In a population with a local interaction structure, where individuals interact with their neighbors and learning is by way of imitating a successful neighbor, cooperation is shown to be a stable strategy that cannot easily be eliminated from the population.

Cooperation, Mimesis, and Local Interaction

ILON ESHEL
Tel Aviv University

DOROTHEA K. HERREINER
University of Bonn

LARRY SAMUELSON
University of Wisconsin–Madison

EMILIA SANSONE
University of Naples

AVNER SHAKED
University of Bonn

How do modes of behavior spread in a society? What makes one convention more successful than another? In particular, how is it that cooperation and altruistic behavior are to be found so frequently in human societies, despite the obvious immediate disadvantage they cause?

Of the numerous explanations of this phenomenon that exist in the literature, two are often mentioned. The one, of a biological nature, due to Hamilton (1964), observes that within a group of genetically related individuals, behavior that makes individuals treat their kin kindly is more likely to succeed. Such behavior, if transmitted from generation to the next by genes, supports itself and propagates itself in the society. The cooperative behavior thus acquired by members of a family may have persisted when societies expanded beyond the immediate family group.
We have deliberately left the details of the local interaction system process.}

We're now in the missing details.

The agreement why cooperation may survive under these assumptions and the interaction process somewhat vague. We first present an initial...

process. There's even thought some learning methods are more comme...

rationality. When the rational approach fails, people may resort to int...

process. Unfortunately, many situations (indeed most are too com...

stand a situation and find out in a rational way what is the best way to

In this case, individuals, no doubt, attempt to use their analytic powers to under...

be a compromise of human behavior and of our learning practices.

be a compromise of human behavior and of our learning practices.

least, that individuals interact with each other their powers to under...

also, individuals interact only with a small subset of the population: nei...

work in society so essentially very individual it is only in very small soci-

Both assumptions seem plausible. Although the acquaintance ne-

behavior by imitating the behavior of other more successful neighbors.

degree of success achieved by others and their help in updating their

also assume that individuals can observe the whole population. We also assume that individuals can observe the

We assume that there is a local structure in the population, that is, indivi-

We assume that individuals are boundedly rational, that they are not

We assume that individuals are boundedly rational, that they are not

nize a detecting individual.

-ize a detecting individual.

that cooperation requires long-term memory and ability to react.
Our two assumptions (local interaction and imitation) are shown to lead to the survival of cooperative behavior. We offer here intuitive arguments that will be made precise in the following sections. To clarify our point, assume that individuals are located on a line, each interacting with and imitating those located within a certain distance from him or her. Imagine that an individual can be either cooperative and helpful to his neighbors or egoistic and noncooperative. Consider first an isolated noncooperating individual surrounded by cooperative players. He does well, for his neighbors support him while he makes no effort to help them or perhaps even exploits them. He will therefore be imitated by his neighbors, this will create a group of noncooperating individuals that is no longer doing well, since no one helps his or her neighbors. So an isolated island of noncooperation will tend to spread but not too much. Once too big, it no longer is an object for imitation. With cooperation, the dynamics seem to go the other way. An isolated cooperator will not do well if surrounded by noncooperators. He helps his neighbors who do not help him. His neighbors, on the other hand, benefit from his being there. His mere existence makes noncooperation more attractive in his neighborhood, and he himself will eventually imitate his neighbors. In contrast, a large group of cooperators is strong in the sense that its members support each other and are therefore (locally) successful. If the cooperators on the group’s boundary (where they interact with and observe noncooperators) hold fast, then the cooperative group will not be eroded and may even spread.

This intuitive argument seems to suggest that if cooperation survives, it will be present in large numbers interspersed with small islands of noncooperation. The intuitive argument leaves open the question of whether cooperation can survive at all. To find out whether cooperation survives, we need to analyze the problem in detail, for the survival or extinction of cooperation crucially depends on what happens at the boundaries between groups of cooperators and noncooperators. This question becomes even more elaborate once the learning process is allowed to be stochastic (the individual chosen to be imitated is chosen at random) or when noise is introduced to the system in the form of mutations. The models we introduce in the following sections address this problem and establish conditions under which cooperation will survive.
We now have a dynamic process. Beginning at an initial state, a conflictual configuration of altruists and egoists on the circle, each defining a pay-off, allows the process to evolve. Each player learns about the pay-offs in his neighborhood, and chooses the type of interaction with his neighbors. This process is represented in a simplified fashion above, which is always better version of the prisoner’s dilemma. If they understand it, they are, in fact, playing a game.

