

Identifying Necessary Conditions for Open-Ended Evolution through the Artificial Life World of Chromaria

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Abstract

A full understanding of open-ended evolutionary dynamics remains elusive. While artificial life worlds have been proposed to study such dynamics and tests have been devised to try to detect them, no theory yet has enumerated the *key conditions* that are essential to inducing them. The aim of this paper is to further such an understanding by hypothesizing four conditions that are essential for open-ended evolution to prosper. Of course, any such conditions must be satisfied by nature (the clearest example of an open-ended domain), but we do not know the scope or range of possible worlds that could achieve similarly impressive results. To complement the hypothesized conditions, a new artificial life world called *Chromaria* is introduced that is designed explicitly for testing them. Chromaria, which is intended to deviate from Earth in key respects that highlight the breadth of possible worlds that can satisfy the four conditions, is shown in this paper to stagnate when one of the four conditions is not met. This initial controlled experiment thereby sets the stage for a broad research program and conversation on investigating and controlling for the key conditions for open-ended evolution.

Introduction

The particular properties that characterize *open-ended evolution* are tricky to pin down and often lack consensus (Bedau et al., 1998; Channon, 2003, 2006; Juric, 1994; Maley, 1999). For example, it has been variously characterized as the continual production of either novel (Lehman and Stanley, 2011; Standish, 2003) or adaptive (Bedau et al., 1998) forms. Yet despite the difficulty of precisely pinpointing this phenomenon, a major goal of artificial life (alife) research remains to observe open-ended evolution in an alife simulation (Bedau et al., 2000). In fact, there is little doubt that no algorithm yet devised has fully reproduced it. Even with milestone artificial worlds like Geb (Channon, 2003, 2006) that have passed tests designed to detect particular signatures of open-endedness (Bedau et al., 1998), no scientist has suggested that any system today reproduces the full generativity of nature in all its glory, which raises a fascinating question: *why not?* What aside from eons of time (which likely is not the sole ingredient missing from artificial worlds so far) could ignite the fire of an open-ended complexity explosion?

The aims of this paper are to provoke progress towards understanding why it has not happened so far by (1) proposing a set of four conditions that are hypothesized to be essential for triggering a genuinely open-ended evolutionary process, and (2) showing how these conditions can be tested using a novel artificial life world called *Chromaria*, which implements all four conditions. An important theme of the proposed conditions is that they are not only satisfied by Earth, but in principle would be satisfied by *any* abstract artificial system that is to achieve open-ended dynamics (including systems radically different from Earth). Thus evaluating these four conditions entails a broad research program that a single conference paper cannot comprehensively address. Nevertheless, as an initial step in this direction, this paper presents an experiment wherein one of the conditions is controlled in Chromaria to demonstrate a general methodology for testing the conditions for open-endedness, and also to show that even *one* condition's absence can profoundly and observably incapacitate evolution. The hope in the longer term is eventually to examine all four conditions, including in alife worlds besides Chromaria, and moreover to initiate a reinvigorated discussion on the essential conditions for evolution of the scale observed on Earth.

Background: Open-Ended Evolution

Attempts to achieve open-ended evolution in alife often center on artificial worlds or simulators inspired by some aspect of natural evolution. Among the first is Tierra (Ray, 1992), which consists of a virtual machine that executes machine code. Tierran creatures are programs (i.e. sets of machine code instructions) that are stored in RAM and compete for CPU cycles. The ideas in Tierra later inspired Avida (Ofria and Wilke, 2004), where unlike in Tierra CPU time is allocated proportionately to a fitness measure called *merit* that is based on a creature's ability to perform various computations. Avida has shown in a landmark study that the evolution of complex behaviors can stem from the evolution of simpler ones (Lenski et al., 2003).

The work of Sims (1994) on evolving three-dimensional creature morphologies has inspired its own less abstract

genre of alife world. For example, the Division Blocks (Spector et al., 2007) environment consists of square islands on a square ocean, with a sun that circles the world and energizes evolving three-dimensional creatures that sometimes evolve altruistic behaviors. In another such three-dimensional world, Evosphere (Miconi and Channon, 2005), creatures coevolve nontrivial strategies through direct physical combat.

