The Emergence of Simple Ecologies of Skill: A Hypercycle Approach to Economic Organization

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Introduction

Buss (1987) and Fontana and Buss (1994) have cogently argued that biology's Modern Synthesis of genetics and Darwinian evolution achieved its impressive advances at the cost of eliding a crucial middle step--the existence of organism (or, more generally, of organization). The distribution of genetic alleles is shaped by selection pressures on the phenotypical "carriers" of those alleles. But the existence of phenotype itself is never explained. As Fontana and Buss themselves put it: "A theory based on the dynamics of alleles, individuals and populations must necessarily assume the existence of these entities. Present theory tacitly assumes the prior existence of the entities whose features it is meant to explain." (1994: 2)

The same existence problem plagues economics. The neo-classical theory of competitive markets presumes that competition among firms (phenotypes) generates selection pressure for optimal policies (genotypes). Yet firms themselves are only posited, not explained, in this foundational theory. Advances in transaction-cost economics (Coase 1937, Williamson 1975) and in principal-agent economics (Jensen and Meckling 1976, Fama 1980) purport to fill this gap, but only through equating the firm with a set of bilateral contracts. Such a transposition of "the firm" down to a series of dyadic negotiations overlooks the institutionalized autonomy of all stable organizations. In organisms, social or biological, rules of action and patterns of interaction persist and reproduce even in the face of constant turnover in component parts, be these cells, molecules, principals, or agents. In the constant flow of people through organizations, the collectivity typically is not renegotiated anew. Rather, within constraints, component parts are transformed and molded into the ongoing flow of action.

Viewing the firm as a dynamic organism highlights the organizational existence question not usually asked in economics: which sets of component parts and of collective actions are, in principle, mutually reproducible? This difficult question will be operationalized and investigated in this paper within a simple, spatially-grounded, hypercycle context. Hypercycle theory (Eigen

and Schuster 1979, Hofbauer and Sigmund 1988) is an extremely prominent approach to the topic of the molecular origins of life on earth.[1] The theory argues that life emerged through the chemical stabilization of an autocatalytic reaction loop of nucleic and amino acid transformations, each step of which reinforces the next step's reproduction and growth: 1 --> 2 --> 3 --> 4 --> 1 -->, etc. The scientific problematic is to learn which chemical conditions (and pertubations) permit various types of hypercycles to emerge and to grow "spontaneously".

The metaphorical leap from RNA to firms is obviously enormous. But the benefit of this particular operationalization is that it will offer an extraordinarily minimalist set of assumptions within which to investigate the emergence of collective order. Not only are no assumptions about hyper-rationality required, no assumptions about consciousness of any sort are required. "Collective order" here is simply the stabilization of chains of action-reaction sequences, which fold back on each other to keep themselves alive. In the human application here, such chains wend themselves through organizationally interacting individuals, shaping and reshaping such individuals in the process. The problematic is to learn which "organizations"--that is, which joint sets of interaction patterns, hypercyclic action chains, and classes of individuals--can exist, in the sense of reproduce themselves through time. It will soon become apparent that such mutual maintenance and reproduction is no mean feat; thus, there are dynamic constraints on what firms are possible within life and, hence, within economic theory.

The Organization of Skill

Perhaps the most natural way to interpret this "hypercycle theory of the firm" is through the concept of skill. Instead of RNA and the like, each element in an "economic hypercycle" is an action-capacity or skill, which simply passively resides within the individual until evoked by some compatible[2] action by another agent in that individual's immediate environment. "Work" in an organization is an orchestrated sequence of actions and reactions, the sequence of which produces some collective result (intended or not). The full set of such sequences is the human "technology" of the firm.

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[1]It is also a predecessor to the more general models in Fontana and Buss (1994), cited above.

[2]"Compatible" just means linked sequences of "if...then" rules--namely, one person's "then" is another person's "if".

The hypercycle representation of "technology" emphasizes form, not content. "Elements in a sequence" are just mathematical entities that can stand for any action or rule; it is the patterning of how such actions are linked that is the focus of attention. The main constraint imposed by the literal hypercycle format adopted here is that only linear chains[3] of action sequences can be investigated. The dynamics of more complicated branching technologies is postponed for future research.

One fundamental difference between human and chemical hypercycles, in degree if not in kind, is the fact that potentially many action-capacities or skills can reside in individuals. Hence, individuals potentially can partake in many different organizational tasks. This greater versatility implies that the compositional mix of skills within individuals is variable, and can change as a function of interactional experience with others. "Learning" in this skill-centered[4] model means that never-used skills are forgotten, and that often-used skills will "reproduce", in the sense of become more frequently usable in the future. Relative rates of skill reproduction, in turn, are functions of how frequently others in your immediate environment call upon you to exercise your skills. And since this, in turn, is a function of how technologies physically become distributed across individuals, one important issue to be studied below, besides just aggregate organizational stbility, is how different organizational ecologies induce different degrees of complexity in the skill mixes of the individuals that comprise them.

As determinants of organizational existence and of individual skill-composition, I will focus, in the simulations below, on two central ways in which hypercycle "games" can be varied: (a) length of hypercycle--that is, 2-element vs. 3-element vs... vs. 9-element hypercycles; and (b) mode of skill reproduction--that is, "source-only reproduction", where only the skill of the initiator of the interaction is reproduced; "target-only reproduction", where only the skill of the recipient of the interaction is reproduced; and "joint reproduction", where both parties' skills are reproduced through compatible interaction. The first of these independent variables measures (within a linear chain setup) the complexity of the technology trying to be seeded into an organization. The second independent variable measures the

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[3]Hence the "simple" in the title of this paper.

[4]"Skill-centered" is meant to be opposed to "person-centered". Individuals certainly learn in this model, but the analytic approach is to adopt the "skill's eye" perspective on this learning--namely, to focus on the reproduction and propagation of skills through the medium of persons, rather than necessarily to assume any cognitive processing.

distribution of reward in micro-interaction: source-only reproduction is "selfish" learning, in which the initiator of the action reaps the learning rewards; target-only reproduction is "altruistic or teacher" learning, in which the recipient of the action reaps the reward; and joint reproduction benefits both learners simultaneously.

A third structural dimension of potentially great interest is variation in the social network pattern of interaction among individuals. In order better to construct a neutral baseline which maintains the focus on hypercycle length and reproduction mode, I suppress this important topic in this paper. In particular, in the models below, individuals interact with each other only in two-dimensional "geographical" space, with their four nearest neighbors. This cellular-automaton spatial framework, while traditional in Santa Fe Institute research, is hardly realistic of human social networks, where cliques and centrality abound. But this simplification will highlight the effects of space per se which, in contrast to fully randomized mixing, appear to be profound. How more realistic social network topologies enable or disable various hypercycle technologies is a topic that can be investigated in the future, once a simple spatial baseline has been established.

The Model

The operationalization of the above ideas is as follows:

1. Assume a fixed number of individuals arrayed on a spatial grid. Each individual can interact only with its four nearest neighbors. In the simulations below, this grid will be relatively small--10 by 10, with boundaries.[5]

2. Assume a number of "action capacity" elements, or "skills", that are distributed originally at random over individuals/cells in the spatial grid. These elements are indexed by integers: {1,2}, {1,2,3}, ..., {1,2,..,t}, the technology set size of which is varied experimentally. Most importantly, there can be a variable number of skills resident in any one spatial site;[6] these resident elements represent the varying skill

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[5]Small size was convenient for my GAUSS program on a 486 machine. Given the tight clustering behavior of this model, small size is not as serious a constraint as it might be in other models. Spatial size clearly can be varied in future research, for those who are interested.

[6]This variable number of elements per site differentiates this model from the typical cellular automaton setup, which imposes a

capacities of different individuals.

3. Assume that technology element-sets are governed by "rule compatibilities," such that action capacities only become "actions" in the presence of compatible other action capacities. In particular, assume a hypercycle technology structure of compatibilities: elements 1 and 2 activate each other, elements 2 and 3 activate each other, up to elements t and 1 activate each other. Otherwise (for example, elements 1 and 3), interactions are inert.

4. Within the above framework, an iteration of the model proceeds as follows: (a) choose at random an action-capacity or skill "looking for" action, located in some individual; (b) initiate interaction (randomly) with one of the four possible interaction partners; (c) if a compatible element exists in the partner's repertoire, the interaction is "successful" and joint action occurs; (d) if not, the interaction is "inert" and nothing occurs.

