Rogers' paradox: An agent-based model in R

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Background

Rogers (1988) presented a model exploring the evolution of social learning relative to individual learning, in a changing environment. The result, since known as 'Rogers' paradox', is that a population containing social learners can never have higher fitness than a population with no social learners. While not inherently paradoxical, this runs counter to the common claim that social learning underpins our species' unusual evolutionary success.

In the model, agents exhibit one of two behaviours. One behaviour is 'correct' in the current environment, the other is 'incorrect'. Correct behaviour results in higher fitness than incorrect behaviour. Periodically, the environment changes such that previously correct behaviours are no longer correct.

Agents can be either *individual learners*, who directly sample the environment and determine the correct behaviour with a fixed probability, or *social learners*, who select another agent at random and copy their behaviour. Individual learning is assumed to be more costly than social learning.

In a changing environment, a frequency-dependent equilibrium exists between social learners (aka information scroungers) and individual learners (aka information producers), similar to producer-scrounger dynamics in feeding behaviour. When rare, social learners can copy adaptive behaviour from individual learners without bearing the higher cost of individual learning. They therefore do better than individual learners and increase in frequency. But when the environment changes, social learners are left copying out-of-date information from other social learners. Individual learners now do better, because they can detect the environmental change and identify the new correct behaviour.

At this equilibrium, social and individual learners must have equal fitness, by definition. Hence, social learning does not increase overall population fitness, relative to a population entirely composed of individual learners.

Model outline

There exist N agents who reproduce each generation. Generations are non-overlapping such that N new agents are created each generation to replace the N previous agents.

Agents are either individual or social learners, and can have either correct or incorrect behaviour given the current state of the environment.

Each generation, individual learners acquire the correct behaviour with probability p. Social learners choose one of the previous generation at random (irrespective of whether they are social or individual learners) and copy their behaviour.

The first generation is entirely made up of individual learners. Agents reproduce asexually in proportion to their fitness, which is determined by whether they have the correct behaviour ($+b$) or not (-b), as well as intrinsic costs to individual (c) and social (s) learning (where $c > s$). There is a small mutation rate μ for learning strategy such that offspring sometimes have different learning styles to their parent. This is how social learning is introduced into the population.

The environment shifts with probability u each generation. The simulation is run for t_{max} generations with multiple independent runs.

In Rogers' model the environment switched between one of two states. However this can sometimes lead to odd dynamics under high rates of environmental change, as agents can copy behaviour from the previous generation that was then incorrect, but is now correct. Instead the current model uses more realistic never-repeating environments, such that with probability u the environment switches to an entirely novel state.

Parameters

Symbols are the same as in Rogers' original paper, where possible.

- w, the baseline fitness given to all agents, fixed at $w = 1$
- b, the fitness bonus/penalty for being in the right/wrong environment, fixed at $b = 0.5$ (so agent fitness is $w + b$ when behaviour matches the environment, or $w - b$ if it doesn't)
- c, where $bc =$ the cost of individual learning. Constrained such that $b(1 + c) < 1$, to avoid negative fitnesses
- s, where $bs =$ the cost of social learning. Constrained again to $b(1 + s) < 1$
- u, the probability on each generation of an environmental shift $(0 < u < 1)$
- N, the number of agents $(N > 0)$
- μ, the probability of a new agent having a different learning strategy to its parent (i.e. the mutation rate) $(0 < \mu < 1)$
- p, the probability of an individual learner learning the correct behaviour. NB this was always 1 in Rogers' original model $(0.5 < p < 1)$
- t_{max}, the maximum number of generations per run
- $runs$, the number of simulation runs

Basic model output

Figure 1 shows an illustrative case of Rogers' paradox, with a moderately changing environment and reasonable cost of individual learning. The top graph shows the proportion of the population who are social learners. The rest are individual learners. The bottom graph shows the overall population fitness. The horizontal line in the bottom figure shows the expected fitness of a population of 100% individual learners. Lines are mean values calculated from multiple runs, with grey areas indicating ranges (maximum and minimum values for all runs).