Another popular genre includes PolyWorld (Yaeger, 1994), where neural network-based organisms that were shown to increase in complexity forage and fight on a two-dimensional plane. Geb (Channon, 2003, 2006) is a similar (yet independently conceived) world consisting of a toroidal, two-dimensional grid. Additionally, Geb is the first and only alife system thus far to qualify as *unbounded* according to the activity statistics classification system (Bedau et al., 1998; Channon, 2003, 2006). This system measures the persistence of advantageous genotypes over evolution, following from the assumption that a gene that is not eliminated by natural selection is in effect a beneficial adaptation. However, there is debate as to whether or not this assumption is valid (Juric, 1994; Miconi, 2008). Furthermore, it is not clear that achieving *unbounded adaptation* is equivalent to achieving a *complexity explosion*. It remains unsettled the extent to which activity statistics capture the essence of open-ended phenomena observed on Earth.

Bearing in mind the controversy surrounding the definition of open-endedness, for simplicity this paper follows the definition proposed by Standish (2003), which is that *open-endedness depends fundamentally on the continual production of novelty*. The continual production of novelty furthermore *entails* increasing complexity because all the possibilities that exist at any given level of complexity will eventually be exhausted in a never-ending process. Therefore, experiments in this paper quantify open-endedness based on the ongoing generation of novel behaviors.

While a variety of alife worlds have been implemented and studied, critics describe them as “lacking” in methodology and theory (Miconi, 2008). Among the limited work aiming for such a theory, Conrad and Pattee (1970) make an initial attempt to isolate minimal conditions for evolution in ecosystems and empirically test them via simulation. Holland (1994) similarly investigates the necessary conditions for emergent phenomena in complex adaptive systems. In contrast, the present work aims to provide concrete, testable conditions for *open-ended* evolution in particular. Furthermore, the hope is to understand how such a phenomenon can be provoked in all possible evolutionary domains, of which nature is only one.

Hypothesized Necessary Conditions

The aim in this paper is to initiate a new direction in identifying the set of necessary conditions that a domain must satisfy to support open-ended evolution. This goal is ambitious

because while evolution in nature must satisfy such conditions, no artificial domain yet devised exhibits the same kind of astronomical complexity explosion. Thus it follows that if any set of proposed conditions is credible, natural evolution must satisfy all of them while every artificial system so far devised likely falls short of meeting at least one condition. Furthermore, unless evolution in nature is the *only* open-ended system that is theoretically possible (which would be a disappointing conclusion for alife), such a set of conditions should admit conceivable worlds far different from our own, thereby elucidating what from nature is genuinely essential to provoking such a process, and what simply lends character to nature. Such differences might then point the way to open-ended domains different from those typical in alife (such as the one later proposed in this paper) while also explaining why many domains that *seem* natural nevertheless can be predicted to fall short.

It is important to note up front that a domain can only support *open-ended* evolution if it is generally suitable to evolution in general. That is, any artificial or natural evolutionary system must satisfy certain minimal prerequisites to have *any* success at all (open-ended or not). These prerequisites include a good genetic representation (tightly coupled with the phenotype space) (De Jong, 2006), a sufficiently large world for every individual to be evaluated, and some initial *seed* (like the first cell on earth) or starting point (such as a random initial population) from which evolution begins. Assuming that these general prerequisites are met, the main hypothesis is that four necessary conditions for open-ended evolution are as follows:

Condition 1: A rule should be enforced that individuals *must* meet some minimal criterion (MC) before they can reproduce, and that criterion must be nontrivial. The role of the MC is to ensure that a minimal level of complexity must always be maintained by every viable organism, thereby ensuring that the population can never degenerate into trivial behaviors. On Earth, for example, individuals become eligible to reproduce only by developing and maintaining functional reproductive apparatuses. No lineage can persist that does not maintain this nontrivial capability, which is the MC on Earth. In worlds that are unlike Earth, however, fundamentally different MC are conceivable; for example, the criterion need not concern the *mechanics* of reproduction at all. That is, offspring could be created by the system, as is common in evolutionary algorithms (EAs), without any reproductive apparatus in the individuals themselves. There simply must be some meaningful limit on which individuals can reproduce, thereby ensuring that the results will remain interesting. For example, every individual could be required to perform a particular complex task. To be *meaningful* or *nontrivial*, the criterion should involve interacting with the world in some way. If the MC is too trivial, the results of evolution will be uninteresting. On the other hand, if it is

too demanding then the search will be too restricted. Interestingly, in evolutionary computation, with a few exceptions (Lehman and Stanley, 2010), most EAs implement no such MC: usually all individuals have at least some small probability of reproduction (De Jong, 2006).

