

Escaping the prison: Emergent cooperation through evolving GRN architecture

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Abstract

Classical models of cooperation evolution pre-specify the strategy space. Agents play tit-for-tat, or always-defect, or some finite set of conditional rules. Evolution selects among them. But where do strategies come from? In living systems, behavior emerges from gene regulatory networks shaped by mutation, selection, and drift. Here we evolve GRNs that sense opponent state during development before making a one-shot choice in the Prisoner's Dilemma. Information is available from the start, but at generation zero, random wiring renders it unusable. Networks experience blind mutual defection. The dilemma is real to them. Through drift and selection, networks discover regulatory configurations that transform available information into conditional response. Two structurally distinct architectures emerge with equal frequency, and early stochastic wiring commits populations to one or the other. The effective game changes not because the environment changes, but because internal architecture does. Our results suggest that the game an evolving system faces is defined not by what information exists, but by what information it can use.

Methods & Results

To study emergent strategy, we need a system where behavior arises from structure rather than prescription. We evolve gene regulatory networks (GRNs) that develop in the presence of an opponent before making a one-shot choice in the Prisoner's Dilemma (Figure 1). Each network has five genes: two outputs (C, D), two sensors (S_C, S_D), and one internal gene (I). We also test 4-gene networks lacking I . Networks begin fully connected with random weak weights (Milocco and Uller, 2024).

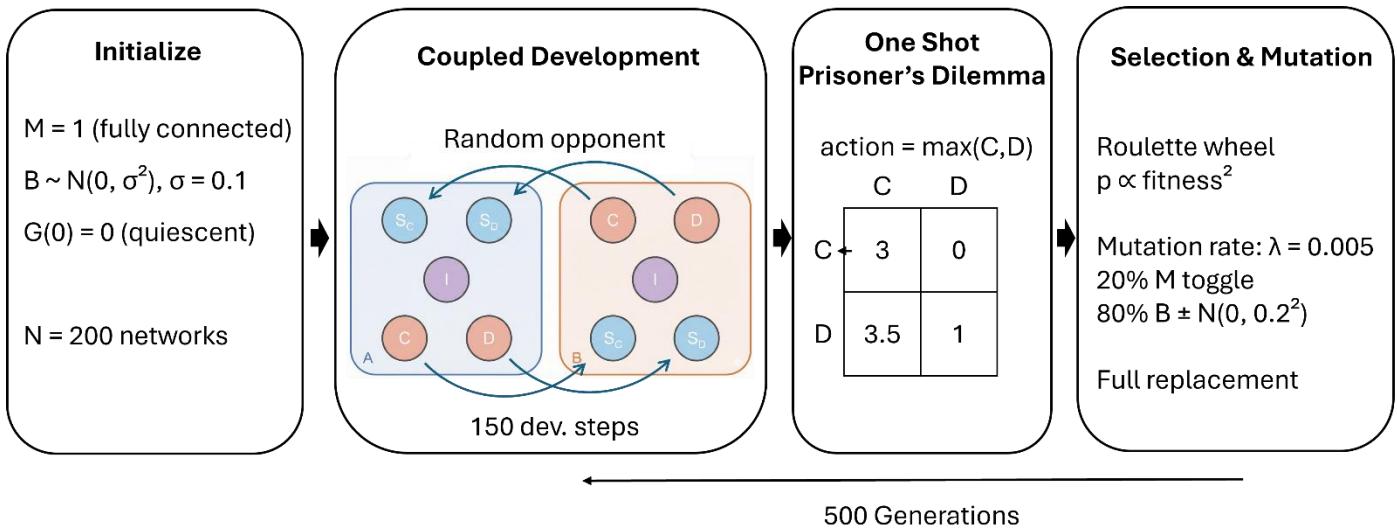


Figure 1. Evolutionary simulation: GRNs develop with sensory coupling to a random opponent, make a one-shot Prisoner's Dilemma choice, and reproduce proportional to fitness over 500 generations.

The design creates a gap between information availability and information use. Sensors provide opponent state, but initial random wiring cannot exploit it. Evolution must discover how to connect input to appropriate output.