For the parameter values shown in Figure 1, one can see that social and individual learners co-exist (top figure) and the population as a whole never exceeds the pure individual learning fitness (bottom figure). This is Rogers' paradox.

Environmental change

Removing environmental change, i.e. setting $u = 0$, causes social learning to entirely replace individual learning (Figure 2). The initial individual learners do all the work of identifying the correct behaviour, and then social learners take over due to their lower learning costs. They never suffer from copying out-of-date behaviour as they do in Figure 1, because behaviour never becomes out-of-date. Here Rogers' paradox no longer applies, as the population of social learners does better than a population of individual learners (bottom graph of Figure 2).

In contrast, when the environment changes very rapidly ($u = 0.8$), then individual learning becomes more common (Figure 3). Individual learners can track the environmental change, unlike social learners.

Cost and accuracy of individual learning

Making individual learning less costly (reducing c) reduces the frequency of social learning (Figure 4). Making individual learning less accurate (reducing p) increases the frequency of social learning (Figure 5). Note that in the latter case, Rogers' paradox still holds. The heatmap in Figure 6 shows how social learning evolves

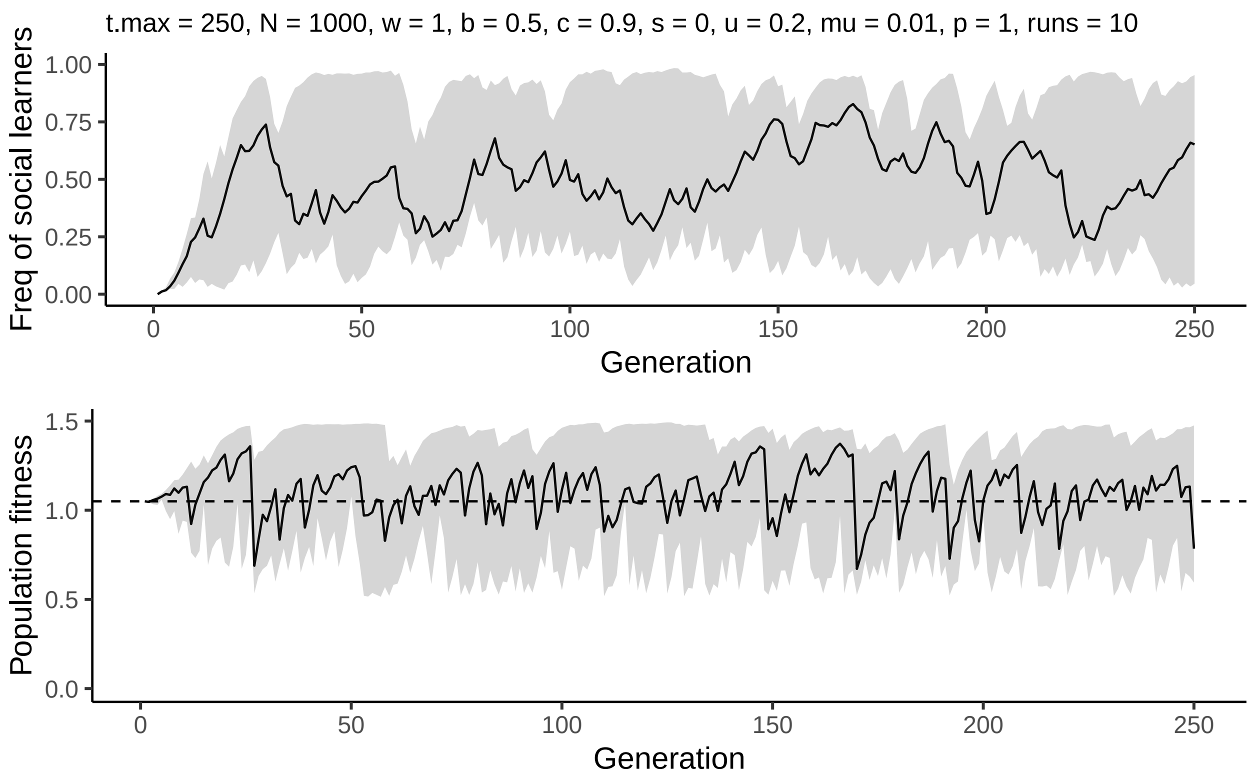

Figure 1: Illustrative run showing Rogers' paradox

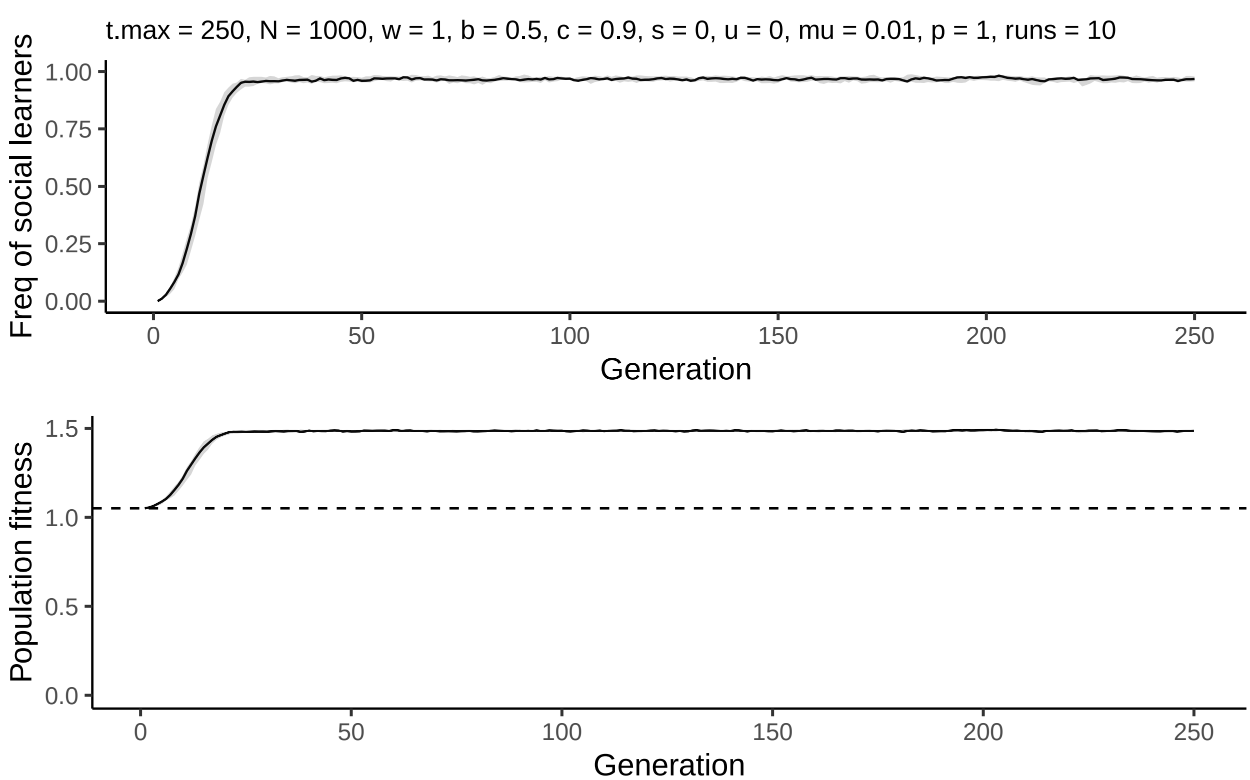

Figure 2: Unchanging environments favour social learning

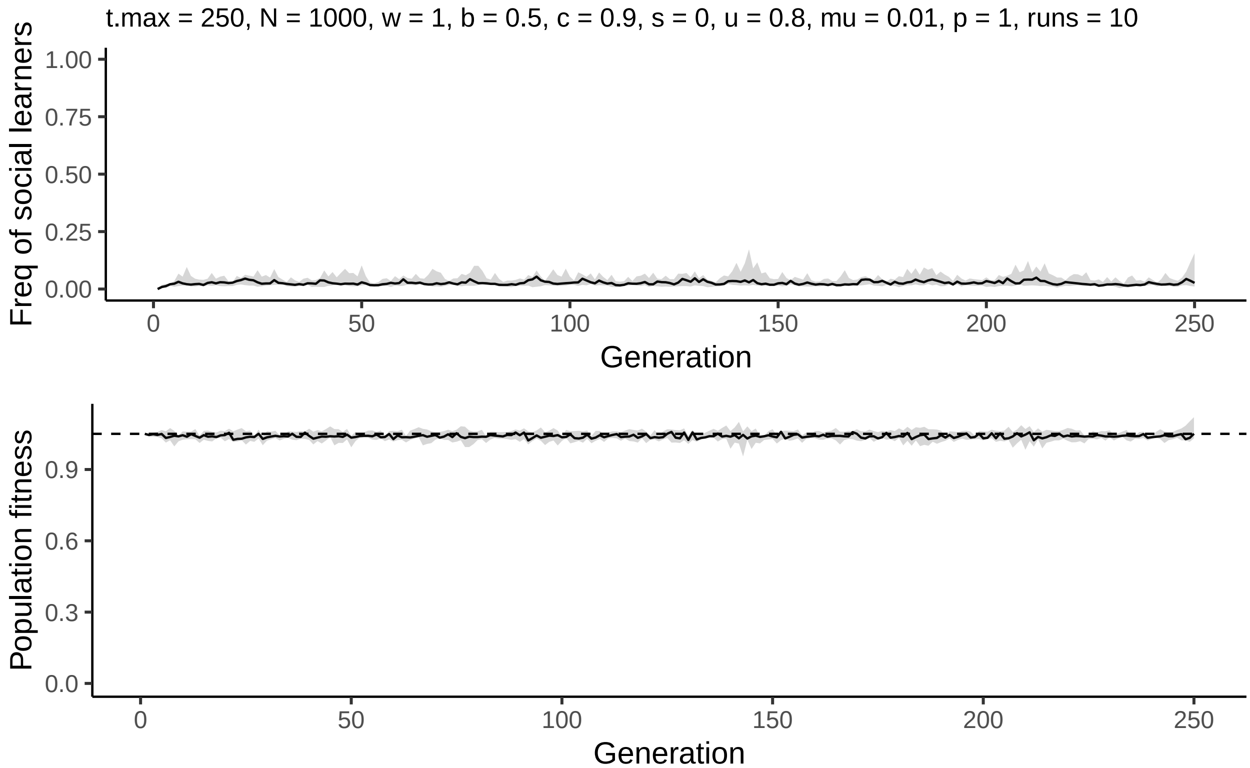

Figure 3: Rapidly changing environments favour individual learning

when environments are stable and individual learning is costly. Figure 7 shows the same, but for inaccurate individual learning.

Critical social learning

Enquist, Eriksson, & Ghirlanda (2007) proposed a 'solution' to Rogers' paradox by relaxing the unrealistic assumption that organisms can only do either individual learning or social learning. In reality organisms typically do both, or at least have the capacity to do both. Enquist et al. (2007) proposed a third heritable strategy, *critical social learning*, in which individuals first try social learning, and if the result is unsatisfactory, then they try individual learning. As shown in Figure 8, critical social learners outperform pure individual learners and pure social learners (top panel). Moreover, they do not suffer from Rogers' paradox (bottom panel), clearly exceeding the fitness of pure individual learners.