This condition implies a necessary **corollary**: The initial seed (from which evolution begins) must itself meet the MC and thereby be nontrivial enough to satisfy Condition 1. Otherwise, if evolution began without any individuals who satisfy the MC, then by Condition 1 no one would be allowed to reproduce and the experiment would end. This corollary further diverges from traditional EAs (and even alife worlds), which often begin with a random population. If no individual in the initial population of such an experiment meets a nontrivial MC then the algorithm could not satisfy Condition 1. In fact, this corollary shows that obtaining the starting seed (such as the first cell on Earth, which already began with a reproductive apparatus) is a challenge in its own right that must be confronted for open-ended evolution even to initiate.

Condition 2: The evolution of new individuals should create novel opportunities for satisfying the MC. This condition is important because it ensures that there is some way for complexity to increase indefinitely beyond the level of the (relatively simple) initial seed. If evolution is to achieve open-endedness, then it must continually find paths from simpler phenotypes to more complex ones. However, such novel paths will be explored only as long as each link in the chain continues to satisfy the MC. Thus it is critical that *new opportunities* to satisfy the MC through previously unsupportable strategies continually open up so that evolution can explore paths that lead arbitrarily beyond the initial seed. Furthermore, *evolution itself* is the only viable generator of such novel opportunities because a human designer could not realistically conceive a ladder of tasks sufficiently rich to continue without limit. The trajectory of biological evolution exhibits many such transitions where new life forms paved the way for further genetic innovation in other lineages. Giraffes, for instance, could not have evolved on Earth before there were trees. In this way, the evolution of trees created an opportunity for evolution later to explore a previously unsupportable path (namely, the path to giraffes) by generating a novel opportunity to satisfy the MC. If the nature of individual interactions is too restrictive (such as predators simply bumping into prey in alife worlds), then this condition may not be possible to satisfy.

Condition 3: Decisions about how and where individuals interact with the world should be made by the individuals themselves. Such decisions determine whether an individual will successfully seek out and exploit novel opportunities for satisfying the MC. Though the MC primarily serves to maintain some degree of complexity, it also creates a coupling between successful phenotypes and the environment. (This coupling follows from the requirement that

a nontrivial MC must involve interacting with the world in some way, such as gathering food for sustenance of the reproductive apparatus in natural evolution.) If an individual cannot choose both its actions and their targets (geographical or otherwise), then the environmental coupling is disrupted and phenotypic evaluation becomes arbitrary. That is, if the individual does not play at least some role in deciding where it interacts, then some kind of *oracle* would need to determine for the individual its best opportunity to satisfy the MC. However, this oracle would require intimate knowledge of the search space to anticipate all possible future opportunities, most of which could not even exist when the search began. In this sense, any decision made by such an oracle would be effectively arbitrary. Thus no human designer can realistically construct such an oracle. For these reasons, behavioral decisions must be made by the individuals themselves, who thereby decide for themselves which opportunities to exploit (like giraffes heading for the trees).

Condition 4: The potential size and complexity of the individuals' phenotypes should be (in principle) unbounded. In practice, the growth of the phenotype must have some limit (e.g., the size of the universe in the real world); achieving infinite growth would of course require infinite time and infinite space. However, at a practical level, the salient point is that the complexity of the phenotype should not be limited by its representation, as there needs to be room for complexity to increase for the kind of complexity explosion desired in open-ended evolution to be realized.

While the hypothesis is that these four conditions are all necessary for open-ended evolution, whether they are sufficient is left open. Perhaps more conditions will be identified. However, the hope is that the set of necessary and sufficient conditions can be kept as small as possible. That way, the conditions can help to illuminate the elusive fundamental and essential ingredients behind open-ended complexity explosions. To this end, what is omitted can be just as illuminating as what is included. For example, one prominent omission from the four proposed conditions is any reference to traditional *fitness*. While the fitness function is ubiquitous in much of evolutionary computation (De Jong, 2006), a major problem for open-ended evolution is that what is genuinely novel is significantly harder to formalize than what is *better*. In effect, we do not know *a priori* which discoveries lead later to more novel discoveries. Any explicit conception of fitness, wherein some individuals are judged less meritorious relative to others, risks blocking potentially promising paths through the search space. By introducing a mechanism that evaluates individuals without judging them against each other (i.e. the MC), evolution can maintain nontriviality without falling prey to such deception. The benefits of search not driven by explicit objectives has been explored previously in e.g. Lehman and Stanley (2011). Of course, fitness is indeed an important concept in natural evolution

(Orr, 2009), but it can be viewed as an *emergent* byproduct of the MC in nature (i.e. to construct a copy of oneself) that changes over time rather than an explicit a priori constraint imposed from outside. By thereby reducing the conditions to rely solely upon the constraint of the MC, the simplest possible hypothesis on the origin of open-ended dynamics can be explored, and fewer assumptions must be satisfied to construct such systems.