5. If successful interaction occurs, reproduction of skill (or equivalently, learning within the individual) follows. This is the same as the notion of catalysis in chemistry. The reinforcement regime that governs this reproduction/learning is manipulated experimentally among (a) source-only reproduction, (b) target-only reproduction, and (c) joint reproduction, as defined above.

6. The total volume of elements in the collectivity is maintained at a fixed level (in the "standard" simulations below, this will be set at 200[7]). This means killing off a random element, somewhere in the system, whenever a new element is created through reproduction.

7. After setting up the model in steps 1-3, steps 4-6 are then repeated, for a large number of iterations--usually 15,000 or 20,000 interations are sufficient for equilibrium behavior to emerge.

The fixed volume constraint in step 6 is not realistic for human systems, but it allows me to investigate compositional or "structural" effects, independent of the dynamics of aggregate

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constraint of only one element per site. See, for comparison, the extremely high quality work of Boerlijst and Hogeweg (1991, 1992, 1993, 1995), who also have studied spatial hypercycles.

[7]This particular total volume imposes an average number of action capacities per person of two. In some of the runs, I increase this total number to 400 (an average of four skills per person).

growth or decline.[8]

The random-element/random-interaction-partner assumption in step 4 is intended to give the model a bottom-up crescive or "emergence" flavor--as opposed, say, to imposing through formal organization a prescribed sequence of elements and partners. Social interaction here is "simple" in that it resembles self-organizing play more than it does formally-dictated work.[9] Formal organizational constraints could easily be added to the model, but the core existence question would remain: which sets of technologies and social networks are reproducible? Adding formal restrictions probably makes self-organization more complicated, so again it seems analytically useful to develop the baseline case first. Only then will we have a good sense of the limits to "natural" self-organization, which the right institutional constraints might (under some circumstances) be helpful in loosening.

The organizational-existence and the individual-construction conclusions that follow from this model will be presented below, first for simple and then for more complicated hypercycles.

The Simplest Hypercycle: Two Elements only

Many of the findings derivable from this model can be illustrated with the simplest possible hypercycle, that of two elements only. Perhaps the most important of these conclusions is this: embedding hypercyclic interaction sequences in physical space induces a sharp asymmetry between "selfish" source-only reproduction and "altruistic" target-only reproduction. Specifically, in a spatial context, target-only reproduction/learning creates more complicated and expansive social ecologies (in equilibrium) than does source-only reproduction/learning. In sharp contrast, this asymmetry between "selfish" and "altruistic" does not exist in fully-mixed, non-spatial interaction, such as

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[8]This fixed volume constraint imposes competitive selection pressure on the system. It is consistent with the usual way chemical hypercycles have been operationalized, although other death regimes (for example, fixed lifetimes) certainly can be envisioned. Consistency of operationalization here insures greater comparability of findings with past studies.

[9]Of course, most close-up ethnographies reveal that much successful and engaged work in formal organizations, such as team or "organic" decision making, resembles "play" much more than standard formal organization charts imply. See the classic works of Barnard (1938), Burns and Stalker (1961), and March (1976) for the distinction between formal and informal organization.

occurs in a fluid.

For the simple 2-element hypercycle special case, the equilibrium outcome of the above 10x10 nearest-neighbor model is virtually always a spatially contiguous clustering of individual cells, which arrange themselves into a checkerboard pattern of 1's and 2's. Within this cluster, all individuals are fully specialized into one or the other skill exclusively; outside this cluster, all individual cells are empty or "dead". But the spatial extension of this "live" (that is, self-reproducing) equilibrium cluster varies widely as a function of mode of reproduction. For target-only reproduction, the average spatial extension of the equilibrium checkerboard cluster was 8.7 contiguous "live" individuals (an average over 10 runs of 15,000 iterations). For joint reproduction, the average spatial extension was 6.8 contiguous live individuals (again, averaged over 10 runs of 15,000 iterations). But for source-only reproduction, the average spatial extension was only 1.8 live individuals[10] (same number of runs).

The 2-element hypercycle is so simple that these simulation results can be understood analytically. In the appendix, I derive growth and decline transition rates for a single interacting dyad, under each of the spatial and non-spatial reproduction schemes mentioned above. These results, plus analogous results for a single interacting triad, are summarized in table 1 and graphed in figure 1.

The developmental dynamic for "selfish" source-only reproduction is depressingly simple in a spatial context. Catalytic source-only social ecologies of three or more interacting individuals inexorably and quickly collapse into isolated dyads of two specialized individuals, who then stably "feed" on each other. The force driving this, and all other, collapses is the selection pressure induced by fixing the total population volume: different pairs of interacting individuals are sharply competing against one another in the relative growth rates of their learned skills. The victorious, but isolated, final dyad is stable in the limited sense that there is no systematic tendency for one or the other of the two remaining individuals to devour the other, no matter what the relative sizes of the two individuals. But the element proportions of this final dyad

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[10]This source-only average was derived from (a) five dyadic pairs of 1's and 2's, which reproduced each other, (b) one self-reproducing cluster of size four, and (c) four isolated singleton cells of either entirely 1's or entirely 2's. Isolated singletons are not "live" self-reproducing clusters, since they have noone left with whom to interact and reproduce.

perform a random walk across the (a/n) line until eventually, after a very long time (typically more than 15,000 iterations), they hit one or other of the absorbing barriers of (a/n)=1 or (a/n)=0. At this point the system as a whole "dies", in the sense that skills no longer reproduce--there being noone left to interact with.

Thus, over the very long run, no spatially embodied social ecology is possible under a purely "selfish" source-only reproduction/learning regime. This conclusion holds true for any level of hypercycle complexity (2-element, 3-element, etc.).

The developmental dynamic for target-only reproduction is dramatically different in a spatial setting. Selection pressures still operate to drive very dispersed random distributions of skills down into tight clusters of contiguous individuals, who reproduce their skills through interaction. But stable social ecologies much larger than just two individuals are possible. The analytic results in figure 1 make it clear why this is true. Both target-only and joint reproduction schemes exhibit very strong equilibrating or "leveling" tendencies, which cause depleted individuals to grow in their skill sets and bloated individuals to shrink. In particular, under target-only and joint reproduction, the two individuals in isolated dyads converge to equal sizes in their skill sets, rather than to the random walk, characteristic of source-only reproduction. Three individuals in isolated triads converge to a stable [.25, .50, .25] relative size distribution for joint reproduction, and to a stable [.29, .42, .29] relative size distribution for target-only reproduction.[11]

Table 1 and figure 1 also present analogous developmental results for the non-spatial, fully-mixed "fluid" context explored by the original hypercycle theorists. For simple hypercycles, like the 2-element case here, final size distributions, in this non-spatial setting, are similar to the results of the target-only and joint reproduction regimes in the spatial setting. But of course in the non-spatial framework, there are no "individuals", because there are no physical sites within which skills reside. The primary equilibrium difference between the non-spatial and the target-only spatial setting will emerge at higher levels of hypercycle complexity: non-spatial hypercycles have a built-in

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[11]The slightly greater sizes of the minority individuals produced by target-only reproduction, as compared to the qualitatively similar joint reproduction, account for the slightly greater spatial extension of the equilibrium cluster in the simulation results. Both target-only and joint reproduction allow for the emergence of social organization, but the target-only version permits more individuals stably to participate in this ecology.

