Full reference:
Bell, S. & Gabora, L. (2016). A music-generating system based on network theory. In *Proceedings of the 7th International Conference on Computational Creativity*. Palo Alto: Association for the Advancement of Artificial Intelligence (AAAI) Press.

A Music-generating System Based on Network Theory

Shawn Bell
Dawson College
Arts, Literature & Communication Program
Interactive Media Arts profile
Montreal QC, H3Z 1A4, Canada
sbell@dawsoncollege.qc.ca

Liane Gabora
Psychology Department
University of British Columbia (Okanagan Campus)
Kelowna BC, V1V 1V7, Canada
liane.gabora@ubc.ca

Abstract

This paper is the first scholarly presentation of NetWorks (NW), an interactive music-generation system that uses a hierarchically clustered scale-free network to generate music that ranges from orderly to chaotic. NW was inspired by the Honing Theory of creativity, according to which human-like creativity hinges on (1) ability to self-organize and maintain dynamics at the ‘edge of chaos’ using something akin to ‘psychological entropy’, and (2) the capacity to shift between analytic and associative processing modes. At the ‘edge of chaos’ it generates patterns that exhibit emergent complexity through coherent development at low, mid, and high levels of musical organization, and often suggests goal seeking behavior. The architecture consists of four 16-node modules: one each for pitch, velocity, duration, and entry delay. The *Core* allows users to define how nodes are connected, and rules that determine when and how nodes respond to their inputs. The *Mapping Layer* allows users to map node output values to MIDI data that is routed to software instruments in a digital audio workstation. By shifting between bottom-up and top-down it shifts between analytic and associative processing modes.

Introduction

This paper introduces NetWorks (NW), a music-generating program inspired by the view that (1) the human mind is a complex adaptive system (CAS), and thus (2) human-like computational creativity is best achieved by drawing on the science of complex systems. NW uses scale-free networks and the concept of the ‘edge of chaos’ to generate music that is aesthetically pleasing and that maintains interest. The approach has origins that date back to a CD of emergent, self–organizing computer music based on cellular automata and asynchronous genetic networks titled, “Voices From The Edge of Chaos” (Bell 1998), and more generally to the application of artificial life models to computer-assisted composition, generative music and sound synthesis (Beyls 1989, 1990, 1991; Bowcott 1989; Chareyron 1990; Horner and Goldberg 1991; Horowitz 1994; Millen 1992; Miranda 1995; Todd and Loy 1991).

We first summarize key elements of a CAS-inspired theory of creativity, and discuss the relevance for computational creativity. Next we outline the architecture of NW, evaluate it’s outputs, and highlight some of its achievements. We then summarize how the NW architecture adheres to principles of honing theory and CAS, and how this contributes to the appealing musicality of its output.

Honing Theory: Creativity as a Complex Adaptive System

The honing theory (HT) of creativity (Gabora 2010, in press) has its roots in the question of what kind of structure could evolve novel, creative forms effectively and strategically (as opposed to at random). We now summarize the elements of the theory most relevant to NetWorks.

Self-Organization

Humans possess two levels of complex, adaptive, structure: an organismic level and a psychological level, i.e., a mind (Pribram 1994). Like a body, a mind is *self-organizing:* a new stable global organization can emerge through interactions amongst the parts (Ashby 1947; Carver and Scheier 2002; Prigogine and Nicolis 1977). The capacity to self-organize into a new patterned structure of relationships is critical for the generation of creative outcomes (Abraham 1996; Goertzel 1997; Guastello 1998). The mind’s self-organizing capacity originates in a memory that is distributed, content addressable, and sufficiently densely packed that for any one item there is a reasonable probability it is similar enough to some other item to evoke a reminding of it, thereby enabling the redescription and refinement of ideas and actions in a stream of thought (Gabora, 2010). Mental representations are distributed across neural cell assemblies that encode for primitive stimulus features such as particular tones or timbres. Mental representations are both constrained and enabled by the strengths of connections between neurons they activate.

