A Framework for Inducing, Recognizing, and Studying Fraternal Evolutionary Transitions of Individuality

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Abstract

1 We analyze the geometry of the species– and genotype-size
2 distribution in evolving and adapting populations of single-
3 stranded self-replicating genomes: here programs in the
4 Avida world. We find that a scale-free distribution (power
5 law) emerges in complex landscapes that achieve a separation
6 of two fundamental time scales: the relaxation time (time for
7 population to return to equilibrium after a perturbation) and
8 the time between mutations that produce fitter genotypes. The
9 latter can be dialed by changing the mutation rate. In the scal-
10 ing regime, we determine the critical exponent of the distribu-
11 tion of sizes and strengths of avalanches in a system without
12 coevolution, described by first-order phase transitions in sin-
13 gle finite niches.

Introduction

14 It is the aim of artificial life research to realize engineered
15 systems that exhibit properties of biological life in order to
16 study them, but also with an eye towards applications such
17 as fault-tolerant infrastructure, artificial intelligence, etc.
18
19 Open-ended evolution
20 evolutionary transitions
21 fraternal transition of individuality
22 * definition
23 * example – social insects: hierarchical
24 in order to we need to design a framework in which we
25 expect such transitions to occur and, importantly, occur in a
26 way that is straightforward to detect.
27 To this end, we introduce the dishtiny framework. seeks
28 to achieve this by making organisms explicitly register in
29 cooperating groups ("channels") to cooperate spatiotempo-
30 rally to maximize the harvest of a resource. Then, detecting
31 transitions of individuality simply by looking for the pres-
32 ence of resource-sharing and reproductive division of labor
33 among organisms sharing a channel and the absence among
34 organisms *not* sharing a channel. We believe that one of
35 the most interesting properties of our system this abstrac-
36 tion is organized so that it can scale to an arbitrary number
37 of hierarchical levels. We see the ability to select for an ar-
38 bitrary number of evolutionary transitions as an important
39 step to achieving open-ended scale in artificial life that more
40 closely resembles that of biological life.

Methods

42 We manually designed strategies that organisms could
43 use to cooperate to experimentally demonstrate that the
44 DISHTINY platform selects for detectable hierarchical tran-
45 sitions of individuality.