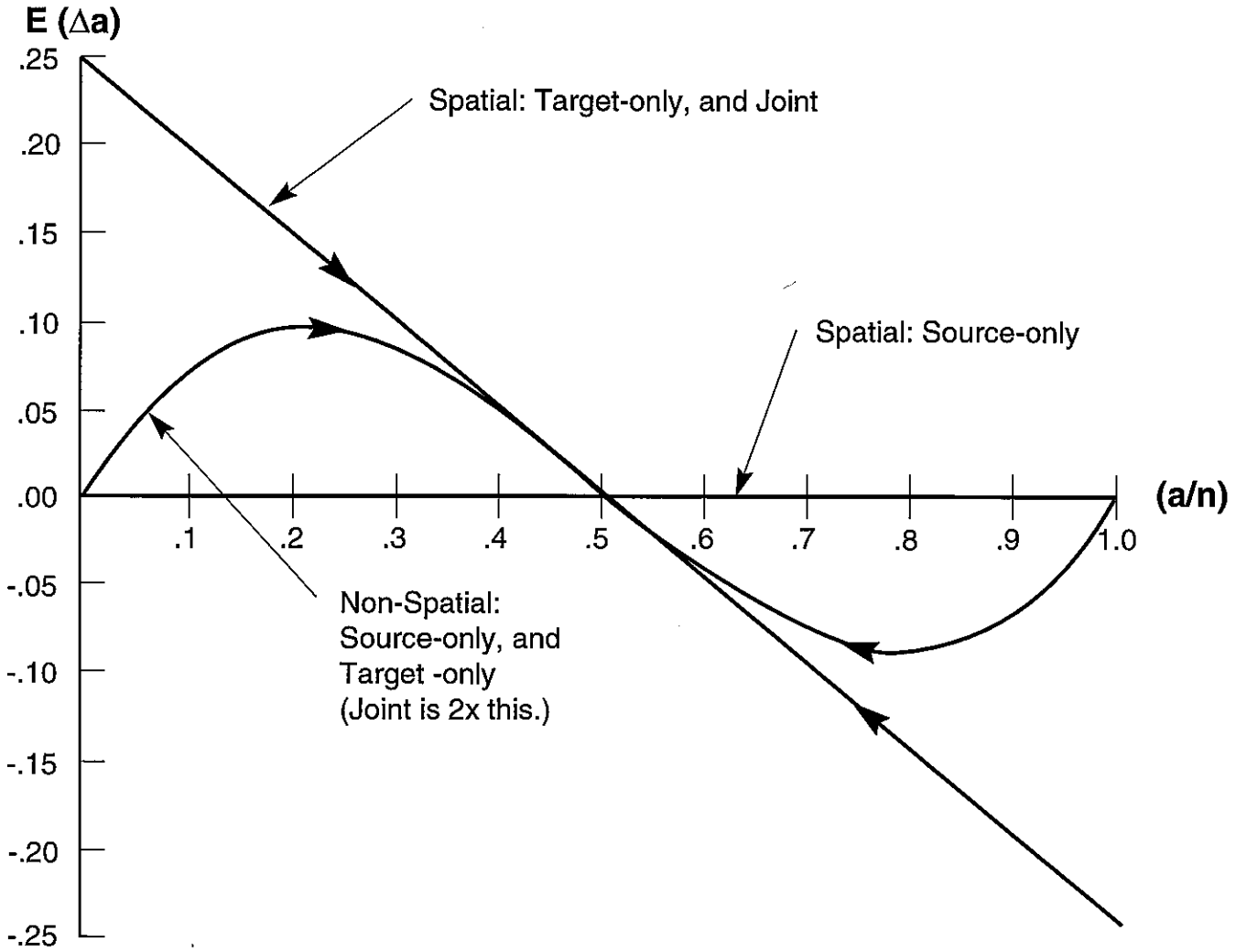


Figure 1a. Graphing Table 1a results: (1) ⇄ (2) ($\boxed{a \mid b}$, with a+b=n)

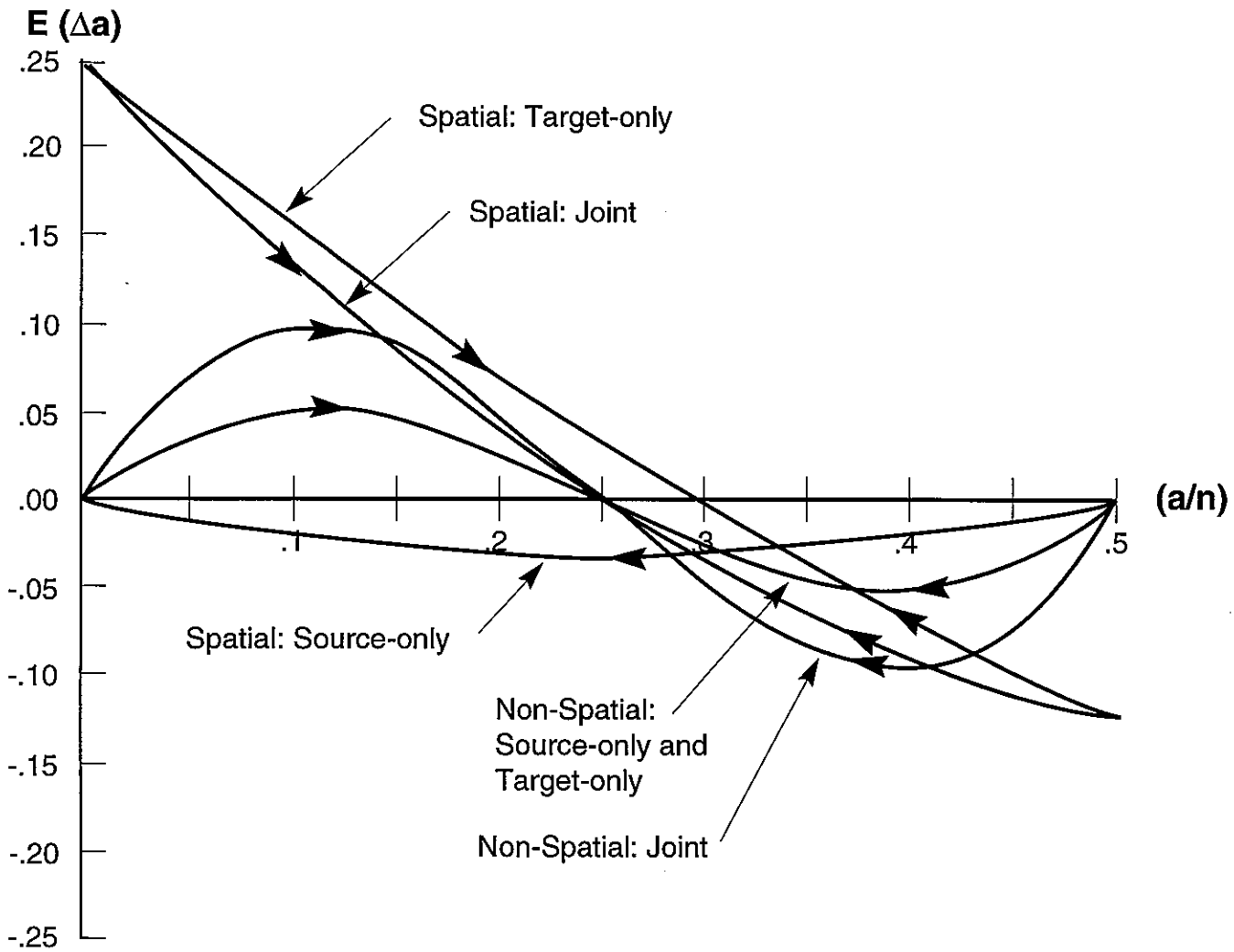
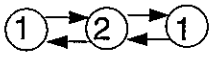


Figure 1b. Graphing table 1b results: (1) ⇄ (2) ⇄ (1) ($\boxed{a}\boxed{b}\boxed{c}$, with a+b+c=n)

N.B.: Graphed under constraint that a=c. Because of this constraint (a/n) cannot exceed .5.