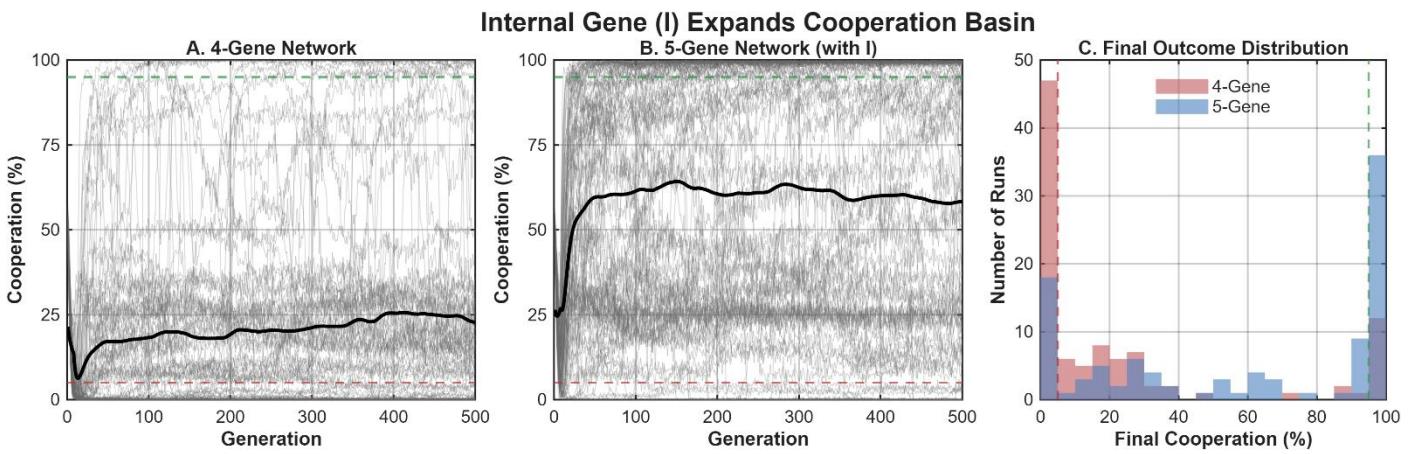


Figure 2. The internal gene (I) increases cooperation success from 12% to 32%, with 5-gene networks showing more stable evolutionary trajectories than 4-gene networks.

Without I, cooperation is fragile and most runs collapse to mutual defection (Figure 2A). With I, cooperation stabilizes (Figure 2B). The outcome distribution shifts dramatically: 5-gene networks achieve stable cooperation ($\geq 95\%$) in 32% of runs, compared to just 12% for 4-gene networks (Figure 2C). The internal gene nearly triples the success rate. To identify the mechanism, we analyzed the structure of the fitness landscape for both architectures.

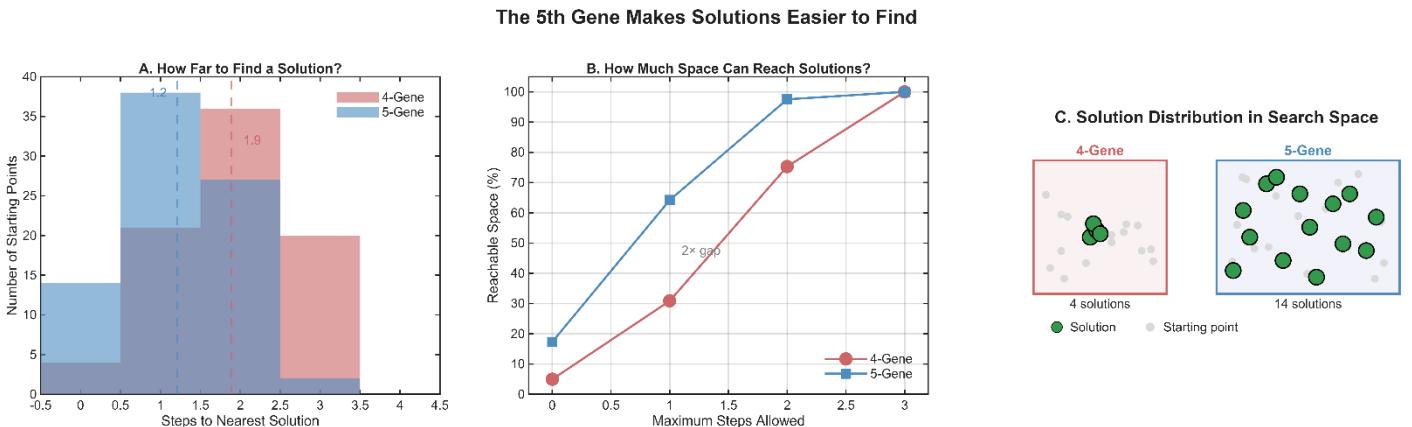


Figure 3. The 5-gene architecture contains more cooperative solutions (14 vs 4) located closer to random starting points (1.9 vs 3.4 steps), expanding the accessible solution space.

The 5-gene landscape contains 14 cooperative solutions versus 4 in the 4-gene space (Figure 3C). Mean distance to the nearest solution is 1.9 mutational steps for 5-gene networks versus 3.4 for 4-gene (Figure 3A). Consequently, a larger fraction of initial conditions can reach cooperative solutions within a given number of steps (Figure 3B). The internal gene increases evolvability by expanding the accessible solution space. The 14 solutions identified in Figure 3 represent distinct weight configurations. We next asked whether these configurations share common structural motifs, specifically, how the internal gene is utilized.