DISHTINY

47 We will begin by discussing the implementation of our arti-
48 ficial environment at a single hierarchical level, then lay out
49 how the system scales to multiple levels.
50 A single continuous-valued resource is tracked. When or-
51 ganisms accrue sufficient resource, they may choose to pay
52 a cost of -8 to reproduce. As shown Figure 1, resource is
53 distributed in waves that emanate from a single point. With
54 each simulation update, the resource wave advances one grid
55 tile outward until it reaches a predefined extent. The re-
56 source wave then ceases. Coincident with the inception of
57 each resource wave, an activation-quiescence signal wave is
58 triggered at the wave's center point. Example signal waves
59 are shown in Figure 1. With every update, the signal wave
60 passes to adjoining cells registered to the same channel as
61 the cell it emanates from. The signal wave is not propagated
62 to any cells on any other channel. In this way, cells sharing
63 the channel of the cell where the resource wave originated
64 are activated coincident with the resource wave.
65 In order to obtain resource, a cell must be activated by
66 a signal wave as the resource wave passes over. The cell
67 at the center of a resource wave will always be activated
68 and absorb resource. However, immediately adjacent cells
69 can only obtain resource by the action of the signal wave —
70 by sharing the channel of the originating cell. Cells further
71 off depend on a continuous path of cells extending from the
72 originating cell that signal on the originating channel in or-
73 der to obtain resource. As shown in Example a of Figure 1,
74 the rate of resource collection is determined by the size of
75 a channel signaling network; small or fragmented channel
76 networks will tend to frequently miss out on resource as it
77 passes over.
78 Importantly, a significant activation cost is paid by each
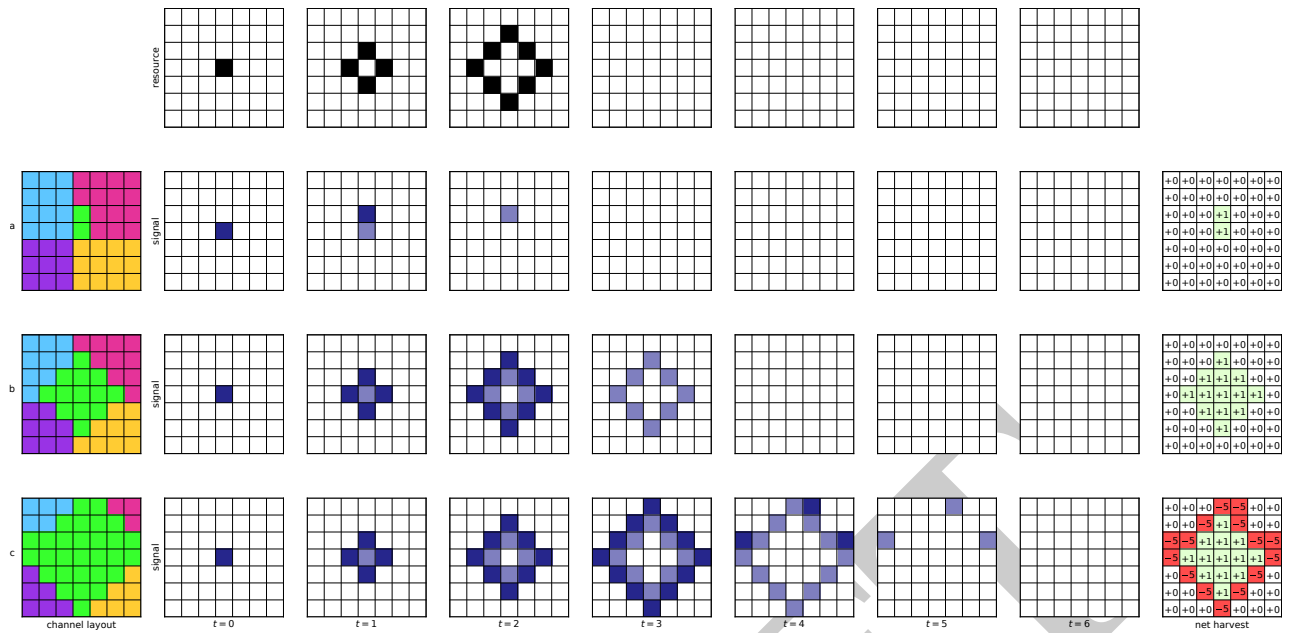79 cell that is activated by a signal wave. This activation cost is

Figure 1: Activation-quiescence signaling, and net resource collection for three different channel configurations during a single resource wave events.

outweighed by the amount of resource collected — cells that activate in concert with a resource wave take away a net benefit. Recall, though, that resource waves have a limited extent. Cells that activate outside of the extent of the resource wave or activate out of sync with the resource wave (i.e. are not connected via a direct path to the originating cell) pay a cost. Cells that frequently activate erroneously bankrupt and die. In our implementation, organisms that accrue a resource debt of -11 or greater are killed. This scenario is depicted in Example c of Figure 1.

In this manner, "Goldilocks" — not to small and not too big — same-channel signaling networks are selected for. In our implementation, resource waves are seeded at a single location drawn with uniform probability from the toroidal grid. Based on this location, resource wave seeds are tiled over the toroidal grid so as to have kissing — but not overlapping — extents. All the waves are updated to completion in synchrony. Then, another batch of resource waves is seeded. This process ensures that selection for "Goldilocks" same-channel signaling networks is uniformly distributed over the toroidal grid.

Organisms may control the size and shape of their same-channel signaling group by strategic control of reproduction. Three choices are afforded: whether to reproduce at all, where among the four adjoining tiles of the toroidal grid to place their offspring, and whether the offspring should be registered to the parent's signaling channel or should instead be registered to a randomly chosen signaling channel. New channels IDs are drawn uniformly from the integer range 1-4194303. No guarantees are made about the uniqueness of an offspring's channel ID with respect to the channel IDs of the parent or other neighboring cells.