At the same time, the conditions can help us to predict which systems can be expected to yield genuine open-endedness, and which cannot. For example, any system (1) without a nontrivial MC or without an initial seed satisfying such a MC, (2) in which the means of satisfying the MC are fixed from the start, (3) in which individuals do not choose for themselves with whom or where to interact, or (4) without the ability to increase the size of the genetic representation is by hypothesis *not capable of open-ended dynamics*.

More generally, the interesting potential of such a set of conditions, if right, is that they can admit worlds radically different from nature yet able to exhibit similar open-ended dynamics. By exploring such alternative worlds, as in the experiment described next, ideally we can begin to learn what may be possible someday to achieve by harnessing open-ended dynamics for our own purposes.

Chromaria Experiment

The aim of this experiment is to observe initial hints of open-ended evolutionary dynamics in an artificial domain that satisfies the four hypothesized necessary conditions, and to show that when one of the conditions is not satisfied, the observed phenomenon is stunted. That way, the main contribution is to suggest a concrete path towards investigating the hypothesized conditions. In addition, by also introducing a world that is intentionally unlike Earth, the implication is that the four conditions admit many possible realizations, of which biology is only one.

The world introduced in this paper, called *Chromaria*, is visually two-dimensional and composed of discrete RGB pixels (Figure 1). The colorful creatures (called *Chromarians*) evolved in this world actively explore it to search for a place to *plant*. Each Chromarian is allowed one planting attempt. If the Chromarian’s RGB sensor field (which can sense prior successful planters and the background) satisfies a specific *planting function* involving matching its color (detailed later), then the planting attempt succeeds and the successful creature is eventually allowed to reproduce. Thus the MC in Chromaria, unlike Earth’s MC, is to navigate to a position in the world with colors matching the Chromarian’s own coloring. If this MC is not met, then the Chromarian is removed without planting and does not reproduce.

Each Chromarian’s morphology consists of a two-dimensional image composed of RGB pixels. The genetic encoding of this morphology is a compositional pattern producing network (CPPN; Stanley 2007), a neural-network-

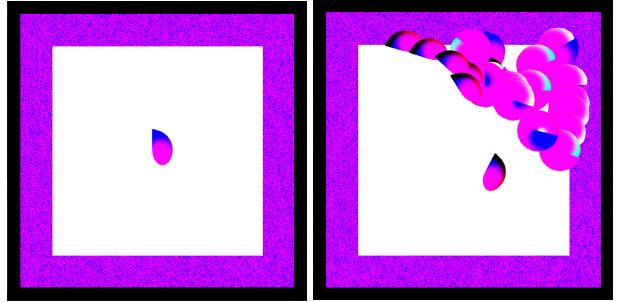


Figure 1: **Chromaria.** Each creature is born at the center of the world (left) and then must find an appropriate place to plant. The color-rich borders initially provide the only viable options, but more emerge as Chromarians continue to plant in the environment (right).

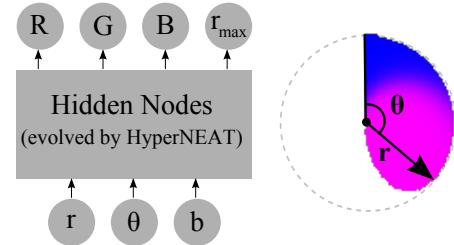


Figure 2: **Morphology-encoding CPPN.** The CPPN encodes both the outline and fill of the Chromarian’s morphology. Input b is a bias set to the constant value 1.0.

like representation that generates patterns with regularities such as symmetry, repetition, and repetition with variation. The CPPN used to encode Chromarian morphologies (Figure 2), which is similar to the encoding in Risi et al. (2012), takes polar coordinates r and θ as input. Such polar coordinates define an unambiguous solid border for the body, which would be harder to determine if the inputs were Cartesian. Upon activation, the CPPN returns an r_{max} for each value of θ , which determines the perimeter of the Chromarian’s body at that angle. Then every pixel on the interior of this border is queried by the CPPN for the corresponding RGB values at the queried (r, θ) , where r is scaled from $[0, 49]$ to $[0, 1]$, and θ from $[-\pi, \pi]$ to $[-1, 1]$. In this way the CPPN determines both the *shape* (via the r_{max} output) and *internal color* (via the RGB outputs) of the Chromarian. These characteristics ultimately determine where the Chromarian can successfully plant. By evolving new colors, Chromarians in effect create novel opportunities for new kinds of planters, thereby satisfying Condition 2.