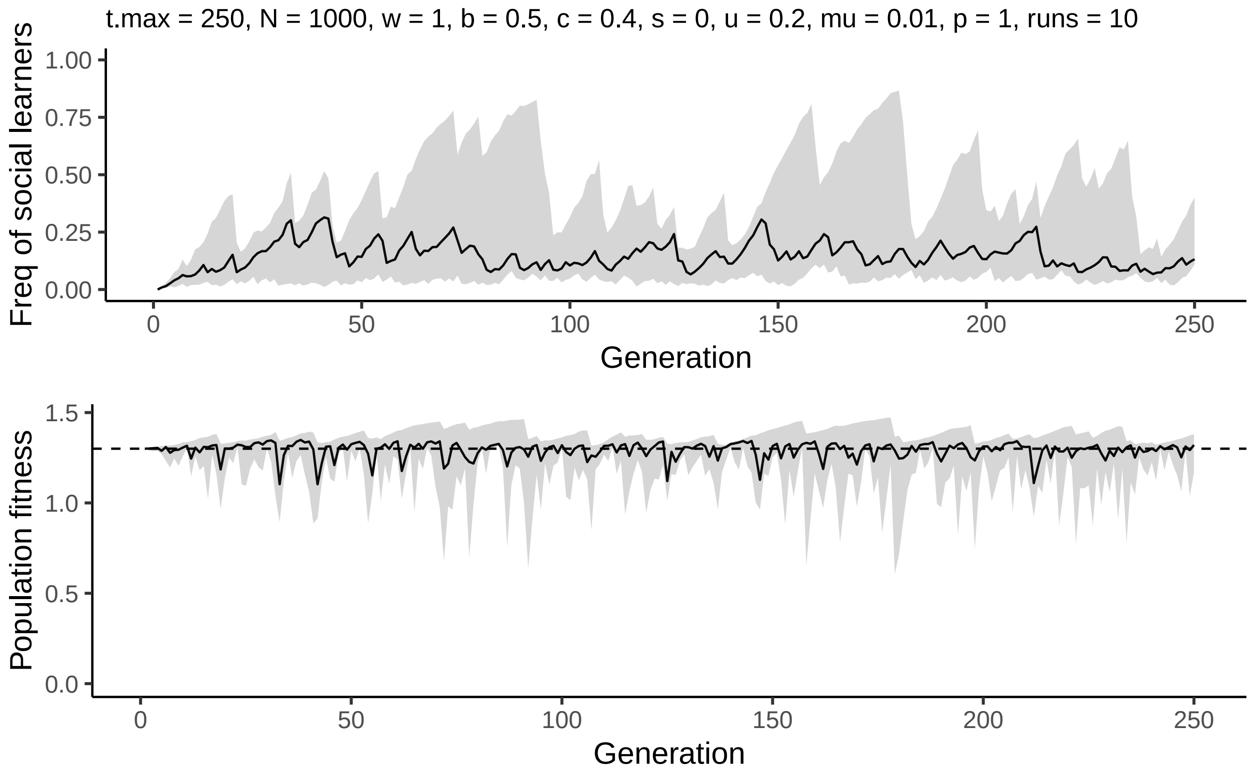

Figure 4: Reducing the cost of individual learning favours individual learning

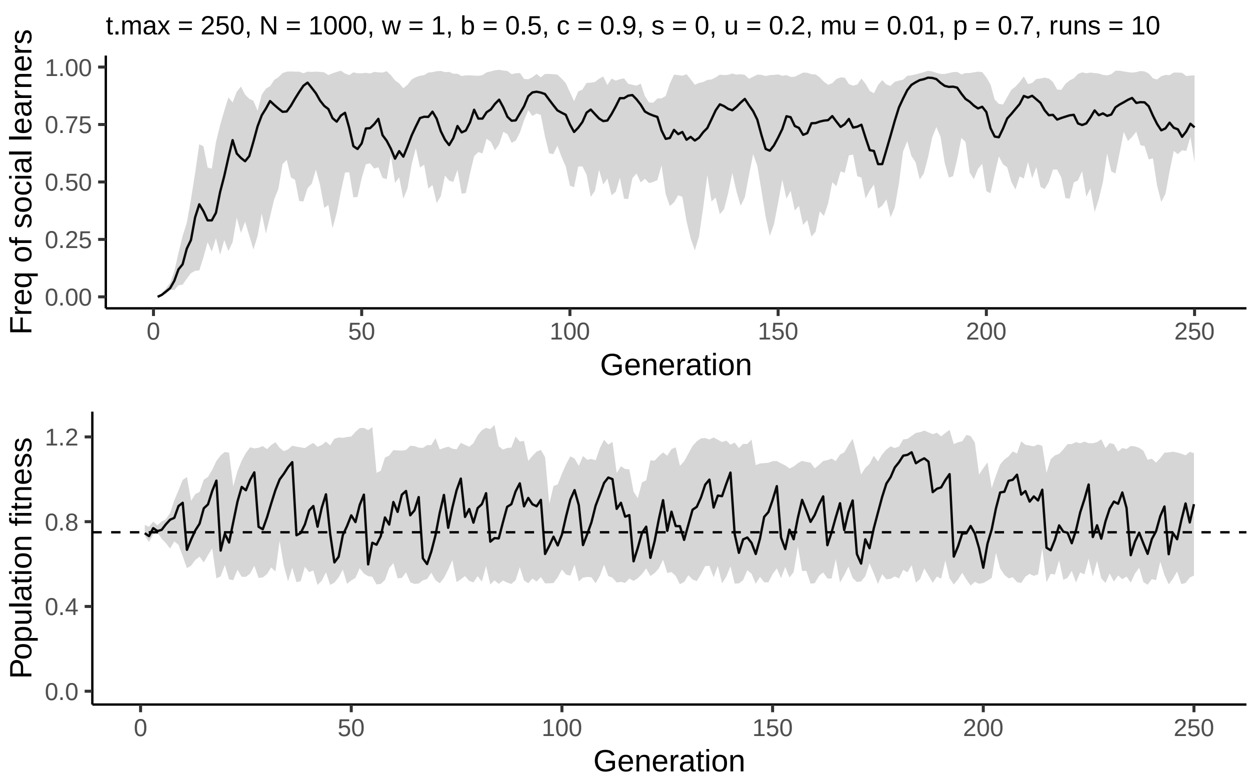