Hierarchical levels are introduced into the system through multiple instantiations of this resource wave/channel-signaling wave scheme. In our experiments, we worked with resource wave/channel-signaling levels. We refer to them as level 0 and level 1. On the zero level, resource waves extended a radius of four toroidal tiles, granted a resource value of $+6$, and cost a signaling activation penalty of -5. On the one level, resource waves extended a radius of twelve toroidal tiles, granted a resource value of $+6$, and cost a signaling activation penalty of -5. Thus, each organism was a member of cooperating signaling groups, each determined by a unique channel ID — a zero level signaling network and a one level signaling network. Due to the different extents of resource waves on the zero and one level, smaller signaling networks are selected for on the zero level and larger signaling networks are selected for on the one level. We enforced hierarchical nesting of these signaling networks through restriction on reproduction. When creating an offspring, we only allowed a cell to generate an offspring with (1) identical zero- and one-level channel IDs, (2) new zero-level ID and identical one-level channel ID, or (3) new zero- and one-level channel IDs. The distribution of IDs across the zero and one level channels can be envisioned like U.S. counties and states. Each county (i.e. zero-level channel network) is a member of exactly one state (i.e. one-level channel network); no county spans two states. Figure 3 depicts hierar-

chically nested channel states at the end of three evolutionary runs.

Channel IDs enable straightforward detection an evolutionary transition of individuality. To recognize an evolutionary transition of individuality, we evaluate

1. Do individuals with the same channel ID share resources (e.g. cooperate)?

2. Is there division of reproductive labor between members of the same channel (i.e. between individuals enveloped in the same-channel signaling network and those on the periphery)?

If these conditions are met among organisms sharing the same zero-level channel, we would conclude that a first-level transition of individuality has occurred. Likewise, if these conditions are met among organisms sharing the same one-level channel, we would conclude that a second-level transition of individuality has occurred.

Organisms

We performed our experiments using organisms comprised of a set of 15 floating-point parameters. Each parameter describes a specific strategy component. On reproduction, mutation was applied to each parameter independently with probability 0.00005. We will overview each strategy parameter below.

Parameters A_0 and A_1 modulate same-channel reproductive competition. Parameter A_0 is the probability an organism would to decline to replace an adjoining organism sharing the same level zero channel ID with an offspring. Parameter A_1 is the probability an organism would to decline to replace an adjoining organism sharing the same level one channel ID with an offspring. Mutation is performed by a redraw from the distribution $U(-0.5, 1.5)$ clamped to the range $[0, 1]$.

Resource sharing is controlled by the P_0, P_1, and P_2 parameters. The P_0 parameter controlled the proportion of resource collected into and activation cost paid from an organism's individual resource stockpile. The P_1 and P_2 parameters, respectively, controlled the proportion of resource collected into and activation cost paid from resource pools shared by organisms with identical zero-level and one-level channel IDs. These parameters are initialized by a draw from $U(0.0, 1.0)$. These parameters is mutated by addition of a value drawn from $N(0.0, 0.2)$ with the result clamped to the range $[0, 1]$. The set P_0, P_1, P_2 is always normalized to sum to 1.

Resource pools accumulate resource just like an organism's individual stockpile, except in the case that any channel resource pool ran negative the deficit was distributed evenly between constituent organism's individual resource stockpiles. On every update, individuals were afforded the opportunity to spend from their individual stockpile to reproduce. Then, in ascending level order, resource pools were afforded the opportunity to spend resource to reproduce. Resource pools carry out reproduction using the cell closest to the centroid of that the pool's channel-ID members that fails to decline to reproduce (i.e. via action of A_0 and/or A_1). As long as sufficient resource remains in the resource pool, the process is repeated to carry out another reproduction. So, pool-funded reproduction fills in a channel-network from the inside out and can result in diamond-shaped same-channel signaling networks. (Distance is measured using the taxicab metric.)

Parameters C_0 and C_1 control the size of same-channel signaling networks. Intuitively, they are caps on how many cooperators each organism wants in its zero-level signaling network and one-level signaling network, respectively. When an organism reproduces, it checks the size of its zero-level signaling network against C_0 and the size of its one-level signaling group against C_1. If neither cap is met or exceeded, then the organism will produce an offspring sharing its zero- and one-level channel IDs. If only the C_0 cap is exceeded, then the organism will produce an offspring with new zero-level ID and identical one-level channel ID. Finally, if the C_1 cap is exceeded, then the organism will produce an offspring with new zero- and one-level channel IDs. These parameters are initialized by a draw from $U(0.0, 48.0)$. These parameters are mutated by addition of a value drawn from $N(0.0, 24.0)$ with the result clamped to be non-negative.