Clearly, our individuals are not aware that they are, in fact, playing a game.

The learning-stabilization process is as follows. Let each individual be in equilibrium or not as described above. The strategy choice will switch once the strategy type (type of the neighborhood) consensus of the immediate neighbor to this individual is reached. If an individual is surrounded by consensual higher average payoff, if an individual is surrounded by lower average payoff, then this individual, the individual will switch to the strategy type.”}

MODEL I: ALTRUISMS AND EGOISMS.
THE LIMIT OF THE DYNAMIC PROCESS

The process defined above, being a deterministic Markov process on a finite space, converges to an absorbing set: a set of states in which it cycles and from which it never exits.

It can easily be shown that beginning with any initial configuration of altruists and egoists on the circle, the process converges to one of the following states or cycles:

1. A state in which all individuals are altruists
2. A state in which all individuals are egoists
3. A steady pair of egoists: A state in which all but two adjacent individuals are altruists (an altruist is represented by a and an egoist by E)

    ...aaaaaaaEEaaaaaaa...

4. A blinker: A cycle of two states in which egoism spreads from an isolated egoist to a string of three egoists and shrinks again because as a larger group egoists are not doing well:

    ...aaaaaaaEaaaaaaa...

    ...aaaaaaaEEaaaaaaa...

(The first line describes the situation at a given time and the next line describes the new configuration at the following period.)

5. A cycle of two states in which isolated strings of egoists (blinkers and steady pairs of egoists) exist among altruists; for example,

    ...aaaaaaaEaaaaaaaEEaaaaaaaEEaaaaaaa...

    ...aaaaaaaEEaaaaaaaEEaaaaaaaEaaaaaaa...

It is easy to verify that in an absorbing state of type 3, no individual wishes to switch to another strategy, and that in a blinker (an absorbing state of type 4), only the immediate neighbors of the egoist at the center wish to change their type and do so in a cyclical manner.

Note that in absorbing sets of type 5, the islands of egoists need be well apart from each other. If they happen to be too close, as in the following example, the islands merge to create a large group of egoists that is no longer viable and will therefore shrink, ending with a single blinker and fewer egoists than we had initially:
There are two such configurations, which the process converges depends on the initial configuration of the absorbing set to which we end up dependent on where we started. The absorbing set is never destroyed, it need not expand as it does in the above example, but it will never be eradicated.

A sufficiently large size of altruists (here a size of five) expands in a sea of egoists. Moreover, it can be shown that a single of five or more altruists survives at all.

The other part of the intuitive argument, that a clump of altruists supports itself and may expand, can be seen by the following example.

The minimal number of altruists between strings of egoists can be calculated, and it can be shown that in any absorbing set where altruists are present, there will be at least 60 percent altruists. Thus, an absorbing set can be calculated, and it can be shown that in any absorbing set where altruists are present, there will be at least 60 percent altruists.
where $N$ is the length of the circle. We can now ask how many of the initial configurations lead to an absorbing set in which there is no altruism. Combinatorial arguments demonstrate that for large $N$, nearly all of the $2^N$ possible configurations will contain a string of (at least) five altruists. Because such a string never vanishes, it follows that most of the initial configurations lead to an absorbing state in which altruists exist and are therefore a majority of at least 60 percent. Thus, for a sufficiently large population on a circle and beginning with an arbitrary initial configuration, it is with probability (approaching) 1 that the absorbing set we reach will have a majority of altruists. This confirms our intuition that in this model, altruism is very likely to survive in large numbers in the population.

So far, we have assumed that the imitation process is deterministic and fully synchronized: All individuals update their strategies each period. These assumptions may be relaxed without changing the result. Imagine that an individual observes the payoffs of his neighbors, as before, except that now, instead of switching with certainty to the strategy with the higher average payoff, he does so with a positive probability that is not necessarily 1. Note that an individual always revises his strategy to a “better” one; he may not switch to a strategy that earns a lower average payoff than the one he currently uses. Choosing not to switch to a better strategy when there is one available effectively means forgoing the opportunity to learn. Thus, under this learning scheme, learning is no longer synchronized.