Figure 5: Reducing the accuracy of individual learning favours social learning

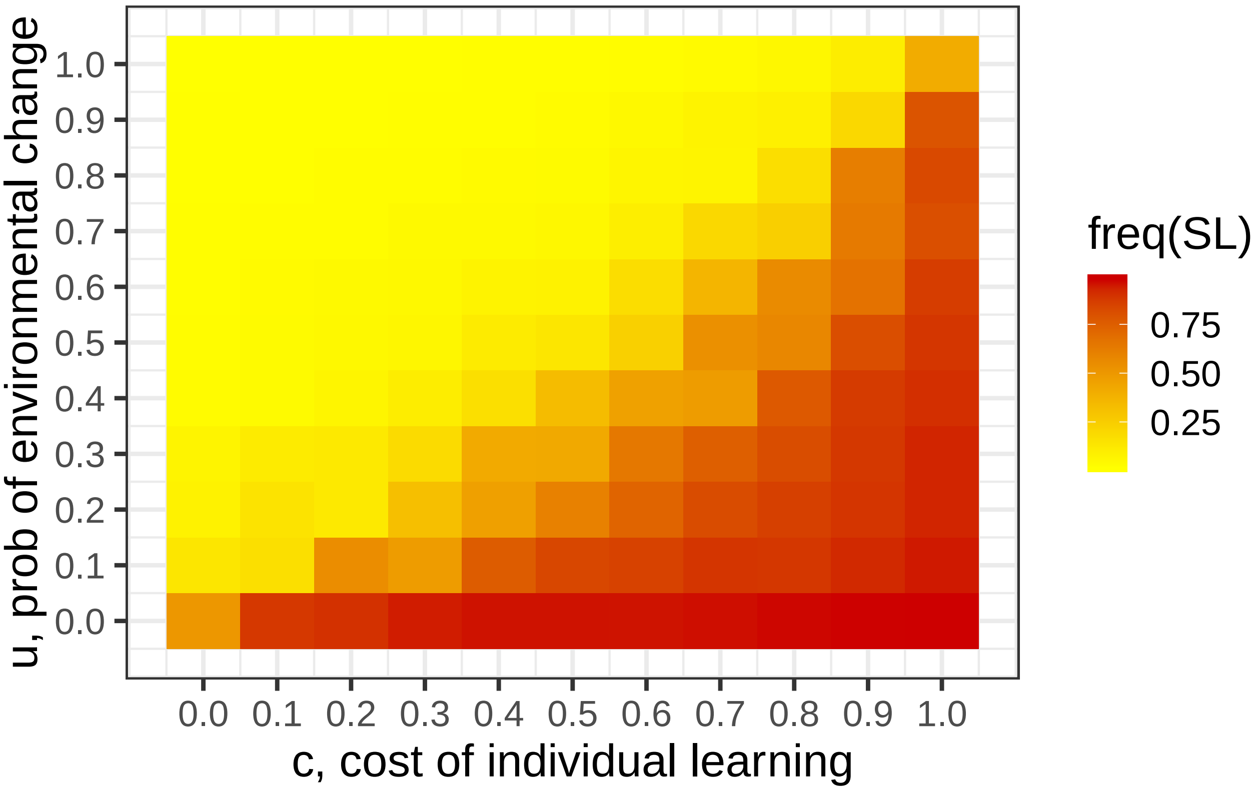

Figure 6: Social learning evolves when environments are stable and