Parameters E_0, E_1, and E_2 control the amount of resource endowed to offspring. This endowment is paid as an additional cost by the cell stockpile (or same-channel resource pool) funding a reproduction. The full amount of the endowment is divided between the offspring's stockpile, zero-level same-channel resource pool, and one-level same-channel resource pool according to the offspring's parameters P_0, P_1, and P_2. Specifically, E_0 is the endowment amount paid to an offspring that shares the zero- and one-level channel ID of the parent; E_1 is the endowment amount paid to an offspring that shares just the one-level channel ID of the parent; and E_2 is the endowment amount paid to an offspring that shares neither the zero- nor the one-level channel ID of the parent. Endowed resource helps new-channel propagules to rapidly grow their signaling network in order to begin collecting resource at a rate competitive with other well-established signaling networks. These parameters are initialized by a draw from $U(0.0, 3.0)$. These parameters are mutated by addition of a value drawn from $N(0.0, 10.0)$ with the result clamped to be non-negative.

Parameters M_0, M_1, and M_2 control the attempt of suicide on genetic damage. Each time that a mutation occurs during reproduction, the mutated offspring attempts suicide with probability M_0 if it shares the zero- and one-level channel ID of its parent, probability M_1 if it shares just the one-level channel ID of its parent, and probability M_2 if it shares neither the zero- nor the one-level channel ID of the parent.

The M_x value referenced is from the offspring's genotype after mutation. Attempted suicide succeeds with a probability of 0.8. This capacity enables first- or second-level individuals to combat somatic mutation. Initialization and mutation each of these parameters is performed by a redraw from the distribution $U(-0.5, 1.5)$ clamped to the range $[0, 1]$.

Finally, parameters S_0 and S_1 affect offspring placement. If an organism is placing an offspring with identical zero- and one-level channel ID, the four possible sites for offspring placement are considered in order of increasing distance from the centroid of the parent's zero-level same-channel signaling network. If an organism is placing an offspring with identical one-level channel ID but different one-level channel ID, the four possible sites for offspring placement are considered in order of increasing distance from the centroid of the parent's one-level same-channel signaling network. Otherwise, the four possible sites for offspring placement are considered in a shuffled order. These parameters were included to enable more exacting control of Initialization and mutation is performed by a draw from the distribution $U(-0.5, 1.5)$ clamped to the range $[0, 1]$.

Experiments

We began by performing experiments to assess the evolutionary trajectories of populations of organisms in the DISHTINY environment. Every tile on the toroidal grid was seeded with a randomly-initialized organism. Then, the simulation was stepped forward 2×10^{10} updates with mutation enabled. We performed 33 replications of this experiment.

Under this, we observed evolutionary outcomes that resembled zero-, first-, and second-level individuality. To assess the relative fitness of these evolved organisms, we ran ecological competitions between three genotypes — one selected as the most common genotype from the evolutionary run where the greatest mean P_0 was observed, one selected as the most common genotype from the evolutionary run where the greatest mean P_1 was observed, and the other selected as the most common genotype from the evolutionary run where the greatest mean P_2 was observed. Each ecological run was seeded with three copies of each genotype. Seeded genotypes were uniformly spaced over the toroidal grid with random arrangement. Then, the simulation was stepped forward 2×10^9 updates with mutation disabled. We performed 191 replications of this experiment.

All experiments were performed using a 120×120 toroidal grid layout.

Implementation

Runtime for evolutionary experiments was approximately 60 hours. Runtime for ecological experiments was approximately 6 hours.

Our experimental system was implemented using the Empirical library for scientific software development in C++ [TODOCITE]. The code used to perform and analyze our experiments is available at `https://github.com/mmore500/dishtiny`. Our figures, data from our experiments, and a live in-browser demo of our system is available via the Open Science Framework at `https://osf.io/ewvg8/`.

