fixation of the cooperator phenotype  $A$  is the only locally stable legitimate equilibrium.

We define new cost boundaries,  $\hat{\gamma}_1$  and  $\hat{\gamma}_2$ ,

$$298 \quad \hat{\gamma}_1 = \frac{bv\alpha T_A + (T_A - T_B)}{v(1 - T_B)}, \quad \hat{\gamma}_2 = \frac{bv\alpha T_B + (1 + b)(T_A - T_B)}{v(1 - T_B) + (1 - v)(T_A - T_B)}, \quad (37)$$

and define a vertical transmission threshold,

$$300 \quad \hat{v} = \frac{T_B - T_A}{1 - T_A}. \quad (38)$$

Now, assume  $T_A < T_B$ . For  $\beta_3 < 0$  we need  $\hat{\gamma}_1 < c$ . For  $\beta_3 < \beta_1$  we need  $c[v(1 - T_B) + (1 - v)(T_A - T_B)] > bv\alpha T_B + (1 + b)(T_A - T_B)$ . Note that the expression in the square brackets is positive if and only if  $v > \hat{v}$ . So, for  $\beta_3 < \beta_1$  we need  $v > \hat{v}$  and  $\hat{\gamma}_2 < c$  or  $v < \hat{v}$  and  $c < \hat{\gamma}_2$ . So, for  $0 < \beta_3 < \beta_1$  we need  $v > \hat{v}$  and  $\hat{\gamma}_2 < c < \hat{\gamma}_1$ , or  $v < \hat{v}$  and  $c < \min(\hat{\gamma}_1, \hat{\gamma}_2)$ ; and for  $\beta_1 < \beta_3$  we need  $v > \hat{v}$  and  $c < \hat{\gamma}_2$  or  $v < \hat{v}$  and  $\hat{\gamma}_2 < c$ . However, some of these conditions cannot be met, since  $v < \hat{v}$  implies  $c < 1 < \hat{\gamma}_2$ . A similar analysis can be made when  $T_A > T_B$ .

The following result summarizes the possible outcomes.

308

**Result 3** (Vertical, oblique, and horizontal transmission of cooperation). *With vertical, horizontal, and oblique transmission, the cultural evolution of a cooperator phenotype will follow one of the following scenarios depending on the cost boundaries  $\hat{\gamma}_1$  and  $\hat{\gamma}_2$  (Eq. 37) and the vertical threshold  $\hat{v}$  (Eq. 38):*

1. Fixation of cooperation: if (i)  $T_A \geq T_B$  and  $c < \hat{\gamma}_1$ ; or if (ii)  $T_A < T_B$  and  $v > \hat{v}$  and  $c < \hat{\gamma}_2$ .
- 314 2. Fixation of defection: if (iii)  $T_A \geq T_B$  and  $\hat{\gamma}_2 < c$ ; or if (iv)  $T_A < T_B$  and  $\hat{\gamma}_1 < c$ .
3. Stable Coexistence: if (v)  $T_A < T_B$  and  $v > \hat{v}$  and  $\hat{\gamma}_2 < c < \hat{\gamma}_1$ ; or if (vi)  $T_A < T_B$  and  $v < \hat{v}$  and  $c < \hat{\gamma}_1$ .

316

4. Unstable coexistence: if (vii)  $T_A > T_B$  and  $\hat{\gamma}_1 < c < \hat{\gamma}_2$ .

318 These conditions are illustrated in Figure 4.

Much of the literature on evolution of cooperation focuses on conditions for initially rare cooperative  
320 phenotype to invade a population of defectors. The next corollary deals with such a condition.

**Corollary 5** (Condition for cooperation to increase when initially rare). *If the initial frequency of*  
322 *cooperation is very close to zero,  $\hat{p}_0 \approx 0$ , then its frequency will increase if*

$$c < \hat{\gamma}_1 = \frac{bv\alpha T_A + (T_A - T_B)}{v(1 - T_B)}. \quad (39)$$

324 Note that the right-hand side equals  $\hat{\gamma}_1$ . This condition follows from combining the conditions for  
fixation of cooperation and for stable coexistence.

326 In general, these conditions cannot be formulated in the form of Hamilton's rule due to the horizontal  
transmission bias  $T_A - T_B$ . Without horizontal transmission bias, i.e., with  $T = T_A = T_B$ , these condi-  
328 tions reduce to a form of Hamilton's rule.

330 **Corollary 6** (Necessity condition for fixation of cooperation.). *Fixation of cooperation is possible*  
*only when*

$$v > \hat{v} = \frac{T_B - T_A}{1 - T_A}. \quad (40)$$

When there is horizontal transmission bias for cooperation, fixation can occur for every value of  
334 vertical transmission because  $\hat{v} < 0$ . However, if the horizontal bias favours defection, for fixation  
of cooperation to occur the vertical transmission must be higher than  $\hat{v}$ .