TABLE 1a. 2-Element Solo Dyad: (1) ⇄ (2) ($\boxed{a \mid b}$, with a+b=n)

(1) Prob (a → a+1) (2) Prob (a → a-1) (3) E (Δa) = (1) - (2)	**Spatial**	**Non-Spatial**
Source-only Reprod.	(1/4) (a/n) (1 - a/n) (1/4) (a/n) (1 - a/n) 0	(a/n) $(1 - a/n)^2$ $(a/n)^2$ (1 - a/n) (a/n) (1-a/n) (1-2a/n)
Target-only Reprod.	(1/4) $(1 - a/n)^2$ (1/4) $(a/n)^2$ (1/4) (1 - 2a/n)	(a/n) $(1 - a/n)^2$ $(a/n)^2$ (1 - a/n) (a/n) (1-a/n) (1-2a/n)
Joint Reproduction	(1/4) $(1 - a/n)^2$ (1/4) $(a/n)^2$ (1/4) (1 - 2a/n)	2(a/n) $(1 - a/n)^3$ $2(a/n)^3$ (1 - a/n) 2(a/n) (1-a/n) (1-2a/n)

TABLE 1b. 2-Element Solo Dyad: 

(a | b | c , with a+b+c=n)

(1) Prob (a → a+1) (2) Prob (a → a-1) (3) E (Δa) = (1) - (2)	**Spatial**	**Non-Spatial**
Source-only Reprod.	(1/4) (a/n) (1 - a/n) (1/4) (a/n) (1 - a/n) + (1/4) (a/n) (b/n) - (1/4) (a/n) (b/n)	(a/n) (b/n) (1 - a/n) (a/n) (b/n) (1-b/n + c/n) (a/n) (b/n) (2b/n - 1)
Target-only Reprod.	(1/4) (b/n) (1 - a/n) (1/4) (a/n) (1/4) (1-c/n) - (3/4) (a/n) + (1/4) (a/n) (1-b/n)	(a/n) (b/n) (1 - a/n) (a/n) (b/n) (1-b/n + c/n) (a/n) (b/n) (2b/n - 1)
Joint Reproduction (1) Prob (a → a+1) (2) Prob (a → a-1) +2 Prob (a → a-2) (3) E (Δa) = (1) - (2)	(1/4) (1-c/n) $(1-a/n)^2$ (1/2) (a/n) (1-a/n) + (1/4) $(a/n)^2$ (1-c/n) (1/4) (1-c/n) - (a/n) + (1/2) (a/n) (1-b/n)	2(a/n) (b/n) $(1 - a/n)^2$ 2(a/n) (b/n) $(1-b/n + c/n)^2$ 2(a/n) (b/n) (2b/n - 1)

stability threshold, at four elements, that does not carry over to the target-only spatial framework. In other words, non-spatial hypercycles are stable at 4-elements or below, but not at 5-elements and above (Hofbauer and Sigmund, 1988: 96). In contrast, stable target-only spatial hypercycles can (but not necessarily will) emerge at any level of complexity.

As can be seen in figure 1, for simple hypercycles, the main dynamic difference between target-only spatial and non-spatial hypercycles is one of degree. The quantitative pressure toward stable equilibrium, and thus the speed of convergence, is greater in the target-only spatial context.

Besides these highly suggestive equilibrium and developmental path results, the most fundamental finding in table 1, and in the simulations, is the asymmetry result described above--namely, that mode of reproduction/learning matters greatly in the spatial context, whereas it does not matter in the non-spatial framework. In particular, in non-spatial interaction "selfish" source-only and "altruistic" target-only reproduction behave no differently in the organizational skill ecologies they produce, whereas these learning modes produce completely different organizational ecologies in spatial grounded interaction.[12] In this paper, I use the suggestive language "selfish" and "altruistic" because these labels exactly describe who in the model benefits, in terms of learning, from the interaction--the one who initiates the interaction or the one who responds. But of course in as resolutely reductionist and behaviorist a modelling framework as this one, concepts of motivation and intentionality play no causal role. The explanation of asymmetry is more basic than psychology.

The derivations in the appendix make it clear why asymmetry exists. Successful reproduction of a skill, in a hypercycle model, is the product of two stages--(a) activation of "action capacity"/ skill into an attempted "action", and then (b) finding an interaction partner with a compatible other skill or "action capacity" with whom successfully to "act". Inserting a hypercycle technology into a spatial context imposes a constraint on possible interaction partners[13], such that differences in individuals'

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[12]In the non-spatial framework, joint reproduction does differ from source-only and from target-only reproduction, but only in a tautological way. The table 1 formulae pertaining to non-spatial joint reproduction have a "2" in them. But by definition, the joint reproduction scheme involves two reproductions and two deaths each successful iteration, whereas both source-only and target-only involve only one reproduction and one death each successful iteration.

[13]Including a constraint against acting with oneself.

activation rates, a function of past learning, are preserved rather than offset in their effect on reproduction. For example, in the simplest spatial case of a 2-element dyad, the probability (before deaths occur) of the successful reproduction of element 1 is (a/n)*(1/4) under the source-only regime, but is (b/n)*(1/4) under the target-only regime. In the non-spatial case, in contrast, the analogous probabilities of element 1 reproduction is (a/n)*(b/n) under the source-only regime, and is (b/n)*(a/n) under the target-only regime.

The spatially-determined importance of activation rates for reproduction implies that active individuals, under target-only learning, reproduce others, but that, under source-only learning, active individuals reproduce only themselves. Under source-only reproduction (before competitive death rates are factored in), the more self is activated, the more self reproduces, the more self is activated--a cycle that, under competition, eventually drives the other out of existence, to the detriment of self. But under target-only reproduction, the more self is activated, the more (compatible) other is reproduced, the more other is activated, the more self is reproduced, with balancing tendencies even in the face of competition. This same equilibrating dynamic exists under joint reproduction.[14] In contrast, non-spatial fluidity destroys the localized concept of "individual" and hence any distinction between "self" and "other".

The specifics of these formulae vary as spatial arrangements change, but the general conclusion remains valid: constraints on interaction partners (spatial or network) permit past learning to be "stored" in current behavior (here activation rates). This storage induces reproductive variance across individuals, because localized histories vary. In a non-spatial context, in contrast, only homogeneous global history matters, because there is no local.

These findings are especially interesting when applied to humans, because they are driven entirely by the dynamic of self-reproducing skills operating through physical sites. "Individuals" here in fact are no more than passive receptacles, brought into reproductive life by the hypercycle technology of interacting skills that operates through them. In spite of a complete absence of consciousness or intent, an asymmetry between selfishness and altruism emerges as a consequence of kinetics, once spatial constraint imposes a meaning for "local".

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[14]Differences between target-only and joint reproduction arise more dramatically at higher levels of hypercycle complexity.

The Three Element Hypercycle

The main causal factor that changes as one moves from 2-element to 3-element hypercycles is the topological fit between element/skill reproduction and individual/site interaction. The very neat checkerboard pattern of specialized individuals, so evident in 2-element hypercycle technologies, is based on the compatibility of 2-element reproduction with 4-nearest-neighbor interaction. With 3-element hypercycles, however, it is impossible for a 3-step closed loop (or indeed for any odd-step closed loop) to find siting in a square grid.[15] This means that any hypercycle with an odd number of elements must find physical instantiation through a linked pair of hypercycles, which together comprise an even number of steps--for example, 1 --> 2 --> 3 --> 1 --> 2 --> 3 --> 1.

This complication does not imply that such a solution is difficult to find. Like in the 2-element case, source-only learning within a 3-element hypercycle never produces a long-term reproductive ecology of any kind. But under target-only reproduction/learning, eight out of ten of the 3-element simulations discovered and reproduced this 6-step paired solution, which then established a stable core for a larger equilibrium cluster of interacting individuals. Because of topological mismatch, however, these "live" equilibrium clusters were more complex in their internal structure than the simple 2-element checkerboard pattern.

These 3-element ecologies are more complex in two ways: (a) individuals within the core[16] frequently are not specialized, but contain more than one skill; and (b) a periphery usually exists of specialized "parasitic" individuals, who survive solely because of their attachment to the core hypercycle, but who do not destroy the hypercycle. The eight successful simulation equilibria are presented in figure 2 in order to illustrate these two features. This more ...
in fact in only one of the ten simulations was the 6-step solution found. And in two out of ten joint-reproduction cases, not even all three of the skill elements had been preserved. These results

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[15]Of course in other spatial topologies, the details of this statement would vary. For example, in a "triangular" interactional pattern, in which every individual cell interacted with its six nearest neighbors, 3-element hypercycles would form very neat "checkerboard" equilibria, while 2-element hypercycles could not possibly link up into contiguous clusters of specialized individuals.

[16]"Core" is defined as the set of individuals whose skill-elements participate in the hypercycle.