	Ecological Seeds			Mean ($\pm S.D.$)		
	$P_0{>}P_{1,2}$	$P_1{>}P_{0,2}$	$P_2{>}P_{0,1}$	$P_0{>}P_{1,2}$	$P_1{>}P_{0,2}$	$P_2{>}P_{0,1}$
A_0	cell2	cell3	cell4	cell5	cell6	cell7
A_1	cell2	cell3	cell4	cell5	cell6	cell7
P_0	cell2	cell3	cell4	cell5	cell6	cell7
P_1	cell2	cell3	cell4	cell5	cell6	cell7
P_2	cell2	cell3	cell4	cell5	cell6	cell7
C_0	cell2	cell3	cell4	cell5	cell6	cell7
C_1	cell2	cell3	cell4	cell5	cell6	cell7
E_0	cell2	cell3	cell4	cell5	cell6	cell7
E_1	cell2	cell3	cell4	cell5	cell6	cell7
E_2	cell2	cell3	cell4	cell5	cell6	cell7
M_0	cell2	cell3	cell4	cell5	cell6	cell7
M_1	cell2	cell3	cell4	cell5	cell6	cell7
M_2	cell2	cell3	cell4	cell5	cell6	cell7
S_0	cell2	cell3	cell4	cell5	cell6	cell7
S_1	cell2	cell3	cell4	cell5	cell6	cell7

Figure 2: TODO

Results

Evolutionary Outcomes

Evolutionary Outcomes

trajectory of evolutionary genetic paths

reproductive division of labor observed altruistic suicide observed resource sharing observed

phenotype progression

generation times

resource harvested by time, regressed on population's genetic composition

ecological experiments? possibly not fair because somatic mutation

Discussion

transition of individuality * reproductive division of labor — edges * pooling resources to endow a propagule with lots of resources * potentially catastrophic somatic mutations ameliorated through suicide

scaling in time and space decentralized! arbitrarily parallelized?

complexity of an organism versus parallelization of a population

Conclusion

our evolving organisms are not open-ended simply evolving parameters for some rather crude manually-designed strate-

gies while sufficient to demonstrate that the environment selects for genetic strategies that program for higher-level individuality, these results are not full-fledged but they show potential for it and that's our next step

briefly, how to integrate open-ended organisms into dishtiny

also, study major transitions — questions about phenotypic plasticity, etc. (look at grant proposal)
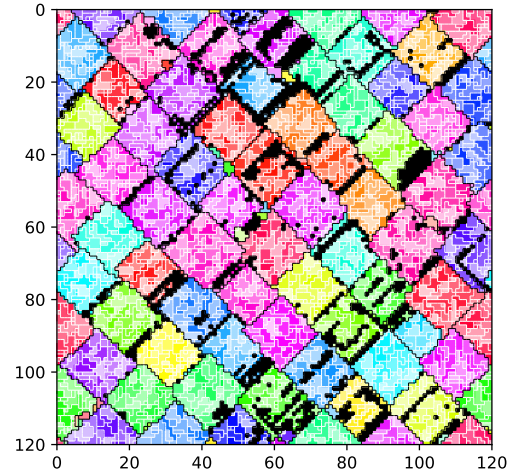
Acknowledgements

References
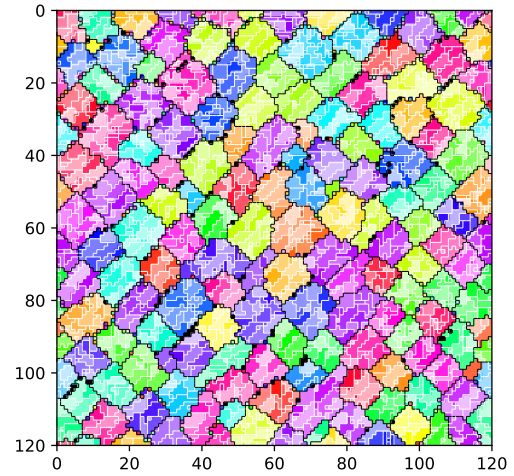
(a) Mean $P_0 = 0.77$, $P_1 = 0.089$, $P_2 = 0.14$
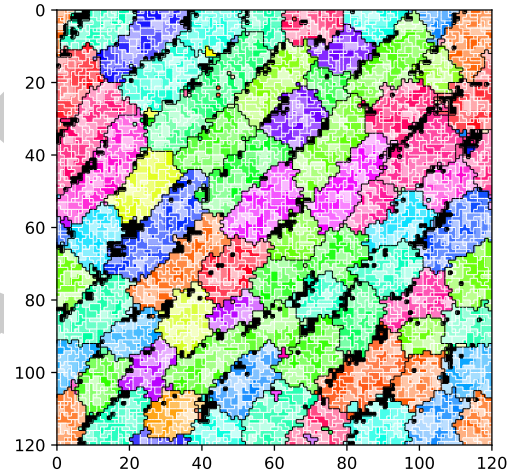
(b) Mean $P_1 = 1.0$