It is interesting to see that under this stochastic learning process, all the above results are valid. The only difference is that a blinker (type 4) is no longer part of an absorbing set. A blinker requires that both neighbors of an isolated egoist simultaneously update their strategy; this is no longer the case in stochastic learning. However, steady strings of egoists (type 3) are still stable. As for deterministic learning, nearly all initial configurations lead to absorbing sets consisting of at least 60 percent of altruists.

**MUTATIONS**

So far, we have assumed that the individuals rigidly follow the learning rules and switch only to a strategy that earns a higher average payoff than the one they are currently using. It is unreasonable to
destroy the strains one by one as our example in the previous section
when at least 60 percent of the population is altruistic. It will not do to
hope. It is not easy for altruisms to eradicate all strains of altruists
the state where all are egoists; it requires only five simultaneous muta-
If it is relatively easy for mutuations to create a strain of five altruists in
at least five altruists when they are the majority. 

persistent groups of altruists when there are none than to eliminate all
absorbing strains to the other. That is, it easier for mutuations to create
it for mutuations to shake the population away once type of
their precise distribution on the circle, we need only find out how easily
because we are only interested in the existence of altruists (and not in
percent altruists and a single state in which there are no altruists.
above there are two types of absorbing sets: those that have at least 60
will end up in (possibly) another absorbing set. As we have seen (or
absorbing sets, a high enough probability of transition to a state outside the absorbing set (or in
and may kick the population in a state outside this absorbing set (or in
the process, when mutuations appear, they will disrupt the dynamics
mutions occur, the process will settle in an absorbing set of low
low the learning process. After a sufficiently long time in which no
mutions are rare, then the dynamics will most of the time, for-
If mutations are rare, then the dynamics will most of the time, will
argument that drives the result.

in Frisch, Samelson, and Shaked (1986). Here, we present an intuitive
mathematical details of this result are rather intricate and can be found
small probability or as long as the circle (N is sufficiently large. The
absorbing survive mutations as long as those occur with a sufficiently
egoists, if will be eradicated. It may therefore come as a surprise that
and survive, whereas if a mutant altruism appears in a population of
If a mutant egoist appears in a population of altruists, it will do well
absorbing to survive. Mutations seem to increase the number of egoists:
On the face of it, it seems that mutations make it more difficult for
once egoists they may have no reason to switch back to altruism.
stable state: Some individuals may mutate to become egoists, and
stable state: Some individuals may mutate to become egoists, and
may therefore come as a surprise that
have a small probability of becoming a mutant and determine this
mutions are introduced. After learning, an individual may
happen and individuals may sometimes act egocentrically. To this pur-
assume that deviations from this procedure do not occur. However,
SOCIOLOGICAL METHODS & RESEARCH
shows. Destroying a string of altruists between two strings of egoists creates a large string of egoists. This large string is not viable and will shrink to a small string of egoists, ending up with more altruists than there were initially. To completely destroy the altruists, all strings of altruists need to be simultaneously eradicated. Depending on how many strings of egoists there are, the strings of altruists are either numerous or long. It can be shown that to destroy all of them, one needs to introduce simultaneously a sufficient number of mutations in each string of altruists. To do this, it can be shown that at least $N/10$ mutations are required. When $N$ is sufficiently large, it is much larger than five, the number of mutations needed to move in the other direction, and so the population will be most of the time absorbing sets with a majority of altruists. Thus, even noise in the form of mutations cannot eliminate altruism.

**ROBUSTNESS AND FRAGILITY OF THE MODEL**

Our model has the following basic components: a population located on a circle where each individual can be one of two types, altruist or egoist, and each interacts and learns from his two immediate neighbors. The intuition presented in the introduction suggests that the result (that altruism will be significantly present in the population) will hold even when the model's basic features will be slightly changed. In this section, we present some generalizations of the model.

The method of analysis we developed can be applied to populations in which the interaction between individuals takes the form of a general normal form game and a type is characterized by the strategy he plays. We can analyze all $2 \times 2$ games; that is, we can follow the evolution of any two strategies in the population and describe some properties of the limit distribution, as we have for altruists and egoists. In particular, altruists and egoists can be viewed as a special case of a type who contributes $K$ to each of his neighbors at a net benefit of $-C$ to himself. An egoist has $K = C = 0$, whereas an altruist has $K = 1$, $C < 1/2$. Our model can be extended to any two or indeed more such types. For example, one may consider a hooligan, an individual who reduces the utility of his neighbors at a possible benefit for himself, $K = -1$, $C < 0$. Compared to a hooligan, an egoist is a (relative) altruist, for he at least
neighbors in the interaction neighborhood, which consists of 4 individuals.