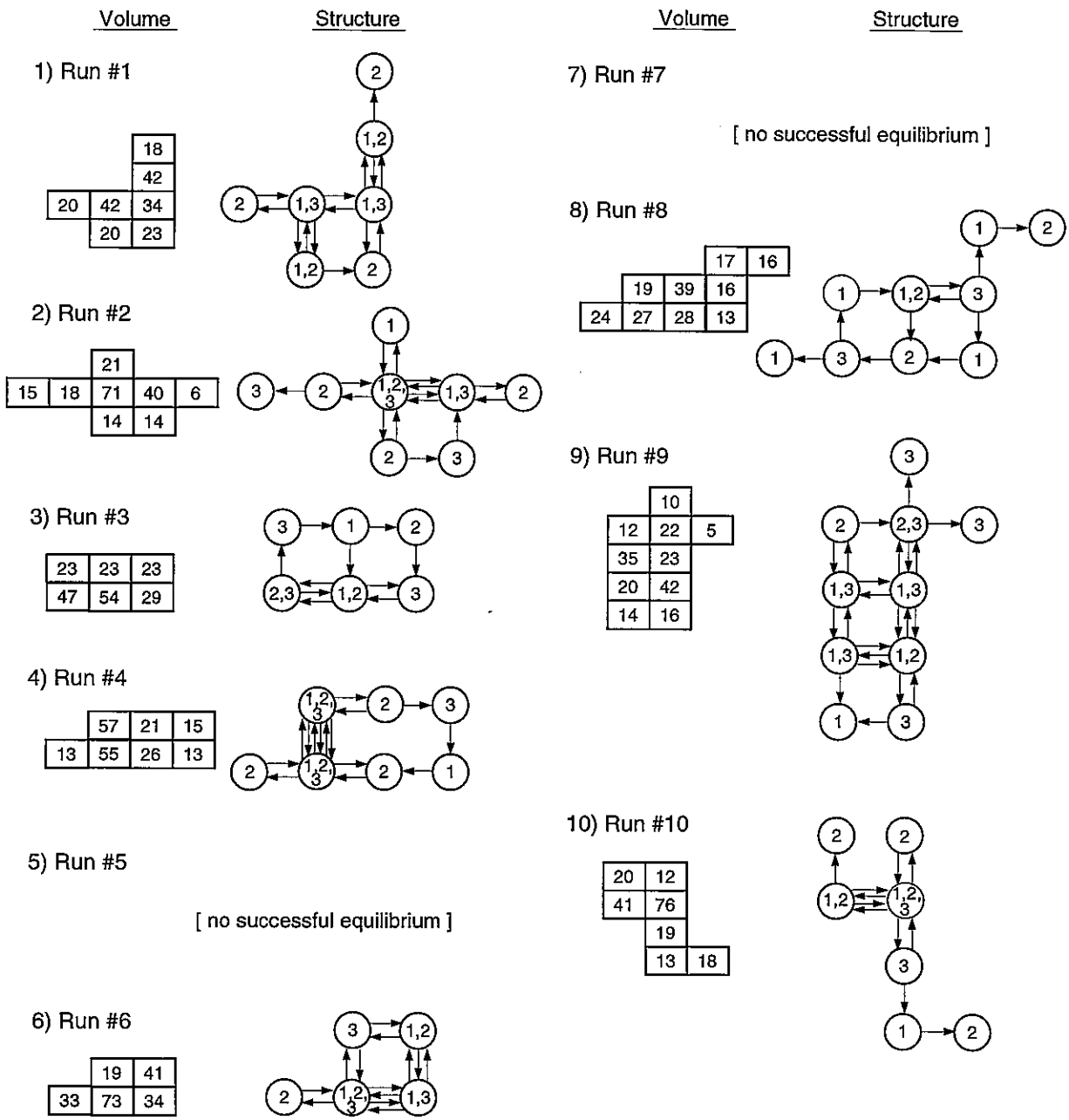

Figure 2. 3-element equilibrium clusters for target-only reproduction (after 15,000 iterations).

highlight the fact that joint reproduction, while a combination of source-only and target-only reproduction, is not truly a hypercycle: it is not catalytic. In the 3-element hypercycle, 1 --> 2 alone can sustain itself (without element 3), since for any adjacent pairs of numbers under joint reproduction, 1 --> 2 effectively is 1 <--> 2. For this reason, the main qualitative difference between joint reproduction and target-only reproduction, in general, is the fact that target-only reproduction forces all skill-elements to be maintained in the population, whereas joint reproduction does not preserve all skills except by chance. If all skills are required for some collective product, then joint reproduction, while reproductively "alive", is effectively useless. Altruistic catalysis is more effective than "fairness" in reward in maintaining complex technologies.

Why are complicated, multi-skilled individuals created by 3-element hypercycles? As already stated, a precondition here is topological mismatch, which forces the simple 3-element hypercycle into a more circuitous 6-step spatial loop--thereby giving that loop greater opportunity to fold back over itself as it wends its way through individual sites. (This is the "skill's eye view" of how multiple skills are laid down in individuals.) This structural possibility cannot be the complete explanation, however, since a single spatial loop of six fully-specialized individuals clearly is an equilibrium. We also need to know what drives the folding. In practice, however, the fully-specialized outcome is almost never observed for two reasons: (a) the simple combinatorics of random initial distributions, and (b) the dynamics of development, which break long spatial loops before they can separate from their local neighbors.

The combinatorial aspect is described in table 2. This table reports the probabilities of the simple element set {1,2,3,1,2,3} being laid down into various reproducible patterns within a simple 6-cell spatial grid, just through the operation of random processes alone.[17] Overall in such a setup, there is a 2.9% likelihood of these six elements arranging themselves into some type of reproducible spatial pattern through chance alone. But 99.1% of these reproducible patterns involve multi-skilled individuals, in which the hypercycle has folded back spatially on itself. Indeed, 47% of the reproducible patterns involve at least one fully skilled individual, who possesses all three skills.

The list of "basic ecologies" in table 2 is a logical itemization of the possible hypercycle cores inside more expansive 3-element equilibrium clusters. As can be seen by comparing figure

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[17]This was the mechanism of the initial distribution in the simulation model.

2 and table 2, the successful simulation outcomes of larger population sizes (200) on a 10x10 grid differ from the basic ecologies in table 2 only by adding parasitic "hangers on" and/or by amalgamating possibly more than one core.

While I can't quantify the magnitude of the effect, it is also clear from observing detailed developmental histories that even those specialized loops that occasionally do form randomly are easily disrupted in their development by the fact that constituent individuals are also embedded in other ecologies that are evolving simultaneously, in competition with the fully specialized loop. Such interference of course occurs between any overlapping ecologies, but the fully specialized hypercycle is maximally vulnerable to disruption because it is maximally extended spatially.

Thus, not only is there low likelihood to begin with for complete specialization to exist in 3-element hypercycles, but also there is an "interference" dynamic mechanism that suppresses any complete specialization that does emerge. Combinatorics and interference are the two forces that translate the structural potential of topological mismatch into actual multi-skilled individuals.

Higher-Element Hypercycles

Almost all of the conclusions derived from the simplest hypercycles carry over into more complex spatially-embedded technologies. In particular, (a) there is always an asymmetry between source-only and target-only reproduction; (b) joint reproduction, unlike target-only reproduction, does not preserve the full hypercycle; (c) odd-numbered hypercycles require paired coupling in order to reproduce; and (d) "live" ecologies, if found, typically involve multi-skilled individuals in their hypercyclic core, with specialized parasitic hangers-on. The main thing that changes as one moves to higher complexity in hypercycles is the likelihood of finding stable reproductive equilibria at all: it declines sharply. Since this likelihood never literally goes to zero, decline can be offset to some extent by increased density, but the greater difficulty of successfully embedding complex technologies in a spatial interaction system cannot be denied.[18]

This greater difficulty of finding and growing more complex

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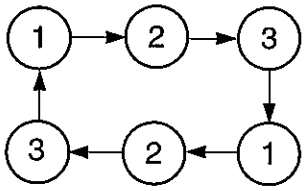
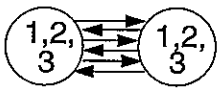
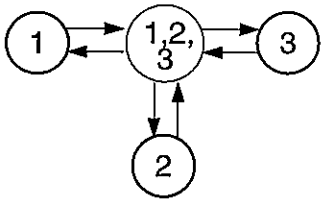
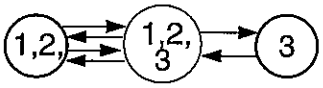
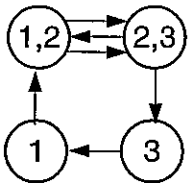
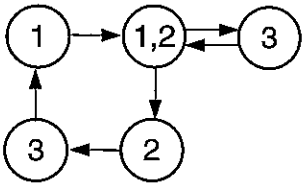
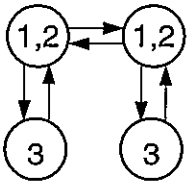
[18]This difficulty might be one evolutionary reason for the emergence of more articulated social networks out of a simple spatial interaction framework.