Each Chromarian is equipped with a 10×10 rectangular sensor field that perceives the RGB values (each scaled from the range $[0, 255]$ to $[-1, 1]$) of the underlying pixels. This field is centered at the forefront of the Chromarian’s body, with half of the pixels falling underneath the body and

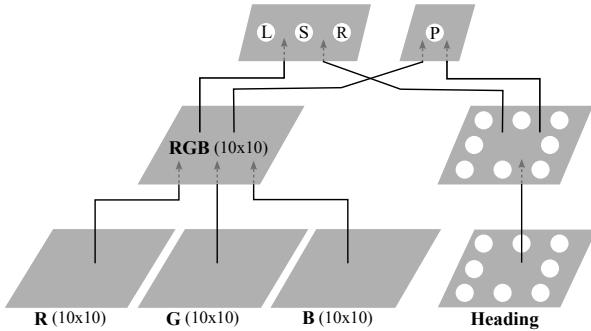


Figure 3: Behavioral controller. Each plane represents an array of sensors or neurons. Arrows between planes in this schematic denote *sets* of connections between one plane and another. The input layer contains three individual color fields, which feed into an intermediate integration layer. There is an additional set of heading inputs, which remain uncombined with the color data until the output layer is reached. The four output nodes control behavior. The maximum number of connections in this network (evolved by HyperNEAT) is 30,448.

the rest extending in front of the creature. The exact resolution of the field depends on the creature’s morphology; as its length and width increase, the distance between neighboring sensors grows. Note that Chromarians can overlap if they have planted in the same location, in which case the pixels of the most recent planter are sensed. Additionally, each Chromarian is equipped with a heading-sensitive *compass* consisting of 8 pie slice sensors. All sensors are input to a multimodal neural controller (Figure 3), whose weights are encoded using a *second* CPPN following the HyperNEAT approach to encoding large-scale ANNs with CPPNs (Pugh and Stanley, 2013; Stanley et al., 2009). The output layer, which receives connections from the hidden layers, has four effector nodes corresponding to the Chromarian’s requested rotation (L and R), speed (S), and desire to plant itself (P). If the planting node exceeds a threshold, then the Chromarian is immobilized and it never moves again. Otherwise, the rotation and speed nodes determine the Chromarian’s next movement. Note that it is through this ability of the Chromarian to decide for itself when and where to plant (based on its senses) that it satisfies Condition 3. HyperNEAT’s ability to evolve multimodal neural networks with tens of thousands of connections is what enables creating an artificial life world like Chromaria, where autonomous control decisions are made based on rich full-color sensory input.

Evolution in Chromaria proceeds in two stages. First, there is a preliminary search for an initial seed that satisfies the MC (i.e. an individual that successfully plants itself), followed by the open-ended phase (which proceeds without a particular desired behavior or morphology).

Preliminary search. Satisfying the corollary to Condition 1 (i.e. that evolution must start with an initial seed that satisfies the MC) presents a puzzle: how can the initial seed be obtained? The proposed solution in Chromaria is to begin with a *preliminary search* for it. The search for an initial seed is important because it decides the starting point for subsequent open-ended evolution (and thereby influences which potential paths to complexity evolution will explore). In this experiment, novelty search (Lehman and Stanley, 2011) is the approach chosen to find a successful controller for the initial morphology (starting morphologies were interactively evolved by the authors). Planters discovered by novelty search for particular morphologies are then the seeds in the experiment that initiate open-ended evolution.

Open-ended evolution. Chromarians are evolved using HyperNEAT (Stanley et al., 2009), a neuroevolution method that gradually complexifies its underlying genetic representation over time. Through the indirect CPPN encoding, HyperNEAT can efficiently evolve complex connectivity patterns that reflect the geometry of their inputs. The large HyperNEAT substrate neural networks (up to 30,448 connections) in this experiment provide sufficient space for complexity to increase significantly over the course of a run, thereby satisfying Condition 4. Recall also that each Chromarian contains *two* CPPNs: one to encode its neural network, and the other to encode its morphology. This experiment uses a modified version of the HyperSharpNEAT 2.1 implementation of HyperNEAT, which is based on Colin Green’s SharpNEAT (Green, 2006). Parameter settings are included with the released code, available at <http://eplex.cs.ucf.edu/chromaria/home>.