Just as a body mends itself when injured, a mind is on the lookout for ‘gaps’—arenas of incompletion or inconsistency or pent-up emotion—and explores the gap from different perspectives until a new understanding has been achieved. We can use the term *self-mending* to refer to the capacity to reduce psychological entropy in response to a perturbation (Gabora, in press), i.e., it is a form of self-organization involving reprocessing of arousal-provoking material. Creative thinking induces *restructuring* of representations, which may involve re-encoding the problem such that new elements are perceived to be relevant, or relaxing goal constraints. However, according to HT, the transformative impact of immersion in the creative process can bring about sweeping changes to that second (psychological) level of complex, adaptive structure that alter one's self-concept and view of the world.

Edge of Chaos

Self-organized criticality (SOC) is a phenomenon wherein, through simple local interactions, complex systems find a critical state poised at the transition between order and chaos—the proverbial *edge of chaos*—from which a small perturbation can exert a disproportionately large effect (Bak, Tang, and Weisenfeld 1988). It has been suggested that insight is a self-organized critical event (Gabora 1998; Schilling 2005). SOC gives rise to structure that exhibits sparse connectivity, short average path lengths, and strong local clustering. Other indications of SOC include long-range correlations in space and time, and rapid reconfiguration in response to external inputs. There is evidence of SOC in the human brain, e.g., with respect to phase synchronization of large-scale functional networks (Kitzbichler, Smith, Christensen, and Bullmore 2009). There is also evidence of SOC at the cognitive level; word association studies show that concepts are clustered and sparsely connected, with some having many associates and others few (Nelson, McEvoy, and Schreiber 2004). Cognitive networks exhibit the sparse connectivity, short average path lengths, and strong local clustering characteristic of self-organized complexity and in particular 'small world' structure (Steyvers and Tenenbaum 2005).

Like other SOC systems, a creative mind may function within a regime midway between order (systematic progression of thoughts), and chaos (everything reminds one of everything else). Much as most perturbations in SOC systems have little effect but the occasional perturbation has a dramatic effect, most thoughts have little effect on one's worldview, but occasionally one thought triggers another, which triggers another, and so forth in a chain reaction of conceptual change. This is consistent with findings that large-scale creative conceptual change often follows a series of small conceptual changes (Ward, Smith, and Vaid 1997), and with evidence that power laws and catastrophe models are applicable to the diffusion of innovations (Jacobsen and Guastello 2011).

Contextual Focus

Psychological theories of creativity typically involve a divergent stage that predominates during idea generation and a convergent stage that predominates during the refinement, implementation, and testing of an idea (for a review see Runco 2010; for comparison between divergent / convergent creative processes and dual process models of cognition see Sowden, Pringle, and Gabora 2015). *Divergent thought* is characterized as intuitive and reflective; it involves the generation of multiple discrete, often unconventional possibilities. It is contrasted with *convergent thought*, which is critical and evaluative; it involves tweaking of the most promising possibilities. There is empirical evidence for oscillations in convergent and divergent thinking, with a relationship between divergent thinking and chaos (Guastello 1998). It is widely believed that divergent thought involves defocused attention and associative processing, and this is consistent with the literal meaning of divergent as "spreading out" (as in a divergence of a beam of light). However, the term divergent thinking has come to refer to the kind of thought that occurs during creative tasks that involve the generation of multiple solutions, which may or may not involve defocused attention and associative memory. Moreover, in divergent thought, the associative horizons simply widen generically instead of in a way that is tailored to the situation or context (Fig. 2). Therefore, we will use the term *associative thought* to refer to creative thinking that involves defocused attention and context-sensitive associative processes, and *analytic thought* to refer to creative thinking that involves focused attention and executive processes. The capacity to shift between these modes of thought has been referred to as *contextual focus* (CF) (Gabora 2010). While some dual processing theories (e.g., Evans 2003) make the split between automatic and deliberate processes, CF makes the split between an associative mode conducive to detecting relationships of correlation and an analytic mode conducive to detecting relationships of causation. Defocusing attention facilitates associative thought by diffusely activating a broad region of memory, enabling obscure (though potentially relevant) aspects of a situation to come to mind. Focusing attention facilitates analytic thought by constraining activation such that items are considered in a compact form amenable to complex mental operations.

According to HT, because of the architecture of associative memory, creativity involves not searching and selecting amongst well-formed idea candidates, but amalgamating and honing initially ill-formed possibilities from multiple sources. As a creative idea is honed, its representation changes through interaction with an internally or externally generated contexts, until psychological entropy is acceptably low. The unborn idea is said to be in a 'state of potentiality' because it could actualize different ways depending on the contextual cues taken into account as it takes shape.