## 336 With population structure

We constructed an additional model in which social association emerges from the population structure.  
338 We model a non-overlapping population colonizing a 2D grid of size 100-by-100, where each site  
is inhabited by one individual, similarly to Lewin-Epstein and Hadany (2020). Each individual is  
340 characterized by its phenotype which is either a cooperator,  $A$ , or a defector  $B$ . In each generation  
individuals interact with their neighbors, i.e. individuals that inhabit adjacent sites, in a prisoner's  
342 dilemma game (Table 1) and in horizontal cultural transmission. As before,  $T_A$  and  $T_B$  are the  
probabilities to transmit the phenotypes  $A$  and  $B$  during horizontal transmission. At each generation,  
344 each individual is chosen to "initiate" interactions with probability  $1/2$ . Initiators then interact with  
a random neighbor for a prisoners' dilemma game and a random neighbor (with replacement) for  
346 horizontal cultural transmission (as both the game and the transmission are symmetrical, the expected  
number of each of these interactions per individual per generation is 1). Therefore, the effective social  
348 association  $\alpha$  in this model is the probability that the same neighbor is picked for both interactions, or  
 $\alpha = 1/m$ , where  $m$  is the number of neighbors. On an infinite grid,  $m = 8$ , but on a finite grid  $m$  can  
350 be lower in edge neighborhoods close to the grid border.

The order of the interactions across the lattice on each generation is random. After all interactions take  
352 place, individual's fitness is determined by  $w = 1 + b \cdot n_b - c \cdot n_c$ , where  $n_b$  is the number interactions of  
that individual with cooperative neighbors, and  $n_c$  is the total number of interactions of that individual  
354 ( $n_b \leq n_c$ ). Then a new generation is generated. Each site is colonized by an offspring of one of  
the individuals that inhabit either this site or one of the neighboring sites. The parent is randomly  
356 drawn with probability proportional to its fitness, divided by the average fitness in his neighborhood.  
Offspring then have the same phenotype as their parents.

Figure 7 shows that the highest cooperation cost to benefit ratio ( $c/b$ ) that permits the evolution of cooperation in simulations of the spatial model is roughly  $\alpha \cdot T/(1 - T)$ , where  $T = T_A = T_B$  is the horizontal transmission rate. This agrees with the condition we derived in Corollary 1 for a population without population structure. This demonstrates that the social association parameter  $\alpha$  can emerge from local interactions between individuals in a structured population.

## Discussion

We studied the evolution of cooperation under non-vertical transmission using deterministic discrete-time evolutionary models with fitnesses in the form of payoffs from a prisoner's dilemma game. Under oblique and horizontal cultural transmission, a horizontal transmission bias for the cooperative phenotype was found to be sufficient and necessary for evolution of cooperation (Result 1). Under a combination of vertical, oblique, and horizontal transmission, cooperation or defection can either fix or coexist at a stable polymorphism, depending on the relationship between the cost and benefit of cooperation, the horizontal bias, and the association between cooperation and transmission (Results 2 and 3). Remarkably, stable coexistence between cooperation and defection can be maintained if horizontal transmission is biased for defection ( $T_A < T_B$ ) and both the cost of cooperation and social association are intermediate (yellow areas in Figure 3).

We tested the applicability of our analytic results to a complex spatial stochastic model. Our derived condition provide a good approximation to simulation results (Figure 7), demonstrating that association between cooperation and transmission can arise in a structured population simply because the choice of individuals for social interactions is small.

Feldman et al. (1985) studied the dynamics of an altruistic phenotype with vertical cultural transmission and a gene that modifies the transmission of the phenotype. Their results are very sensitive to this genetic modification: without it, the conditions for invasion of the altruistic phenotype reduce to Hamilton's rule. Further work is needed to include such genetic modification of cultural transmission to our model.

Woodcock (2006) has previously argued the significance of non-vertical transmission for the evolution of cooperation. He executed simulations with prisoner's dilemma payoffs but without horizontal transmission or social association ( $\alpha = 0$ ). Nevertheless, his results demonstrated that it is possible to sustain altruistic behavior via cultural transmission for a significant duration of time. Our results provide strong evidence for his hypothesis that horizontal transmission can have an important role in the evolution of cooperation.

To understand the role of horizontal transmission, we first discuss the role of *assortment*. Eshel and Cavalli-Sforza (1982) showed that altruism can evolve when there is enough *assortative meeting*, namely, a tendency for individuals to interact within their phenotypic group. Fletcher and Doebeli (2009) have further argued that a general explanation for the evolution of altruism is given by *assortment*: the correlation between individuals that carry an altruistic trait and the amount of altruistic behavior in their interaction group; see also Bijma and Aanen (2010). They therefore suggested that to explain the evolution of altruism, we should seek mechanisms that generate such assortment, like population structure, repeated interactions, and individual recognition. Our results highlight another mechanism for generating assortment: an association between social interactions and horizontal transmission that creates a correlation between one's partner for interaction and partner for transmission. This mechanism does not require population structure, repeated interactions, or individual recognition. We show that high levels of such social association greatly increase the potential for evolution of cooperation (Figure 3). With enough social association ( $\alpha > (c(1 - T_B) + (T_B - T_A))/bT_A$ ), cooperation can increase in frequency when initially rare even when there is horizontal transmission bias against it ( $T_A < T_B$ , see Result 2).