In the unconventional main loop in Chromaria, the Chromarians that have successfully planted most recently are kept in a *parent queue* with maximum size 100. A *current parent* pointer always points to one position in the list. When the simulation begins, the list only contains one Chromarian (i.e. the initial seed found in the preliminary search). The newborn then attempts to plant. Each tick of the simulation (capped at 200 ticks per Chromarian) proceeds as follows:

1. The Chromarian’s sensors are updated and its controller is activated.
2. If the planting effector node is negative, the Chromarian moves according to its other effector nodes. Otherwise, the Chromarian attempts to plant at its current location. This attempt succeeds if the the RGB ratios in the Chromarian’s morphology are collectively no greater than 12.5% different from the RGB ratios in its sensor array contents (Figure 4). Furthermore, to ensure that Chromarians must learn to move (to keep the MC non-trivial), they are eliminated if they attempt to plant within a small radius of their starting position.
3. If the planting attempt succeeds, the Chromarian generates an offspring. Note that reproductive dynamics in

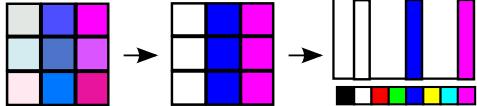


Figure 4: RGB ratio calculation. Each pixel of both the morphology and sensor field is placed into one of eight bins: black, white, red, green, blue, yellow, cyan, or magenta. Here, a simple morphology is shown to the left of its binned equivalent and a histogram of the bins. The bins are defined by halving the ranges [0,255] that the R, G, and B component values can take. For instance, any pixel with $R \in [0, \frac{255}{2}]$ (more non-red than red), $G \in [0, \frac{255}{2}]$ (more non-green than green), and $B \in [0, \frac{255}{2}]$ (more non-blue than blue) falls into the black bin because black has values $R,G,B = 0,0,0$. Once every pixel is binned in this way, color ratios are calculated for each bin by dividing the bin size by the total number of pixels. Ratios are recorded for both the morphology and sensor field. The differences between these ratios for each color are summed to get a *matching value*. If this value is less than 1 (out of 8), the planting function is satisfied.

Chromaria are unlike those in many other alife worlds. The next Chromarian to reproduce is always next in the parent queue. If the current parent is at the end of the queue, the pointer simply wraps back to the start of the queue. In this way, *all* Chromarians who successfully plant eventually get to reproduce. That is, explicit competition, which is usually central to alife worlds, is intentionally absent from Chromaria (because it still satisfies the four conditions anyway). As soon as an offspring is created from the current parent, it attempts to plant, starting as always from the center of the world. If it succeeds, then it is inserted into the parent queue directly *preceding* its own parent. Then the next Chromarian in the queue reproduces, and so on. This mechanism of always inserting offspring preceding their parent forces the system to allow every preexisting member of the population to reproduce before a newcomer.

- Whenever a new Chromarian succeeds at planting, the oldest preexisting member is removed from the population list if the list contains at least 100 members. However, *all* bodies of previously successful planters remain in the world for the duration of evolution.

Chromaria thus satisfies the four hypothesized necessary conditions for open-ended evolution: (1) individuals must satisfy a nontrivial MC (finding a valid location in which to plant) before they can reproduce; (2) individuals can plant within each other, wherein the possible color matchups are unlimited, thereby creating novel opportunities for satisfying the MC; (3) individuals decide themselves where and when to plant based on information from their sensors; and (4) the CPPN encodings for the creatures' morphologies and

controllers have no complexity ceiling; thus complexity has room to increase significantly.

It is also instructive to consider how Chromaria is unlike Earth, which is the canonical example of an open-ended domain. First, the MC in Chromaria decouples the function of reproduction (producing offspring) from the process that allows one to reproduce. Second, there are no predator-prey relationships between any individuals. This absence highlights the variety of conceivable ways that individuals in a non-Earth-based domain can satisfy Condition 3 by creating opportunities for each other. Furthermore, unlike in many alife worlds, *there is no explicit competition*: Anyone who satisfies the MC will eventually reproduce. This lack of explicit competition, and the implication as suggested by Juric (1994); Lehman and Stanley (2011); Standish (2003) that open-endedness is still possible without it, is the reason that activity statistics (Bedau et al., 1998), which track *adaptive* evolution, are not the chosen measure in this paper.