This individual has a strategy (mixed or pure) that he plays against all
his neighbors. In order to win, an individual has to be located at the interior point of the
intermediate line between 0 and 1, and the same applies to all neighbors. The
interaction between players takes the form of a

\[
\begin{array}{c}
1, \\
1, \\
1, \\
1,
\end{array}
\]

This model features an infinite population located on a line. Each

LEARNING AND UNBARRIERABLE STRATEGIES

MODEL 1: CONSERVATIVE STOCHASTIC

For the model which states that "less successful" than the current one,

strategies that are less successful than the current one

are more likely to survive. The probability of this neighborhood according to some probability.
The probabilities are

such that they are more likely to survive. The strategy from

This model features an infinite population located on a line. Each

LEARNING AND UNBARRIERABLE STRATEGIES

MODEL 2: CONSERVATIVE STOCHASTIC

We have not been able to obtain analytic results for a population

function of that cost.

important role, and the percentage of altruists in the population is a

hubs are of a larger radius. Here, the cost of being an altruist plays a

Our method enables us to analyze the dynamics when the neighborhood

interaction neighborhood and the learning neighborhood, are of radius 1.

In our model, we have assumed that both neighborhoods, the inter-

causes no damage. It can be shown that in a population of egocists and

SOCIOLOGICAL METHODS & RESEARCH

350
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>a, a</td>
<td>b, c</td>
</tr>
<tr>
<td>D</td>
<td>c, b</td>
<td>d, d</td>
</tr>
</tbody>
</table>

... to his right and k to his left. After obtaining their payoffs, a single individual is chosen at random to learn and update his strategy. He does so by picking up a "guru" in his learning neighborhood, a neighborhood of radius n around him, whose strategy he will imitate. Choosing a guru is a probabilistic process. A guru is chosen with a probability that is his relative success in that neighborhood; that is, if the total payoff of the individuals in the learning neighborhood (including the learning individual himself) is M and a particular individual has the payoff m, then the probability that he will be chosen to be the guru is m/M. For technical reasons, time in this model is taken to be continuous, so that at each point in time individuals earn a payoff, and very few individuals are chosen, according to a Poisson process, to learn and update their strategy. The population is taken to be infinite so that even large neighborhoods (large n,k) will be local relative to the population.

We introduce an additional assumption about learning that distinguishes between cultural and biological evolution. We assume that individuals are conservative and are not keen to adopt strategies that are not popular in their neighborhood. Thus, when called to learn, an individual will not change his strategy if his two immediate neighbors play the same strategy as he does. Only if at least one of his immediate neighbors plays a strategy different than his—that is, he is on a border between regions of two strategies—will he look at his learning neighborhood (of radius n) and choose an object for imitation.

This conservative learning process is a stringent version of a learning process that requires an incentive to learn by way of gradual search. When called upon to learn, a player will consider his two immediate neighbors; if neither is different than him, he will with high probability abandon his search and give up learning. With small probability, he will continue to search and look at his four immediate neighbors; if none of those plays a strategy different than his, he will
PLANNING THE PRISONERS' DILEMMA
UNBEATABLE STRATEGY IN A POPULATION

Strings of mutants will be created by the process.

Our conservative learning ensures that the mutants remain consen-

The reader familiar with the biological and game theoretic li-

We call such a strategy, if it exists, an unbeatable one.

In the following sense: Is there a strategy that is immune to an invasion of

Instead of such an elaborate stochastic process it is difficult to ana-

Concentrate on a different aspect of the evolution. We

The path of such an elaborate stochastic process may lead to different re-

The biological and cultural evolution may lead to different results.

In the hood is a property of cultural and not biological evolution. In the

Whether the dead organism was similar to its neighbor's. Resistant to

Plant his seed in the vacant location. This will be done irrespective of

Knows how to grow his seed. A more successful organism is more likely to

Here the learning neighborhood represents how far an organism

Is replaced by a clone of one of the organisms in his learning neighbor-

In a similar biological process, an organism occasionally dies and

We do not claim that cultural learning is always conservative, only

Receive an immediate incentive to learn.