404 How does non-vertical transmission generate assortment? Lewin-Epstein et al. (2017) and Lewin-  
 406 Epstein and Hadany (2020), who suggested that microbes that manipulate their hosts to act altruistically  
 can be favored by selection, and may help explain the evolution of cooperation. From the kin selection  
 point-of-view, if microbes can be transmitted *horizontally* from one host to another during host  
 408 interactions, then following horizontal transmission the recipient host will carry microbes that are  
 closely related to the microbes of the donor host, even when the two hosts are (genetically) unrelated.  
 410 However, we are more interested in the assortment point-of-view: infection by behavior-determining  
 microbes during interactions effectively generates assortment because recipient of help may be  
 412 infected by the behavior-determining microbe and therefore become a helper. Cultural horizontal  
 transmission can similarly generate assortment between the cooperative phenotype and the benefit  
 414 of cooperation if cultural transmission and helping interactions occur between the same individuals,  
 which in our model occurs with probability  $\alpha$ .

416 Thus, with horizontal transmission, “assortment between focal cooperative players and cooperative  
 acts in their interaction environment” (Fletcher and Doebeli, 2009) is generated not because *the helper*  
 418 *is likely to be helped*, but rather because *the helped is likely to become a helper*. These conclusions  
 highlight the importance of non-vertical cultural transmission for explaining complex evolutionary  
 420 phenomena, and furthers our understating of the cultural evolution of cooperation.

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## 424 Appendices

### Appendix A

426 We want to find the frequency of juveniles with phenotype A in next generation  $\hat{p}'$  as a function of  
 frequency of juveniles with phenotype A in the current generation  $\hat{p}$ . Starting from Eq. 6,

$$428 \quad \hat{p}' = v\tilde{p}' + (1 - v)p', \quad (\text{A1})$$

we substitute  $p'$  using Eq. 8 and  $\tilde{p}'$  using Eq. 11, we have

$$\begin{aligned}
 \hat{p}' = & \frac{v}{\bar{w}} \left\{ \hat{p}^2(1 + b - c) [1 - (1 - \hat{p})(1 - \alpha)T_B] \right\} \\
 & + \frac{v}{\bar{w}} \left\{ \hat{p}(1 - \hat{p})(1 - c) [\hat{p}(1 - \alpha)T_B + 1 - T_B] \right\} \\
 430 \quad & + \frac{v}{\bar{w}} \left\{ \hat{p}(1 - \hat{p})(1 + b) [\hat{p}(1 - \alpha) + \alpha] T_A \right\} \\
 & + \frac{v}{\bar{w}} (1 - \hat{p})^2 \hat{p}(1 - \alpha) T_A \\
 & + (1 - v) \hat{p}^2 (T_B - T_A) + (1 - v) \hat{p} (1 + T_A - T_B),
 \end{aligned} \quad (\text{A2})$$

where  $\bar{w} = 1 + \hat{p}(b - c)$ . We define  $f(\hat{p})$  as

$$432 \quad f(\hat{p}) = \bar{w}(\hat{p}' - \hat{p}) \quad (\text{A3})$$

Using *SymPy* (Meurer et al., 2017), a Python library for symbolic mathematics, we simplify Eq. A3  
 434 to eqs. 29-30.

## Appendix B

436 Denote  $f(p) = \lambda(p' - p)$ , where  $\lambda > 0$ , and assume  $f(p^*) = 0$ ; i.e.,  $p^*$  is an equilibrium. We want a condition for  $|p' - p^*| < |p - p^*|$ .

438 If  $p > p^* = 0$ , we want a condition for  $p' < p$ , or  $\frac{p'}{p} < 1$ , or  $\lambda \frac{p' - p}{p} < 0$ , or  $\frac{f(p)}{p} < 0$ . Using a linear approximation for  $f(p)$  near 0, we have

$$\begin{aligned} p' < p &\Leftrightarrow \\ 440 \quad \frac{f'(0) \cdot p + O(p^2)}{p} < 0 &\Leftrightarrow \\ f'(0) + O(p) &< 0. \end{aligned} \tag{B1}$$

Therefore, by definition of big-O notation, if  $f'(0) < 0$  then there exists  $\epsilon > 0$  such that for any  
442  $0 < p < \epsilon$ , it is guaranteed that  $0 < p' < p$ , that is,  $p'$  is closer than  $p$  to zero.