Two distinct circuit architectures achieve cooperation

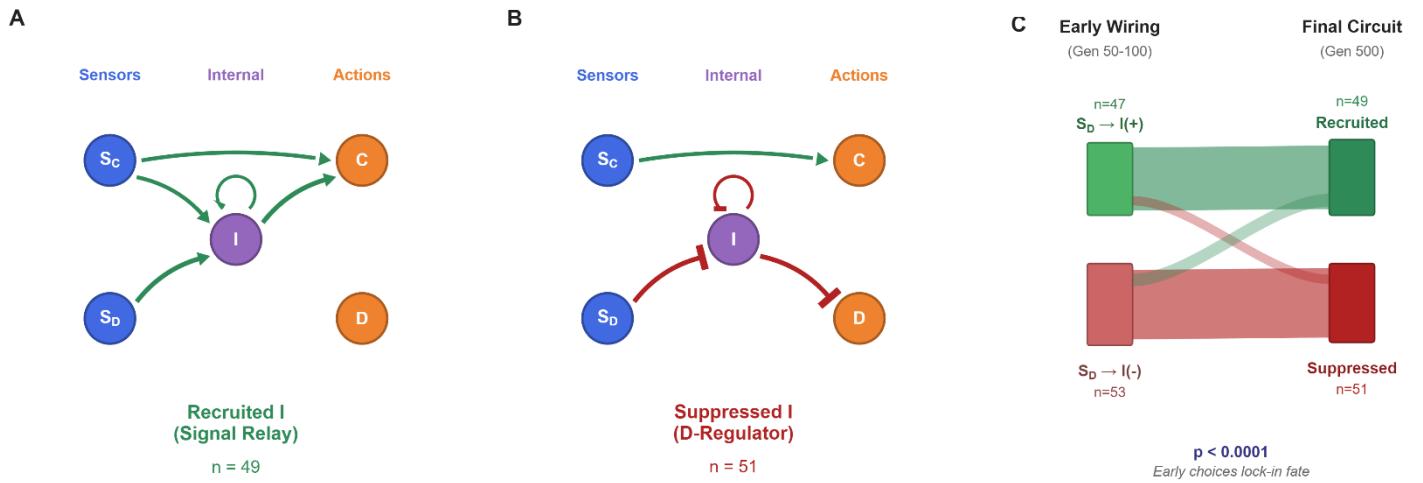


Figure 4. Two distinct architectures emerge with equal frequency: Recruited I (signal relay, n=49) and Suppressed I (D-regulator, n=51), with early $S_D \rightarrow I$ wiring predicting final architecture ($p < 0.0001$).

Despite variation in specific weight values, solutions cluster into two architectures based on I utilization (Figure 4A-B). "Recruited I" (n=49): net positive input to I, which relays signals to C. "Suppressed I" (n=51): net negative input to I, which regulates D. The internal gene serves one of two functional roles: signal amplifier or output suppressor. Architecture is determined early: $S_D \rightarrow I$ sign at generations 50-100 predicts final role ($p < 0.0001$, Figure 4C).

Discussion

Emergent versus pre-defined strategies

Classical evolutionary game theory defines strategies *a priori* and asks which is selected. This assumes a closed strategy space. Our results demonstrate an alternative: when behavior emerges from evolvable regulatory architecture, the strategy space is constructed during evolution. The two architectures we observe (Recruited I, Suppressed I) were not specified in advance. They crystallized from the interaction of selection, drift, and developmental constraint. This distinction between prescribed and emergent strategy spaces may explain behavioral diversity not captured by classical models.

Degeneracy and evolutionary innovation

The internal gene enables structural degeneracy: multiple distinct architectures solve the same functional problem. This has two consequences. First, degeneracy increases evolvability through more paths to success. Second, degeneracy enables divergence as populations reaching different architectures may subsequently specialize in different directions. The early path-dependence we observe ($S_D \rightarrow I$ sign at generation 50-100 determines final architecture) indicates that stochastic events during evolutionary search can have lasting structural consequences. Innovation, in this view, is not optimization within a fixed space but exploration of a space that expands as new structures emerge.

Scope and limitations

Information about opponent state is objectively available via sensors, but at generation zero, random wiring makes it unusable. Networks experience blind mutual defection. Evolution discovers wiring that transforms available information into accessible information. The effective game changes not because the environment changes, but because internal architecture changes. The PD was real for networks that could not process their sensors; it dissolves for networks that can. Our findings concern how regulatory architecture shapes the boundary between information that exists and information that can be used.

Implications for open-ended evolution

Pre-specified strategy spaces are closed; evolution eventually finds the optimum and stops. Emergent strategy spaces can remain open as new structures create new possibilities. The internal gene in our model is minimal (one additional node), yet it doubles the number of functional motifs. More complex regulatory architectures may support correspondingly richer structural diversity. Understanding how architectural features expand or constrain the space of evolvable strategies is a step toward understanding open-ended evolutionary dynamics.

Conclusion

Under identical selection and initialization, two solutions emerged. In our model, the internal gene enables degeneracy: multiple developmental paths to the same functional outcome. Whether this extends to other architectures, selection regimes, or biological gene regulatory networks remains open. Our results suggest that when strategies emerge from evolvable developmental structure, the organization of that structure shapes what evolution can find, and early contingencies may constrain later outcomes.

References

Milocco, L. and Uller, T. (2024) “Utilizing developmental dynamics for evolutionary prediction and control,” *Proceedings of the National Academy of Sciences*, 121(14), p. e2320413121. Available at: <https://doi.org/10.1073/pnas.2320413121>.