We have chosen a simplified version of this process in which a player stops his search if he does not

dialemate neighborhoods, and so on. The process we have chosen is a simplified

Will continue searching for an incentive to learn among his six nearest

With high probability abandon learning. With small probability, he
and interaction neighborhoods. When $\theta$ is large, it is the cooperative strategy of the Prisoners' Dilemma that is unbeatable. This happens when an individual interacts only with people in his village but learns from a large neighborhood by reading a national newspaper; in such situations, new ideas may travel far when adopted by faraway people. When $\theta$ is small, in the unlikely case when individuals interact with a large group but adopt ideas only from their close neighborhood, then it is the noncooperative defect strategy that is unbeatable.

This result is due to the conservative learning process. Imagine a situation in which all individuals play the cooperative strategy $C$ and a finite number of mutants playing another strategy invade the population. The mutants' strategy, being different from the cooperative strategy, is necessarily less cooperative; that is, it gives a mutant who confronts a mutant a payoff less than $a$ (the payoff of a cooperator playing against a cooperator). The finite number of mutants on the infinite line guarantees that the mutants have only a local effect; most individuals on the line do not confront the mutants at all. The conservative learning process ensures that only individuals on the boundaries between cooperators and mutants may learn and possibly change their strategy, thereby shifting the boundary one step to the right or to the left. Mutants remain therefore concentrated on the line; no new strings of mutants appear, and only the existing strings expand or shrink. It can be shown that it is sufficient to study situations in which the mutant strings have expanded to form large patches and test whether in these situations mutants continue to expand. When $\theta$ is large (i.e., $n$ is very large compared to $k$), an individual on the boundary who is permitted to learn will look deep into the region where cooperating individuals interact with their own kind (since the radius of their interacting neighborhood $k$ is relatively small) and are therefore doing very well. On the other hand, an individual may observe many mutants playing against mutants, whose payoff is therefore less. Thus, he is more likely to choose a cooperator as his guru and switch to cooperation. The group of mutants is therefore likely to shrink, and it can be shown that it will be eliminated with probability 1. This argument is reminiscent of the intuitive argument presented in the introduction: Defection cannot spread too much, for then the individuals on its boundary will observe prosperous cooperators and imitate them.
Playing against munites and players playing against a situation identical to their own munites
individuals playing against a strategy identical to their own munites will see mostly
between the munites and the individual populations. A player on the boundary
our section. Let all the population play another strategy. This arrangement is similar to one in the prev-
the unbeatable strategy. The argument is similar to the case in the prev-
free. For a sufficiently large n (holding k fixed), this strategy x will be
however, there is no guarantee that it does well against other stra-
Dilemma has this property. This strategy is successful against itself.
Playing against itself (the cooperative strategy) in the Prisoners'
Dilemma, playing against ourselves is (the cooperative strategy) in the Prisoners'
should be shown to depend crucially on the conservation of the learning
process, a high mobility of ideas leads to cooperation. This result
This result highlights $\nu$ when learning is conservative (in cultural
small $\nu$ think. This ensures that detection is the unbeatable strategy when $\nu$ is
always game, the highest payoff. Thus, a learning individual is
same interaction environment again of a given neighborhood, decrease
for misfitting. All the observed individuals face, practically, the
large, the difference between the various interaction neighborhoods will
large, individuals interact with a large neighborhood. (Implying $\nu$ to be
ermination players who are close to him (measuring n to be small).
mutually playing another strategy. An individual above to learn considered-
population playing the defection strategy, with only a finite number of
For small $\nu$ (where $\nu$ is considerably smaller than $\kappa$), consider a

PLANNING AN ARBITRARY GAME
UNBEATABLE STRATEGY IN A POPULATION

SOCIOLOGICAL METHODS & RESEARCH
choice of $x$, the $x$ players do better than the mutants. He sees a few players who confront a strategy different than their own, but this does not change the fact that it is the $x$ players who are successful in his neighborhood, and that he is therefore likely to become an $x$ player himself. Thus, the $x$ strategy will take over and eliminate the mutants.