individual learning is costly

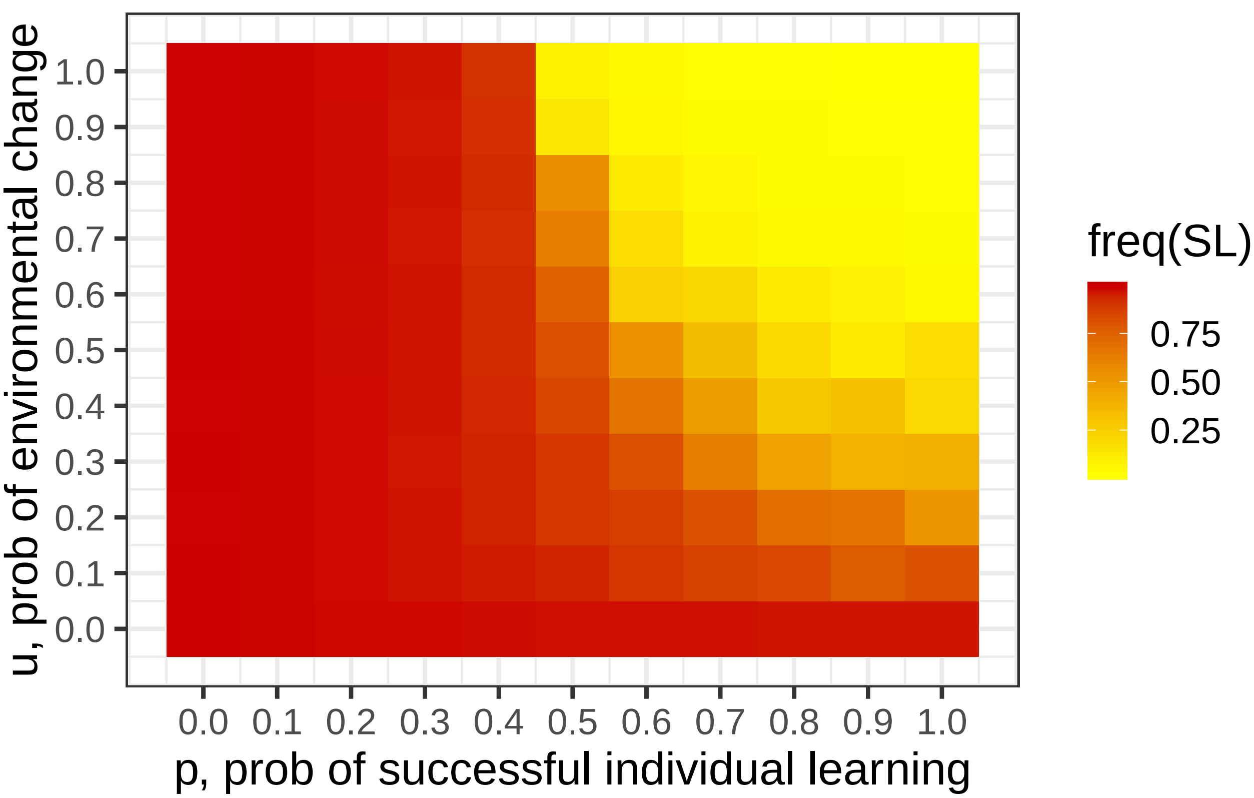

Figure 7: Social learning evolves when environments are stable and individual learning is inaccurate