If  $p < p^* = 1$ , we want a condition for  $1 - p' < 1 - p$ , or  $\frac{1 - p'}{1 - p} < 1$ , or  $\lambda \frac{-(p' - p)}{1 - p} < 0$ , or  $-\frac{f(p)}{1 - p} < 0$ .  
444 Using a linear approximation for  $f(p)$  near 1, we have

$$\begin{aligned} 1 - p' < 1 - p &\Leftrightarrow \\ \frac{f'(1)(p - 1) + O((p - 1)^2)}{p - 1} < 0 &\Leftrightarrow \\ 446 \quad f'(1) - O(1 - p) &< 0. \end{aligned} \tag{B2}$$

Therefore, if  $f'(1) < 0$  then there exists  $\epsilon > 0$  such that for any  $1 - \epsilon < 1 - p < 1$  it is guaranteed that  
448  $1 - p' < 1 - p$ , that is,  $p'$  is closer than  $p$  to one.

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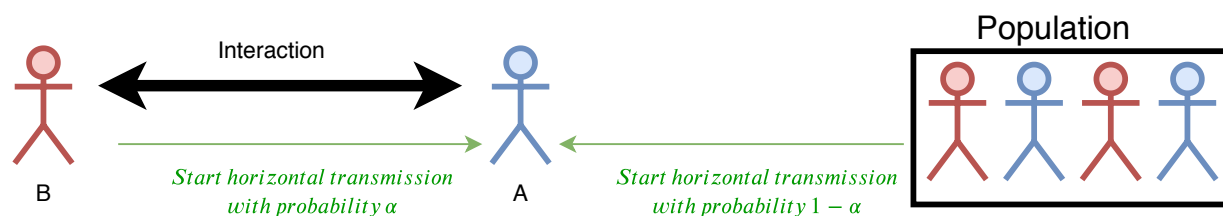
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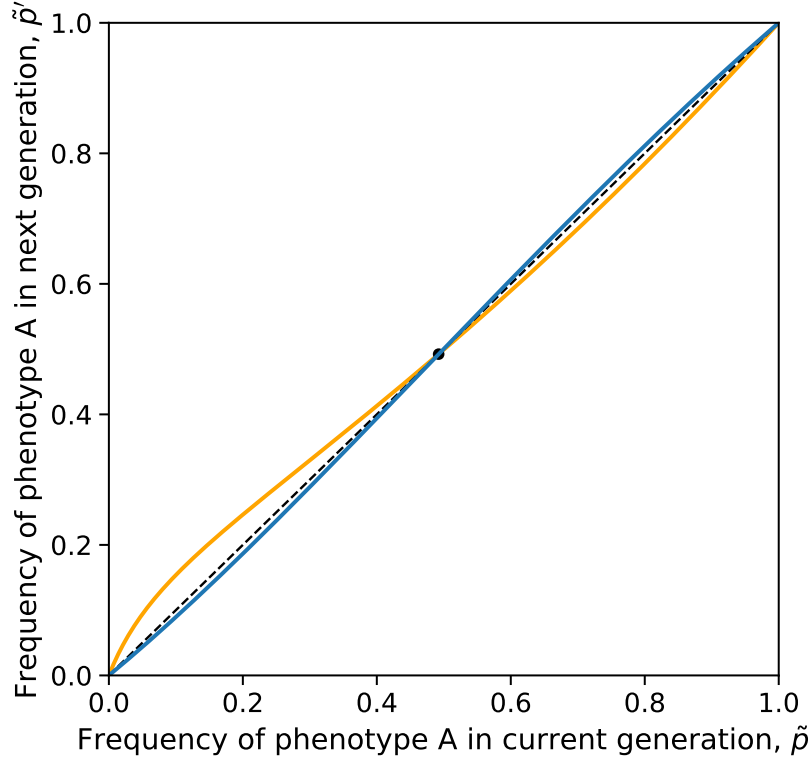
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## Figures