TABLE 2. Random probabilities of producing hypercycles, within the setup: 3-elements within 2x3 array

Possible 3-Element Hypercycle Ecologies	Random Likelihood*
A) 	$2 \cdot 6 \cdot \left(\frac{1}{6}\right)^6 = 12 \cdot \left(\frac{1}{6}\right)^6$
B) 	$7 \cdot 8 \cdot \left(\frac{1}{6}\right)^6 = 56 \cdot \left(\frac{1}{6}\right)^6$
C) 	$2 \cdot 8 \cdot 6 \cdot \left(\frac{1}{6}\right)^6 = 96 \cdot \left(\frac{1}{6}\right)^6$
D) 	$3 \cdot 16 \cdot 10 \cdot \left(\frac{1}{6}\right)^6 = 480 \cdot \left(\frac{1}{6}\right)^6$
E) 	$6 \cdot 8 \cdot 8 \cdot \left(\frac{1}{6}\right)^6 = 384 \cdot \left(\frac{1}{6}\right)^6$
F) 	$4 \cdot 4 \cdot \left(\frac{1}{6}\right)^6 = 16 \cdot \left(\frac{1}{6}\right)^6$
G) 	$3 \cdot 8 \cdot 12 \cdot \left(\frac{1}{6}\right)^6 = 288 \cdot \left(\frac{1}{6}\right)^6$

* Random likelihood calculated with all possible element and spatial permutations of the type of hypercycle indicated, within a 2x3 grid.

hypercyclic solutions out of a random initial configuration can be readily documented. For target-only simulations of "standard" size (volume=200, an average of two elements per individual), the number of runs out of ten that converged on a "live" ecology were the following: for 4-element hypercycles, ten; for 5-element hypercycles, zero; for 6-element hypercycles, five; for 7-element hypercycles, zero; for 8-element hypercycles, two; and for 9-element hypercycles, zero. This likelihood decline is monotonic once one recalls that odd-numbered hypercycles need to double in length in order to site. Joint reproduction almost always found some "live" ecology, but at the cost of implementing only a small fraction of skill elements. And source-only reproduction, as we already know, never generated stable ecologies at higher levels of technological complexity.[19]

The magnitude of this target-only decline can be moderated substantially by increasing the density of skill/action capacities per person. For example, in the case of an 8-element target-only hypercycle, doubling the volume to 400 elements (an average of four skills per individual) increased the chances of finding a reproductive ecology from two out of ten to four out of ten. In other words, not too surprisingly, increasing the average number of skills per individual increases the chances for stably reproductive social ecologies to emerge, which then better sustain these individual multiple capabilities. While straightforward, this density effect provides a kinetic foundation for more complex organizations to develop--<u>once</u> density somehow is increased exogenously. (Alternatively, as I speculate in footnote 17, more efficient interaction configurations may have the same effect.)

Perhaps the most important finding in the simulations of higher-element spatial hypercycles, however, is the fact that stable reproductive ecologies were found at all. As mentioned above, Hofbauer and Sigmund (1988: 96) have shown that non-spatial hypercycles are not dynamically stable at complexity levels of 5-elements and above. This sharp discontinuity does not exist in the spatial setting, even though quantitative likelihoods of stable reproduction do indeed decline as technology becomes more complex.

In the context of the current simulations, this Hofbauer and Sigmund finding was reproduced in the following sense. Non-spatial

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[19]Even in those target-only cases that did not converge on a "live" social ecology, there was a quantitative difference between them and the analogous source-only failures. Source-only learning converged very quickly to death. Incomplete target-only learning, in contrast, lingered on well past 20,000 iteractions, reproducing subsets of the hypercycle. Such incomplete reproduction is doomed to long-term failure, but "long term" in target-only learning could be quite long indeed. This suggests (but I have not proved) a random-walk behavior.

hypercycle models were created out of the above framework simply by substituting fully-mixed, random interaction for nearest-neighbor, spatial interaction. The results were: All twenty-five runs of the 3-element and 4-element (source-only and target-only[20]) non-spatial simulations converged on stably reproducing ecologies.[21] In sharp contrast, all twenty runs of the 5-element and above (again, source-only and target-only) non-spatial simulations "crashed", in the sense that all but one element vanished in frequency. Joint reproduction behaved the same way in the non-spatial version as it did in the spatial version: namely, regardless of complexity level, the entire hypercycle splinters into just two neighboring elements who keep each other alive, even as all other elements vanish.

Locking autocatalytic skill sequences into physical space--that is, into embodied individuals in interaction--thus seems to be crucial for complicated skill sequences to emerge. The reason for this is not hard to understand: spatial clustering endogenously generates a localized density that keeps interactions reproductively focused.[22] My spatial hypercycle models do not explain where physical space itself comes from, since grids were imposed exogenously. But "individuals" were indeed derived here, in the minimalist sense of showing how autocatalytic skills sharply cluster spatially, through competitive reproduction, onto interacting physical sites.[23]

Conclusion

Physical space is more than just a passive receptacle for social and chemical technologies to be located within. Dynamic barriers of technological complexity can be transcended once

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[20]As explained above, in the non-spatial setting there is no difference between source-only and target-only reproduction.

[21]The 3-element simulations converged on a simple equilibrium, which fluctuated stochastically around (1/3, 1/3, 1/3). The 4-element simulations converged on a limit cycle, which persisted as long as I allowed my computer to run (20,000 iterations).

[22]Social networks could generate even higher levels of density.

[23]A later step in this derivation of "individuals" might be to demand some limited consistency among the possible skills that can coexist on site. This constraint no doubt will inhibit the emergence of "live" social ecology, but it may be a precondition for enabling movement of skill-set individuals across space. In such an extension, however, I would surely search for the minimal consistency constraints possible; otherwise, the flexibility of learning so necessary to dynamically stable social ecology would be eliminated.

global is transformed into the concatenation of locals. This is because reproductive variation and behavioral "memory" are created thereby. Social technologies of action/reaction rule sequences, once enabled, produce individuals as they wend themselves back and forth across sites. This social production of individuals, while spontaneous, is not accidental. The seeding of "work" into social interaction among distinct locational units (phenotypes) permits both more complex skill-sets and more multi-faceted individuals to become alive.

One corollary of siting technology into physical location, discovered in this paper, is the asymmetry between selfish and altruistic. Only the latter, true catalysis, enables "organization"--that is, the reproducible interweaving of technology, social interaction, and skilled individuals--to exist over the long run. This asymmetry has nothing to do with the usual distinction between private and collective interests. Catalysis is important because whole sets of diverse individuals can then coexist, even in the face of sharp competition.[24] Altruism, by extension, is more crucial to the life of dynamic firms than most social scientists realize, not because of selfless sacrifice for the collective good, but because of the reproductive logic of chemistry.

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[24]Lest I be too one-sided in my emphasis, it should equally be noted that target-only catalysis without the discipline of competition produces nothing organized (perhaps only chaos).