In the case when $k$ is not small, or when the ratio between $n$ and $k$ is not small, the individuals close to the boundary who play against strategies different than their own are no longer an insignificant group and may influence the learning individual’s decision. In that case, a more subtle argument is required: The candidate strategy for unbeatability should do well against itself but at the same time it should do well against other strategies. The balance between these two requirements depends on how many of the $x$ players that the learner observes interact with strategy $x$ and how many with the mutants. If most of the interactions of those $x$ players are with $x$, then in order for $x$ to be unbeatable it should do well against itself. If most of the interactions of the observed $x$ players are with mutants, then $x$ should do well against any mutant and so better be aggressive if it is to eliminate any mutant. Thus, if most of the interactions are “within the family,” then $x$ should be friendly to itself, whereas if its interactions are mostly with outsiders, then what counts is that it should do well against them. It therefore seems as if an unbeatable strategy measures whether it is related to its opponents, and if it is, it plays cooperatively. This idea is captured by Hamilton’s (1964) inclusive fitness. Hamilton suggested that when individuals are related to a degree $r$, then the relevant payoff of an interaction should be given by the individual’s payoff plus $r$ times the payoff of his related opponent. Thus, when the opponent is my twin brother (i.e., $r = 1$), I give his welfare the same weight as to mine. Given the parameter $r$, a new game is derived from the interaction game in which the payoff to a player of an interaction consists of his original payoff plus $r$ times his opponent’s. This degree of “kinship” $r$, which in our case measures how often an $x$ player interacts with similar $x$ players (as opposed to mutants), is a simple increasing function of $\theta = n/k$.

An unbeatable strategy can be shown to be a Nash equilibrium in this new game. In fact, an unbeatable strategy is more than a Nash equilibrium; it is an ESS of this inclusive fitness game.
are neighborhood.

For a second, learning will be mostly conservative; only with small

We expect that for small values of this probability, a strategy that
will lead to learn, the observer and considers a neighborhood or radius n.
Note that this probability governs only his immediate to learn; once
and will only sometimes learn when he is not directly on a border

bords play a different strategy. This means that an individual will learn
neighbors play a strategy identical to his but one of the next two neigh-

bords permitted to learn with a certain probability when his two immediate
neighbor play a strategy different than his. However, he will be
the way. An individual will learn with certainty when one of his twenty-

but he should be rejected to do so. We capture this idea in the follow-
even if his two immediate neighbors play a strategy different than his, then learn.

assumption.

whether the results we obtained are robust to changes in this
neighborhood to consider changing his strategy. In this section, we test

It is cultural evolution that we are interested in, then make

the conservative learning assumption depends on which interpretation
than learning or a biological propagation process. The way to relax

The evolutionary process may be interpreted in two ways, as cult-

The analysis of the theoretical models presented in the previous

RELA Zac n CONSERVATION

guarantee that they will behave as if they were related.

need for the individuals to be related; the frequent local interactions
as it turns behavior arises from frequent local interactions. There is no
structure is found to be one that is “friendly” to similar opponents. It is
strategy that is “strong” in the population, with the local interaction

The interaction emerging from this analysis is rather surprising.

SOCIOLOGICAL METHODS & RESEARCH
TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>S, S</td>
<td>S + 1,1</td>
</tr>
<tr>
<td>D</td>
<td>1, S + 1</td>
<td>2, 2</td>
</tr>
</tbody>
</table>

If, however, evolution should describe biological propagation, then no such conservative restriction is appropriate. An individual dies and is replaced by an offspring of a neighboring individual. This replacement is independent of whether or not the deceased individual was identical to his two immediate neighbors. Thus, in the biological case, relaxing the conservative assumption would mean that an individual can "learn" whenever someone in his learning-propagation neighborhood (a neighborhood of radius \( n \)) plays a strategy different than his own.

In this case, we do not necessarily expect the results of the theoretical model to hold. An invading mutant may take over a population playing a strategy that is unbeatable in the previous model. The fact that a mutant can spread far from his current location due to the new learning rule, and that this may happen often (in contrast to cultural learning, where this rarely happens), makes the existing population vulnerable to invasions by mutants.

Both ways of easing the learning rules (the cultural and the biological) lead to models that are analytically intractable. We therefore turn to computer simulations to test our intuitions.

**COMPUTER SIMULATIONS**

For the computer simulations, we consider the Prisoners’ Dilemma shown in Table 2 (with \( S > 2 \)). The first strategy \( C \) (cooperate) is an unbeatable strategy when the radius of the learning neighborhood is sufficiently large relative to the radius of the interaction neighborhood: \( n \gg k \).