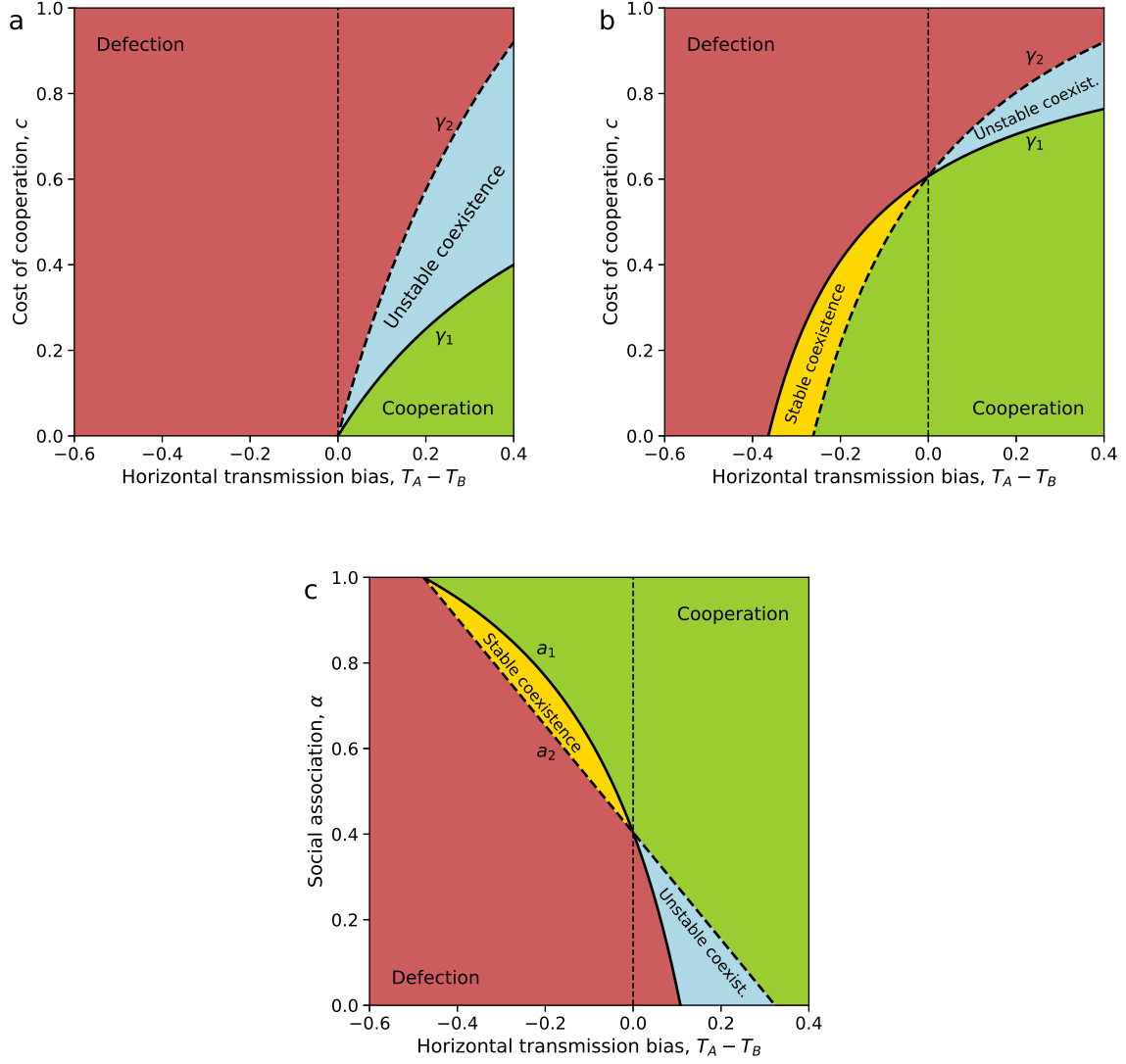


**Figure 1: Cultural horizontal transmission with assortment.** Transmission occurs between interacting partners with probability  $\alpha$  (left) or between two random peers with probability  $1 - \alpha$ .