Recall that one of the four conditions will be tested in this paper through a controlled experiment in Chromaria to show how Chromaria can serve as a testbed for such investigations. For that purpose, in this initial experiment the second condition is controlled by *preventing Chromarians from sensing each other*. That way, new opportunities to plant can never arise beyond the preexisting colored border region and white background present at the start of the run (recall that the right to plant is based on the contents of the Chromarians' sensors), violating Condition 2. Five runs each of the **control** and **standard** (i.e. satisfying all four conditions) versions of Chromaria were performed, starting from the same initial seed (discovered by novelty search to plant in a magenta and blue border region) and ending after 50,000 reproductions. Additionally, a second set of ten runs (five control and five standard) was initiated from a different seed evolved for a world with a cyan and blue border region.

Results

The goal of the experiment is to observe the continual production of novel and successful planters in Chromaria, and to show that such continued innovation (hinting at open-ended evolution) is precluded when Condition 2 goes unmet. The most salient evidence of such a dichotomy between standard and control runs is from observing the worlds themselves. A key benefit of the visual design of Chromaria is to make observing the implications of different variants easy. For this purpose, representative snapshots of Chromaria at equivalent stages in different variants are shown in Figure 5. These snapshots illustrate a clear expansion and diversification (both in terms of planting locations and colors) of the population, which was observed in *every* standard run but absent from the control runs. Furthermore, distinct color-behavioral groups can be seen gradually emerging and unfolding over the 50,000 reproduction attempts of each world. Importantly, appreciating the full

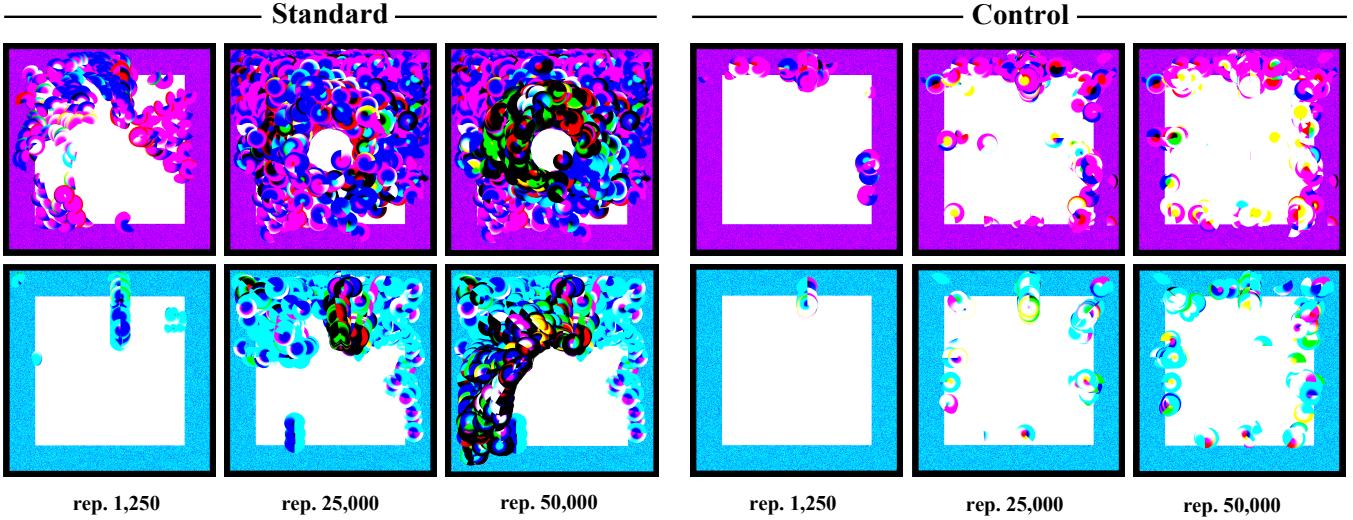


Figure 5: Representative world snapshots. Control and standard versions of Chromaria were run through 50,000 reproductions. Here, representative worlds (magenta/blue world at top and cyan/blue at bottom) are shown at various reproduction numbers. While each run followed a different trajectory, *every* standard run exhibited principled growth beyond the initial world state, while *no* control runs did. Thus interactions between individuals are clearly required for open-ended evolution.