(c) Mean $P_2 = 1.0$

Figure 3: State of same-channel zero- and one-level signaling networks after 1.95×10^{10} updates of evolution by population mean P_0, P_1, and P_2. Zero-level channels coded by HSV value are separated by white borders and one-level channels coded by HSV hue are separated by black borders.
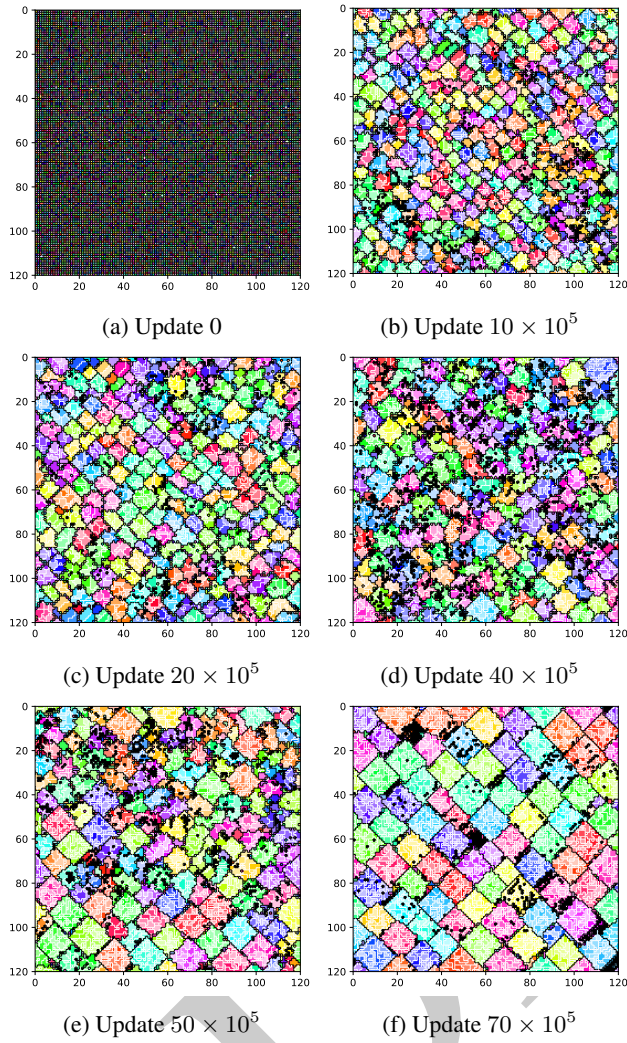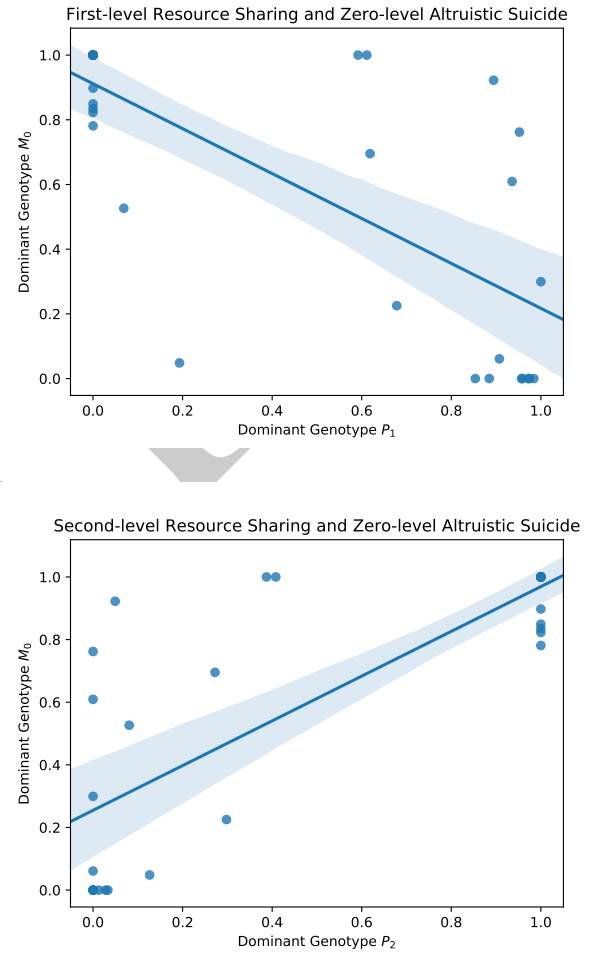
(a) Update 0

(b) Update 10×10^5

(c) Update 20×10^5

(d) Update 40×10^5

(e) Update 50×10^5

(f) Update 70×10^5

Figure 4: Progression of of same-channel zero- and one-level signaling networks states in an evolutionary run where population mean $P_2 > P_0, P_1$ evolved. Zero-level channels coded by HSV value are separated by white borders and one-level channels coded by HSV hue are separated by black borders.