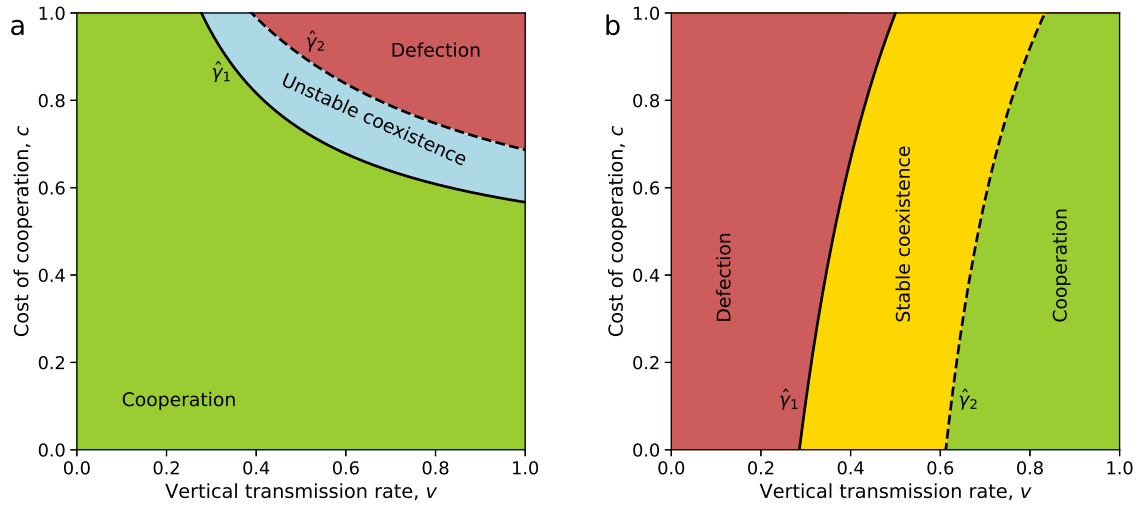


**Figure 2: Stable and unstable coexistence between cooperation and defection without oblique transmission.** The curves show the frequency of the cooperative phenotype A among parents in the next generation  $\tilde{p}'$  vs. the current generation  $\tilde{p}$  (Eq. 14). The dashed black line is  $\tilde{p}' = \tilde{p}$ . The curves and the dashed line intersect at the polymorphic equilibrium  $\tilde{p}^*$  (black circle). When the curves are above the dashed line,  $\tilde{p}' > \tilde{p}$ , then  $\tilde{p}$  increase. When the curves are below the dashed line,  $\tilde{p}' < \tilde{p}$ , then  $\tilde{p}$  decreases. The orange curve, for which the polymorphic equilibrium is stable, is given by  $T_A = 0.4$ ,  $T_B = 0.9$ ,  $b = 12$ ,  $c = 0.35$ , and  $\alpha = 0.45$ , which give  $\gamma_2 < c < \gamma_1$  (Eq. 23) The blue curve, for which the equilibrium is unstable, is given by  $T_A = 0.5$ ,  $T_B = 0.1$ ,  $b = 1.3$ ,  $c = 0.904$ , and  $\alpha = 0.4$ , which give  $\gamma_1 < c < \gamma_2$ . In both cases there is no oblique transmission,  $\nu = 1$ ; see Figure 5 for  $\nu < 1$ .