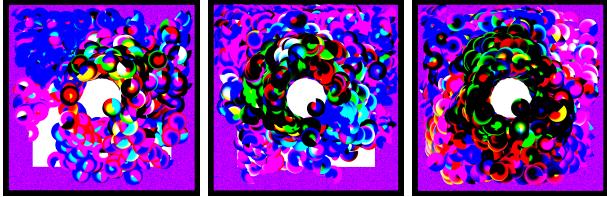


Figure 6: Typical standard run end states. At 50,000 reproductions, standard runs in the magenta world typically exhibit circular patterns of growth. However, while such patterns are discernible, differences in the individual snapshots indicate unique trends in individual runs.

breadth of Chromaria requires observing Chromarians in action (i.e. exploring and attempting to plant) because much of the complexity of evolved Chromarians is in their dynamic *behavior*, which is based on their rich sensory inputs. For that purpose highlight videos are available at <http://eplex.cs.ucf.edu/chromaria/home>.

Another intriguing result is that even though the world is stochastic, the end states among the standard runs exhibit some consistent dynamics (an outcome that could not necessarily be predicted from the start). As shown in Figure 6, the magenta worlds results consistently in ringlike configurations. Mostly-black Chromarians, who are not present at the start, tend to encircle the middle of the world.

To quantify the dramatic difference Condition 2 makes, the diversity of behaviors generated in different variants was measured. The path of an individual Chromarian is represented as a vector of (x, y) coordinates with range $[(0, 0), (1000, 1000)]$. For the purpose of sampling the vari-

ance of behaviors, position is sampled ten times (at every 20 simulation ticks), giving a vector of length 20 for each individual. The breadth of behavioral trajectories in a run can then be characterized by calculating the average variance in position (\bar{var}) at each sampled tick. It is important to note that these behaviors (represented by the vector of all sampled positions) capture both a period of intelligent seeking and then planting once a suitable color destination is identified. Given that successful planting is a nontrivial behavior, this metric captures not just the amount of diversity produced by evolution, but the amount of *interesting* or *non-trivial* diversity. In the blue world, the average \bar{var} is 379.8 (with its own *across-runs* standard deviation $ar-\sigma = 96.4$) for control runs and 1,272.9 ($ar-\sigma = 465.4$) for standard. In the magenta world, the average \bar{var} is 625.31 ($ar-\sigma = 114.8$) for control runs and 1579.40 ($ar-\sigma = 123.8$) for standard. In both worlds, the p-value from a Student's t-test is under 0.05, indicating significance. Thus the quantitative results match the intuition that a significantly wider breadth of intelligent planting behaviors results when Condition 2 is met.

Discussion

The intent of this work is to set the stage for investigating the necessary conditions for open-ended evolution. By controlling for Condition 2, the experiment in this paper shows that the dynamics of Chromaria are altered significantly without the ability of Chromarians to provide new opportunities for each other. While that outcome makes sense and of course can still be tested further, the larger implication is that this experiment shows how hypotheses about the key conditions can be tested, which in turn means that the open-endedness of other alife worlds can potentially be predicted and ex-

plained. For example, any world or experiment wherein individuals do not interact (and hence do not create new opportunities for each other to meet the MC) would be expected to exhibit muted dynamics, as with the controls here. Additionally, while alife worlds often do involve interaction, Condition 3 suggests that individuals must be able to *choose* their interactions; some existing worlds thus do not meet this condition. The other conditions (once validated) similarly offer their own intriguing opportunities to assess existing alife worlds from a new perspective and thus provide insight into their own potential and limitations. While some may argue that further conditions than those proposed here are necessary (e.g. explicit competition), those can similarly be hypothesized and checked. In this way, Chromaria offers a unique opportunity to visualize the implications of different conditions, as well as opening a fascinating set of questions in its own right. For example, why does the “black ring” seem inevitable in the magenta world (Figure 6), and what might follow it far beyond 50,000 reproductions?

Conclusion

The aims of this paper were twofold: (1) to propose a new theory about what is necessary for open-ended evolutionary dynamics, and (2) to show how this theory can be tested using a new artificial life world called Chromaria. In this initial report, one hypothesized requirement for open-ended evolution was shown to be necessary; when individuals could not create new *opportunities* for each other, evolution stagnated. When the world was left unperturbed, however, it *did* exhibit some open-ended dynamics, which highlights Chromaria’s utility as a platform for scientifically testing theories about evolution. Further experiments with Chromaria will test the remaining hypothesized conditions for open-ended evolution, allowing us to begin to pinpoint what is truly essential to the quest for ever-complexifying life.

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