Throughout this section, we keep the interaction neighborhood small, \( k = 1 \), and the learning neighborhood relatively large, \( n = 3 \). The parameter \( S \), which measures the cooperator's contribution to his opponent, took the values 3, 5, and 7; later, it was increased to \( S = 18 \). It
The simulations were run as follows. For each part of values $p, q,$ and $d$, we were interested in whether cooperation took over the entire population. However, in some cases, cooperation was sometimes the mutant strategy. In both cases, the strategy that was sometimes the mutant strategy was the other strategy that was introduced in some corner post.

For the simulations, we took a population of 1,000 individuals.

Weber determined that the population evolved to cooperate with certainty. Therefore, any model that does not follow the biological evolution model should be eliminated. In this case, we checked whether increased values of $p$ can help cooperation.

2. When all the population plays cooperate and mutants playing defect

3. The defective, when all the population plays cooperate, the cooperators should eliminate. No players who play cooperate, the cooperators should eliminate.

Learning processes for which the cooperative assumption is relaxed:

Undenialability of cooperation when learning is cooperative implies that learning is cooperative, hence we assume the following properties, which were tested in simulations for the entire population, and where the model describes biological evolution. In the simulations, the learning is cooperative.

Theorem 1.1: $d = p - q$. Because $u = 0$, there was no need to consider higher values of $d$. For $d = 1$, the learning is cooperative, hence learning is cooperative.

For $d = 2$, the learning is cooperative, hence learning is cooperative.

For $d = 3$, the learning is cooperative, hence learning is cooperative.

When asked immediate two neighbors learn with probability 1, whereas when asked immediate two neighbors learn with probability 0. The learning rule was changed in two ways, desribing how increased $q$ makes the cooperative more robust against mutants.

We wished to test whether the learning rule works.
the line, we first calculated the average payoff of each individual. We then randomly chose an individual to learn and tested whether he was permitted to learn; if so, he will have used the stochastic learning rule and imitated one of his neighbors. This led to a new configuration for which we calculated the payoffs and so on. We continued the process until one of the strategies took over the entire population. A time limit of $10^7$ periods that was incorporated in the program was never met. For each pair of $p, S$ we iterated this experiment 1,000 times and noted in how many of those runs the strategy cooperate won the population over.

In the first set of simulations, all but the central 10 individuals played defect whereas the 10 mutants played cooperate. The block of 10 proved to be sufficiently large so as to allow the mutants (cooperate) to win when learning was close to conservative. In the second set of simulations, the roles of cooperate and defect were swapped; then, all but a few mutants were cooperators. Here as before, we asked whether cooperation won; to obtain convincing results, we made it as difficult as possible for cooperation to win. Defectors are better off when they are isolated; hence, we introduced four isolated defectors in the center of the population (in positions 1, 7, 13, and 20 of the central 20 positions).

**Simulation Results.**

In the first simulation, a block of mutant cooperators was introduced in a population of defectors. Figure 1 clearly shows that for small values of $p$, when learning was close to conservative, cooperation won the population over. For higher values of $S$, when cooperation had a greater advantage, cooperation won close to 100 percent of the runs even when departure from conservatism was significant. For lower values of $S$, the curve was not as flat; that is, the results are sensitive to deviation from conservatism. Note that below $S = 2.4$, cooperation is no longer unbeatable; for $S = 3$ when cooperation is close to being beatable, the block of 10 cooperator mutants may not have been sufficiently large to enable them to win in all cases when learning was conservative, but they still won more than 75 percent of the runs. When $p$ was close to 3, and the model was more adapted to biological evolution, defection comfortably won the population over.
SUMMARY AND CONCLUSIONS

runs even when learning was not conservative.

high values of L cooperation eliminated defection in almost all the
depicted in Figure 3. Here, we increased L to L = 14 and found that for
eliminate mutant defectors. This is verified by the simulations
results seem to suggest that as L increases, cooperation can

runs

where is close to 3. For L > 7, cooperation continued to win in most
"biological" end of the figure, and the results are not as clear as the
population of cooperators. Figure 2 shows that cooperation eliminated
the mutants unless the deviation from conservatism became signifi-

In the second simulation, four defection mutants were placed in a

Figure 1: Test 1

The Frequency of Mutant Cooperators Versus a Population of Defectors
tion can survive even in a biological process when the altruistic act
beatable and defection could win the population over. However, coop-
cultural toward biological evolution, cooperation was no longer un-
when cooperation is relaxed. We found that as we moved away from
ensitive assumption (and resisted whether it remains unappeal-
reached a situation in which cooperation is unappealing (with the)
robust when the cooperative Learning assumption is relaxed. We
We investigated by computer simulations whether our results are

biological evolution.