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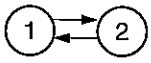
APPENDIX

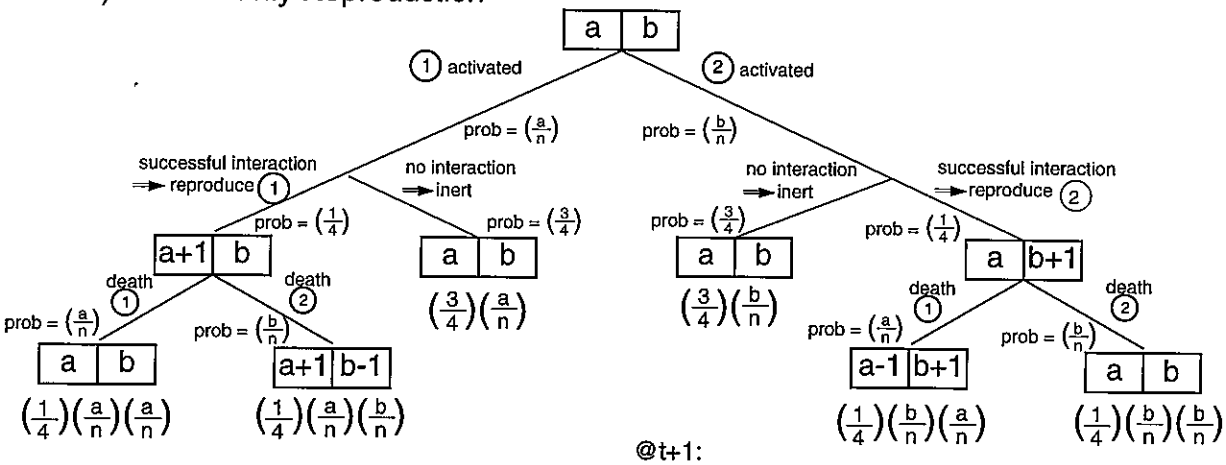
I) Solo Dyad; Only 2 Elements

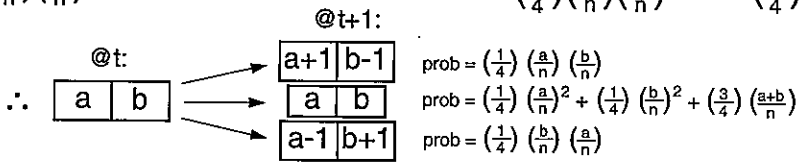


a	b

, where a+b = n

A) Source-Only Reproduction





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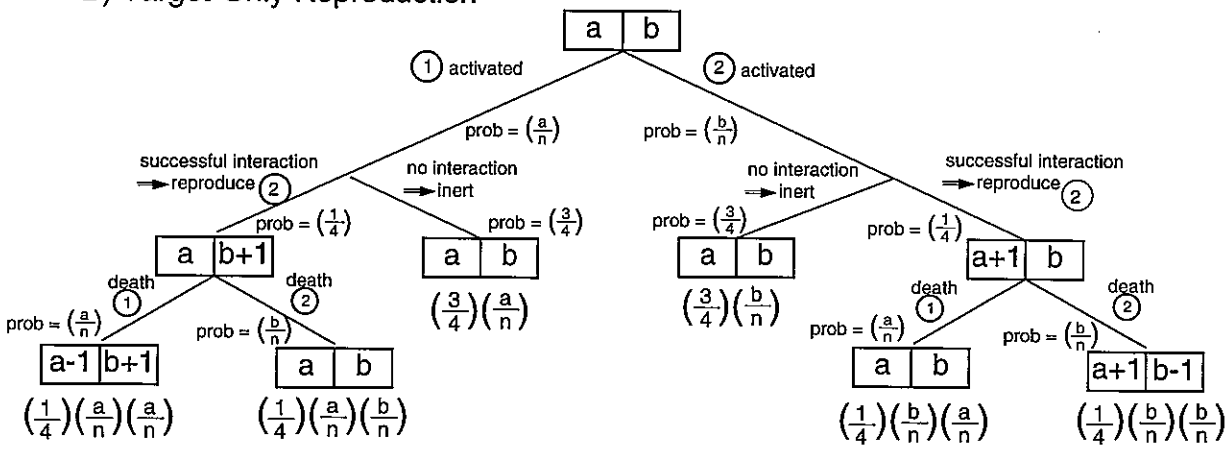

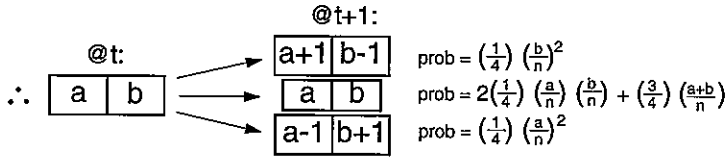

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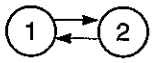
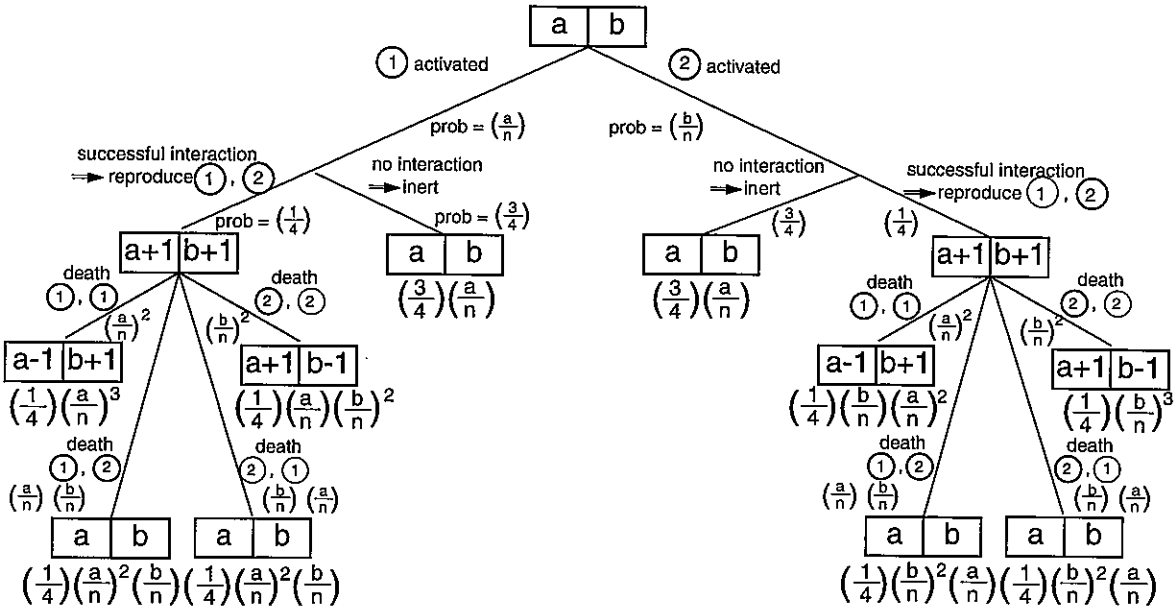
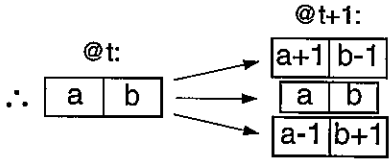


C) Joint Reproduction





prob = $\left(\frac{1}{4}\right)\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)^2 + \left(\frac{1}{4}\right)\left(\frac{b}{n}\right)\left(\frac{b}{n}\right)^2 = \left(\frac{1}{4}\right)\left(\frac{b}{n}\right)^2$

prob = $\left(\frac{3}{4}\right) + \left(\frac{1}{2}\right)\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)$

prob = $\left(\frac{1}{4}\right)\left(\frac{a}{n}\right)\left(\frac{a}{n}\right)^2 + \left(\frac{1}{4}\right)\left(\frac{b}{n}\right)\left(\frac{a}{n}\right)^2 = \left(\frac{1}{4}\right)\left(\frac{a}{n}\right)^2$

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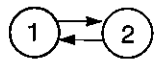
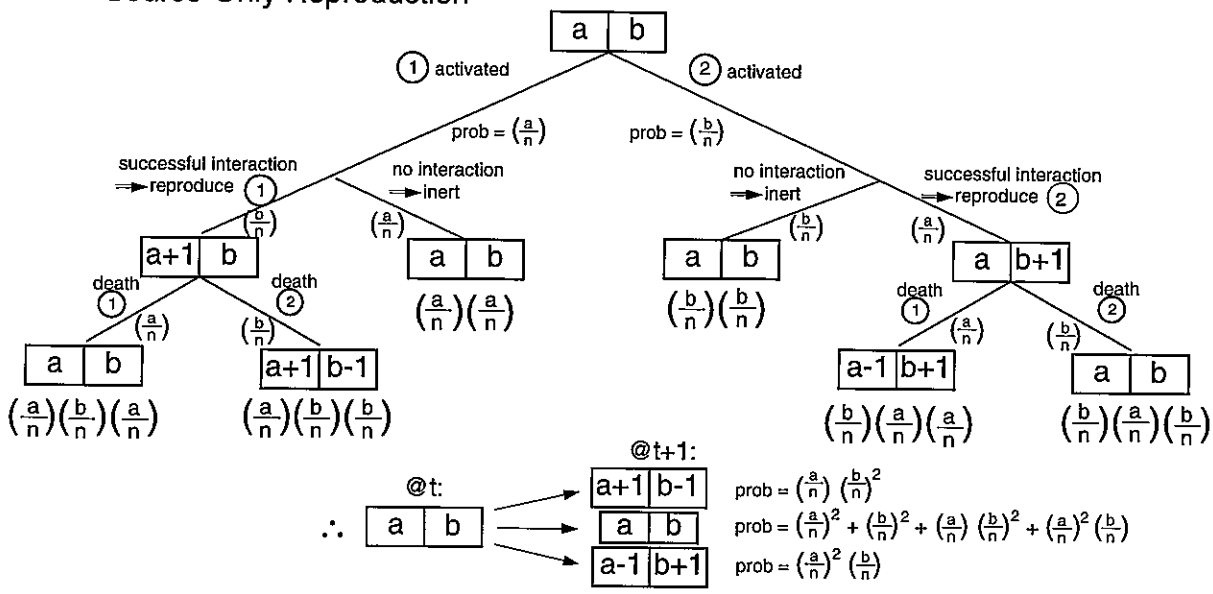