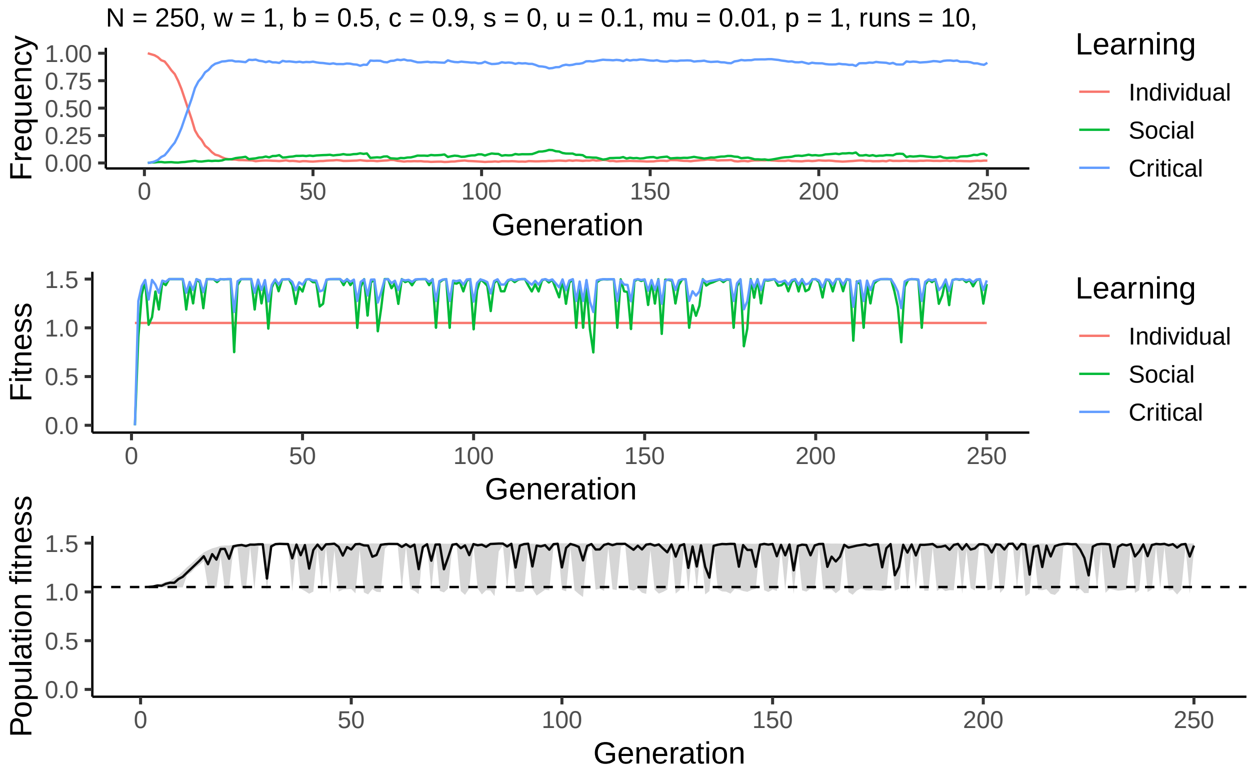

Figure 8: Critical social learning outperforms both social learning and individual learning

References

Enquist, M., Eriksson, K., & Ghirlanda, S. (2007). Critical social learning: A solution to rogers' paradox of nonadaptive culture. *American Anthropologist*, *109*(4), 727–734.

Rogers, A. (1988). Does biology constrain culture? *American Anthropologist*, *90*(4), 819–831.