may be a feature of some cultural evolutionary processes but not of
then with incentives to learn. We argue that cooperative Learning
not learn when their immediate environment does not provide
of this result, we assumed that Learning is coordinate: Individu-
developed as a result of the local nature of interaction and Learning.
Thus, the message of this model is that cooperation could have

which by the rank of the Learning and interaction neighborhoods.
individuals can adapt the payoff of this opponent to a degree deter-
be shown to be an ESS of a related interaction game in which each
able stategic, a strategy that it all play if and a

where it exists, can

 Retrieves success in the Learning neighborhood. In this model, we
The probability of imitation is proportional to his

We therefore introduced the second model in which we rested, as in

if its success to make the model analytically intractable.

Although this requires a chain of events that occurs with low probab-
spatially (initially) wholly cooperative population.

too much for sustaining cooperation, if enabled a single defection to
large Learning neighborhoods with stochastic Learning provided to be

however, the combination of

that even the introduction of mutations cannot destroy the robustness
although the introduction of mutations will evolve to have a majority of cooperators. We found
found that when the circle is sufficiently large, with high probability
Learning the highest average payoff in his neighborhood. We

We presented two models. In the first model, a wholly population was

SOCIOLOGICAL METHODS & RESEARCH
costs little relative to its contribution to the beneficiary. Thus, local interaction supports cooperation against invading new forms of behavior in conservative cultural environments and even in biological setups when the costs of helping the other are sufficiently small.

NOTES

1. This model is described in detail in Eshel, Samuelson, and Shaked (1998). A similar model can be found in Bergstrom and Stark (1993).

2. We assume that his costs of providing the public good are \( 1 + C \), so that his net benefit is negative: \( 1 - (1 + C) = -C \).

3. It is our assumption \( C < 1/2 \) that enables the long-term existence of altruists. If \( C > 1/2 \), it is so disadvantageous to be an altruist that altruists can no longer coexist with egoists. In that case, the only absorbing state that includes egoists is the one in which there are no altruists.

4. Rare mutations were first introduced to evolutionary game theory by Young (1993) and Kandori, Mailath, and Rob (1993).

5. The details of this model are taken from Eshel, Sansone, and Shaked (1999).

6. We will see what happens when the game is not the Prisoners' Dilemma.

7. The results of this model remain unchanged when the probabilities of choosing the next strategy depend on the average payoff of each strategy (as in the previous model of altruists and egoists) and not on the sum of payoffs.

8. An unbeatable strategy has the additional feature that if it appears as a mutant in a population playing another strategy, then it has a positive probability of defeating the other strategy and winning the population over.

9. The difference between the concepts is that unbeatability is defined for a population with a local interaction structure whereas evolutionary stable strategy (ESS) is defined for totally mixed, panmictic populations. Moreover, ESS does not specify the process by which the mutants may be eliminated, whereas we have a well-defined process.

10. Both payoff and learning of the individuals situated at the edge of the population were modified to account for their fewer neighbors. This cannot be avoided in a finite simulation but has little influence on the results.

REFERENCES


Evolution and learning.

Interests are game theory and evolutionary models of economies, in particular local in-

Tom Shieh is a professor of economic history at the University of Bonn. His research

systems, population game theory, and complex dynamics in structured populations.

research interests include mathematical physics, long-term dynamics of complex systems.

Emilia Sandomeno is a researcher of mathematical physics at the University of Naples. Her

Evolutionary ideas of bounded rationality and learning.

Evolution, learning, matching, and electronic money

Lauri Salmi was a professor of mathematics at the University of Wisconsin-Madison.

Evolutionary game theory and complex dynamics in structured populations.

Donna E. Hefner is an assistant professor in the Department of Economics at the

Evolutionary game theory and complex dynamics in structured populations.

Deirdre E. Henderson is a professor of economics at the University of Wisconsin-Madison.

Social Choice and Psychological Variables in Learning.


Scientific American 272 (6): 76-83.


Chaos 3.5-78

1993, "The Special Dynamics of Evolution," International Journal of bifurcation and


Kanagawa, Michiko, George J. Mailath, and Rafael Rob 1999, "Learning, Mutation, and Long