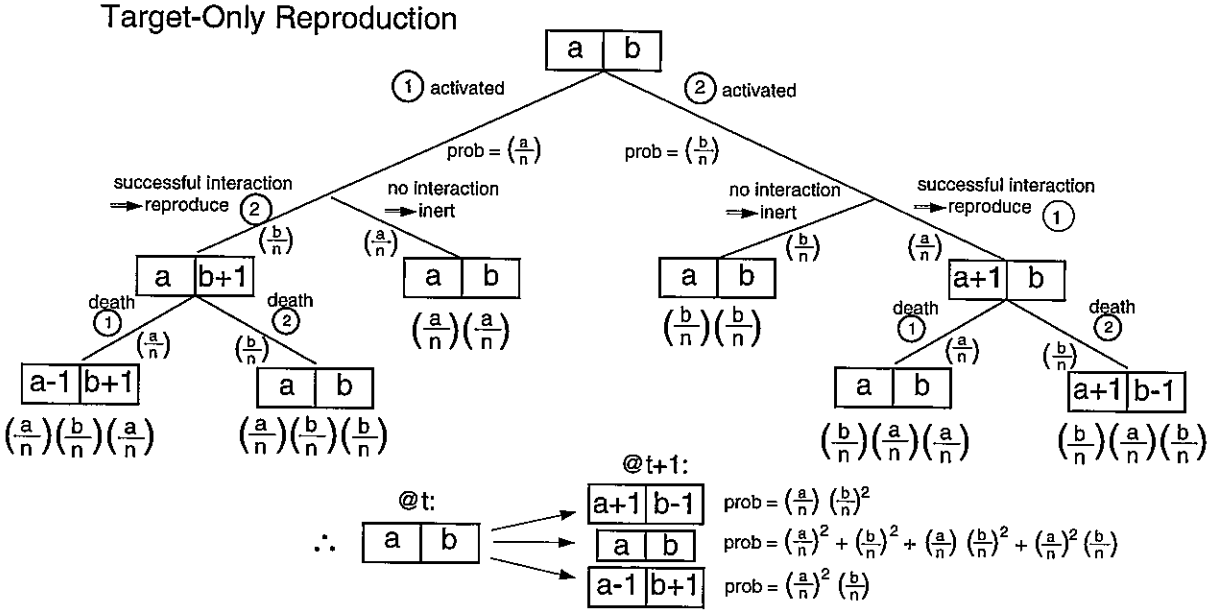
a	b

, where a+b = n

D) Fully Mixed Solution - No Spatial Source-Only Reproduction



E) Fully Mixed Solution - No Spatial Target-Only Reproduction



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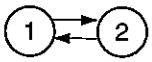
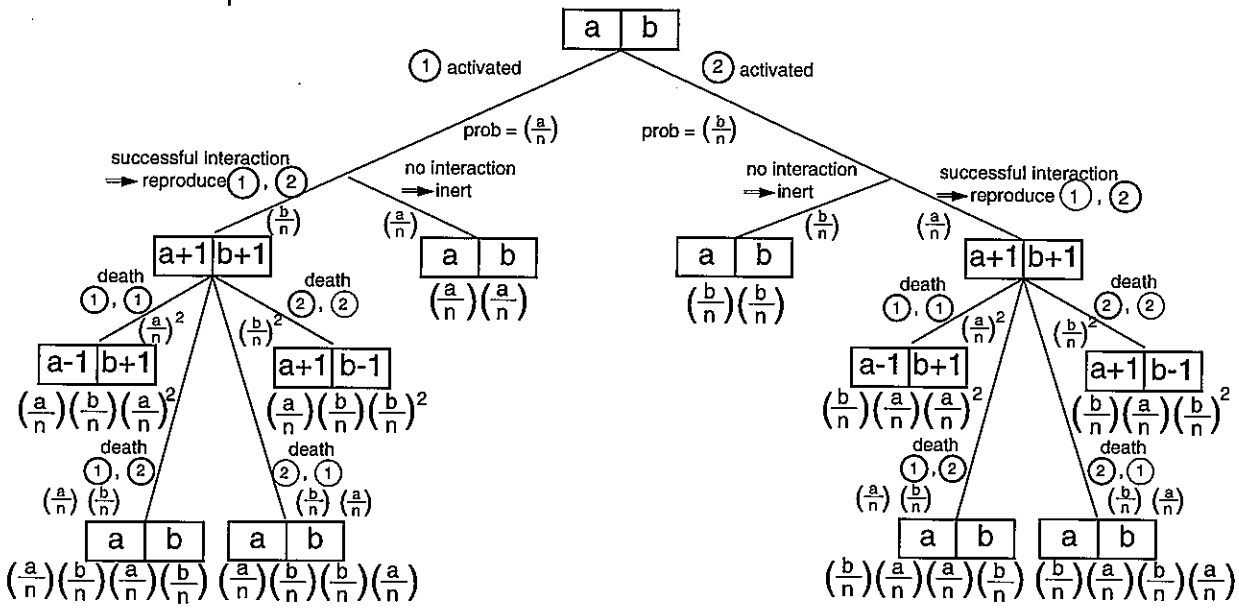
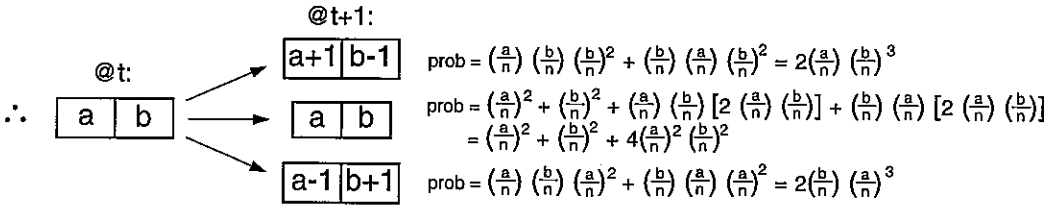


F) Fully Mixed solution - No Spatial Joint Reproduction





$$\text{prob} = \left(\frac{a}{n}\right)\left(\frac{b}{n}\right)\left(\frac{b}{n}\right)^2 + \left(\frac{b}{n}\right)\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)^2 = 2\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)^3$$

$$\text{prob} = \left(\frac{a}{n}\right)^2 + \left(\frac{b}{n}\right)^2 + \left(\frac{a}{n}\right)\left(\frac{b}{n}\right)\left[2\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)\right] + \left(\frac{b}{n}\right)\left(\frac{a}{n}\right)\left[2\left(\frac{a}{n}\right)\left(\frac{b}{n}\right)\right]$$
$$= \left(\frac{a}{n}\right)^2 + \left(\frac{b}{n}\right)^2 + 4\left(\frac{a}{n}\right)^2\left(\frac{b}{n}\right)^2$$

$$\text{prob} = \left(\frac{a}{n}\right)\left(\frac{b}{n}\right)\left(\frac{a}{n}\right)^2 + \left(\frac{b}{n}\right)\left(\frac{a}{n}\right)\left(\frac{a}{n}\right)^2 = 2\left(\frac{b}{n}\right)\left(\frac{a}{n}\right)^3$$