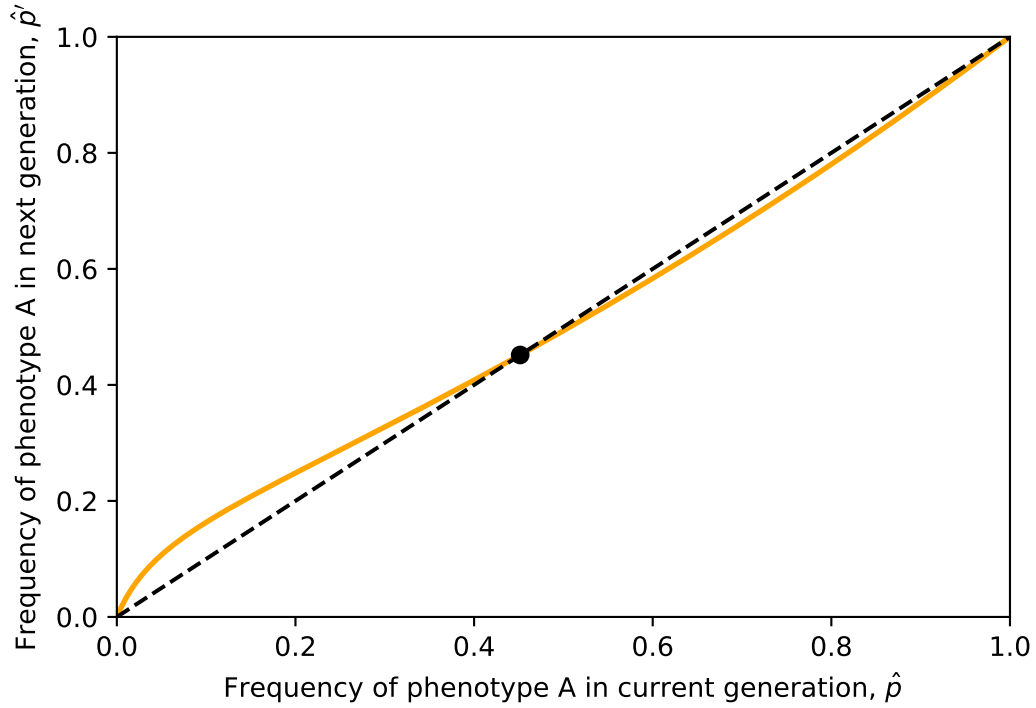




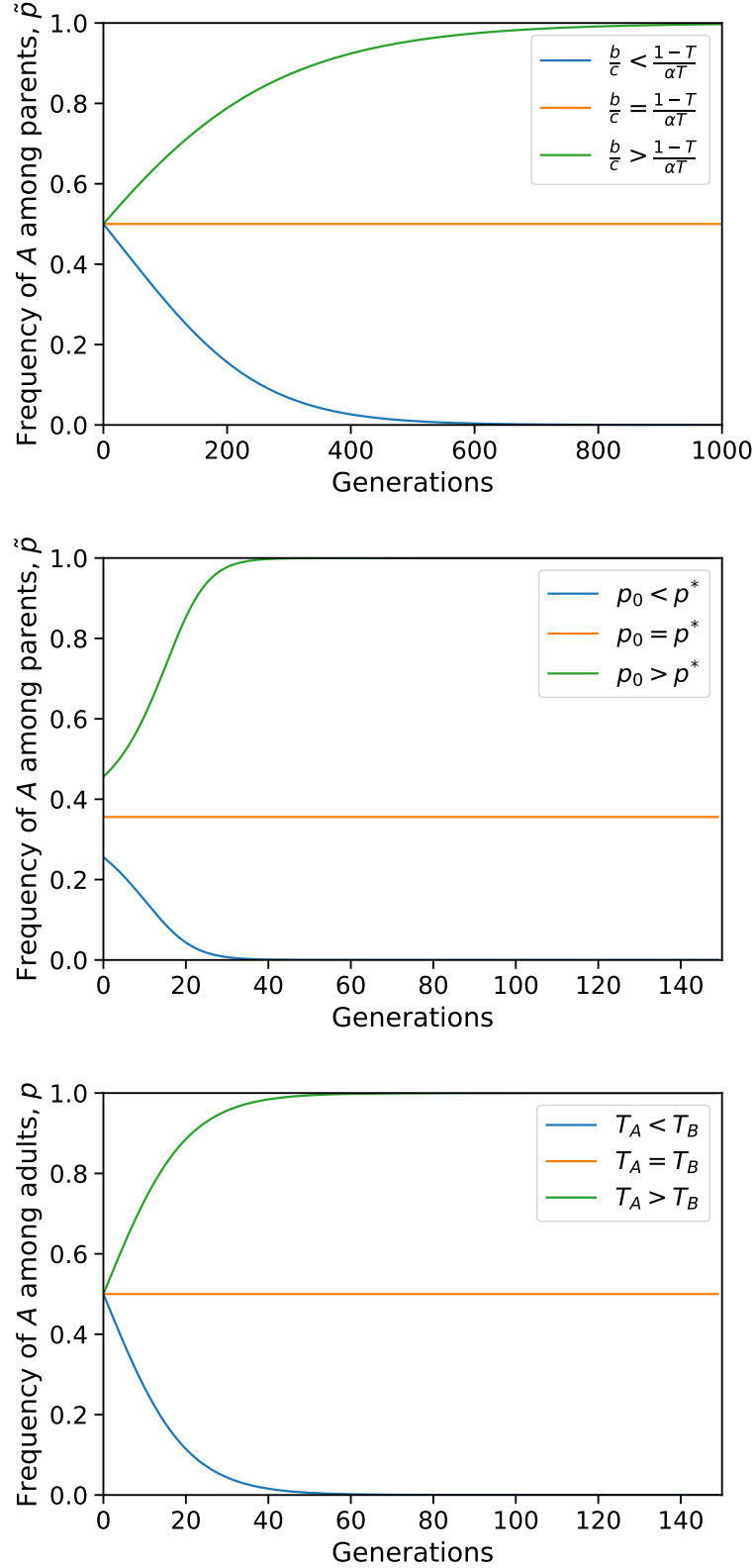
**Figure 3: Evolution of cooperation under vertical and horizontal cultural transmission.** The figure shows the global fixation of cooperation (green), global fixation of defection (red), fixation of either cooperation or defection depending on the initial conditions, i.e. unstable coexistence (blue), and stable coexistence of cooperation and defection (yellow). In all cases the horizontal bias ( $T_A - T_B$ ) is on the x-axis. **(a-b)** The cost of cooperation  $c$  is on the y-axis; the cost boundaries  $\gamma_1$  and  $\gamma_2$  (Eq. 23) are the solid and dashed lines. **(c)** social association  $\alpha$  is on the y-axis; the social association boundaries  $a_1$  and  $a_2$  (Eq. 27) are the solid and dashed lines. Here,  $b = 1.3$ ,  $T_A = 0.4$ . **(a)**  $\alpha = 0$ . **(b)**  $\alpha = 0.7$ . **(c)**  $c = 0.35$ .