First-level Resource Sharing and Zero-level Altruistic Suicide

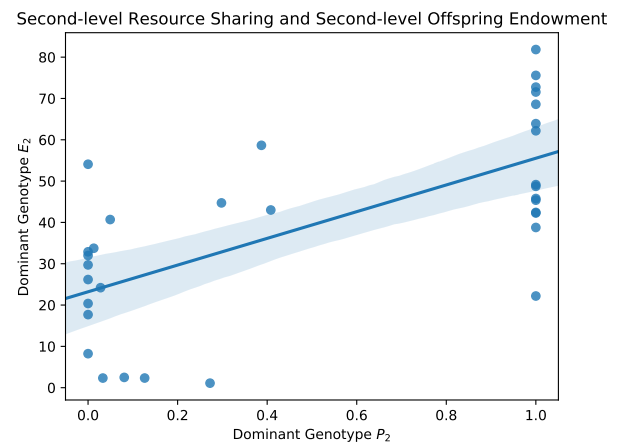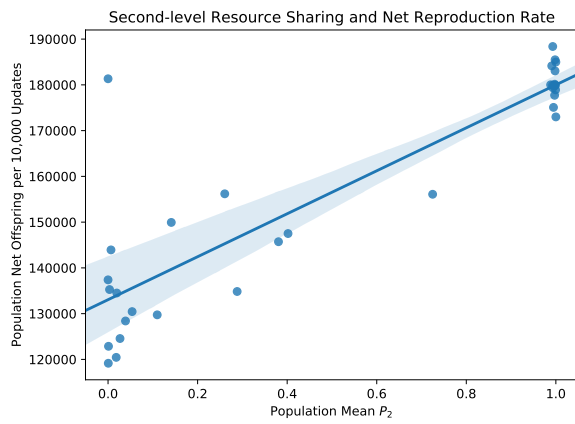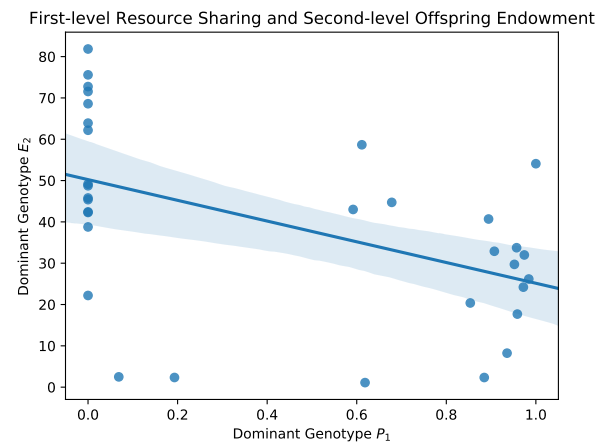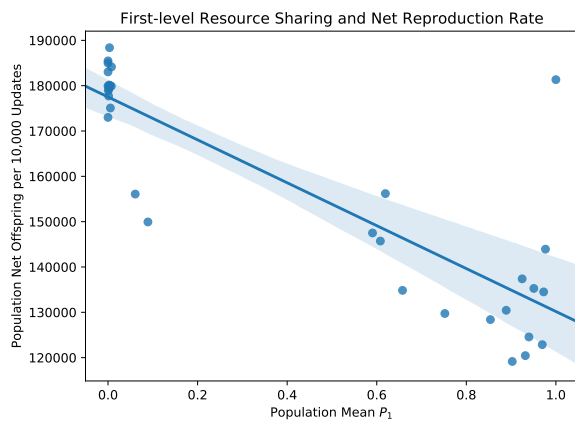Second-level Resource Sharing and Zero-level Altruistic Suicide

Figure 5: TODO

Figure 6: TODO

Figure 7: TODO