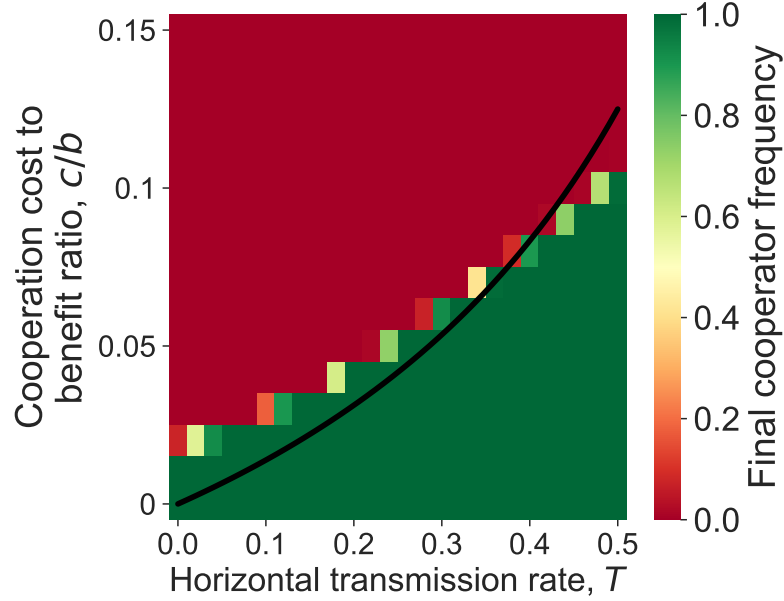
**Figure 4: Evolution of cooperation under vertical, oblique, and horizontal cultural transmission.** The figure shows the global fixation of cooperation (green), global fixation of defection (red), fixation of either cooperation or defection depending on the initial conditions, i.e. unstable coexistence (blue), and stable coexistence of cooperation and defection (yellow). The vertical transmission rate  $v$  is on the x-axis. Horizontal transmission bias (a) for cooperation,  $T_A > T_B$  and (b) for defection,  $T_A < T_B$ . Cost boundaries  $\hat{v}_1$  and  $\hat{v}_2$  (Eq. 37) are represented by the solid and dashed lines. (a)  $b = 1.2$ ,  $T_A = 0.5$ ,  $T_B = 0.4$ ,  $\alpha = 0.4$ . (b),  $b = 2$ ,  $T_A = 0.5$ ,  $T_B = 0.7$ ,  $\alpha = 0.7$ .



**Figure 5: Stable coexistence between cooperation and defection with oblique transmission.** The curve shows the frequency of the cooperative phenotype  $A$  among juveniles in the next generation  $\hat{p}'$  vs. the current generation  $\hat{p}$  (Eq. 6). The dashed black line is  $\hat{p}' = \hat{p}$ . The curve and the dashed line intersect at the stable equilibrium  $\hat{p}^*$  (black circle). When  $\hat{p} < \hat{p}^*$  then the curve is above the dashed line,  $\hat{p}' > \hat{p}$ , and  $\hat{p}$  increases towards  $\hat{p}^*$ . When  $\hat{p} > \hat{p}^*$  then the curve is below the dashed line,  $\hat{p}' < \hat{p}$ , and  $\hat{p}$  decreases towards  $\hat{p}^*$ . Here,  $T_A = 0.4$ ,  $T_B = 0.9$ ,  $b = 20$ ,  $c = 0.1$ ,  $\alpha = 1$ , and  $\nu = 0.4$ , which give  $0 < \beta_3 < \beta_1$  (Eq. 30).



**Figure 6: Dynamics of the frequency of cooperation.** The frequency  $\tilde{p}$  of parents with cooperative phenotype A in (a-b) and the frequency  $p$  of adults with cooperative phenotype A in (c). The different lines correspond to parameter values that lead to fixation of cooperation (green), extinction of cooperation (red), or stable coexistence of cooperators and defectors (yellow). (a)  $v = 1$ ,  $T_A = T_B = T = 0.2$ ,  $\alpha = 0.5 \neq 0$ ,  $\tilde{p}_0 = 0.5$  and  $c = 0.1$ ; (b)  $v = 1$ ,  $\alpha = 0$ ,  $\tilde{p}^* \approx 0.35$ ,  $T_A = 0.65$ ,  $T_B = 0.1$ ,  $b = 1.3$  and  $c = 0.65$ ; (c)  $v = 0$ ,  $\alpha = 0.5$ ,  $p_0 = 0.5$ ,  $T_A = 0.5$ ,  $b = 1.3$  and  $c = 0.5$ .



**Figure 7: Evolution of cooperation in a spatial model.** The expected frequency of cooperators in a structured population after 10,000 generations is shown (red for 0%, green for 100%) as function of both the ratio between the cost and benefit of cooperation ( $c/b$ ) on the y-axis, and the horizontal transmission rate (without transmission bias,  $T = T_A = T_B$ ) on the x-axis. The population evolves on a 100-by-100 grid. Selection, cooperation, and horizontal cultural transmission are all local between adjacent sites. The black curve represents the condition for the evolution of cooperation in a well-mixed population with social association,  $c/b < \alpha T / (1 - T)$ , where  $\alpha = 1/8$ ; see Eq. 24. Note that in the structured population, selection is local, whereas in the unstructured population, selection is global. This can explain the small difference in the results. Here, population size is 10,000 (100-by-100 grid); cost of cooperation,  $c = 0.05$ . 50 simulations were executed per parameter set. Simulations were stopped at generation 10,000 or if one of the phenotypes fixed.