The NetWorks System

NW consists of a music-generating system and the music it has produced. The goal of NW is to generate "emergent music," i.e., self-organizing, emergent dynamics from simple rules of interaction, expressed in musical forms. In terms of creative agency, NW has been designed as a closed, autonomous system while generating MIDI data. In selecting the network architecture and interaction rules, the artist-user may be viewed as the system's mentor. The MIDI data generated by the system is orchestrated and mixed by the artist-user, who may be viewed in this role as a collaborator (McCormack and d'Inverno 2014).

Network theory, as it pertains to the study of complex adaptive systems (Mitchell 2006) was used in the design of the NW system. NW is currently configured to explore the expressive potential of hierarchical scale-free networks, as the properties of such networks underlies the interesting dynamics of many real world networks, from the cell to the World Wide Web (Barabási 2002). Moreover, a variety musical genres exhibit a scale-free structure (Liu, Tse & Small 2009). Assuming that constraints define genre, the generation of "emergent music" is primarily a search for new genres. Given the ubiquity of hierarchical scale-free topology and dynamics found in CAS it is not surprising that such architecture have creative potential. In NW, the components mutually constrain and enable one another: *nodes* represent the components of a system, and *links* represent the couplings between them. Connected nodes interact through an exchange of values, which change the states of the nodes as well as the state of a network as a whole.

Since in complex systems science the term "hierarchical" often indicates top-down control, the use of hierarchical networks might appear to be at odds with the goal of generating complex emergent behaviour. However, in this model, communication and control flow both top-down and bottom-up between connected nodes. The architecture consists of *clusters* of interconnected nodes, connected by *hubs*, such that the nodes within a hub are more interconnected than nodes between hubs. A hub contributes input to—and thus co-determines—the next state (output value) of the nodes to which it is connected. Likewise, these connected nodes contribute input to—and thus co-determine—the next state of the hub.

Since NW MIDI data is computer-generated, sampled acoustic instruments are often used to give the music a "human feel", and to help the listener to relate and compare the self-organizing output patterns of NW to known genres. In general, the sounds chosen to manifest the musical patterns discovered by the network attempt to reflect the mystery and wonder that virtually unlimited diversity can come from such simple interactive models. When mapping patterns to sound, an effort is made to preserve the integrity of the patterns rather than obfuscate them with complex synthetic textures or other effects (such as echo effect) that are readily available during mixing. NW is composed of two layers:

1. The *Core,* which allows users to define how nodes are connected, as well as the rules that determine when and how nodes respond to their inputs, and
2. The *Mapping Layer,* which allows the user to map node output values to MIDI data that are routed to software instruments in a Digital Audio Workstation (DAW).

We now discuss these two layers in more detail.

The Core

There are several aspects to the core: the relationship between the architecture and the functions, the rules, and the relationship between the architecture and the rules. We now discuss each of these in turn.

Relationship between Architecture and Functions NetWorks consists of 64 nodes linked together in a scale-free architecture (see diagram below). There are four, 16 node modules: one for pitch, velocity, duration and entry delay (ED). The nodes that comprise the pitch module, are responsible for producing "notes". A note has five basic attributes: pitch, loudness (usually corresponding to MIDI "velocity"), duration, timing (or entry delay), and timbre. Pitch nodes output values for pitch, but require values for velocity and duration to produce a note. These values are provided by the nodes that comprise the velocity and duration modules. The pitch modules is unique in that it includes the largest hub, which sends its output to, and receives inputs from, 40 nodes: 12 pitch nodes, 9 nodes each from the duration, velocity, and ED modules, and itself. The pitch node, as well as all other nodes in the network, receive their own outputs to participate in, and trigger the calculation of, its next output.

The ED module is responsible for keeping corresponding nodes of the four modules synchronized (see the diagram below). When a pitch node is activated, as determined by the delay value it receives from its ED module node, the corresponding velocity and duration module nodes are activated simultaneously to provide the values required to specify a "note". The function of the ED module is to determine timing, that is, *when* nodes produce an output, and therefore the pattern of activation across the network as a whole. In musical terms, the entry delay module generates rhythmic patterns, phrases and sections.

Note that nodes receive values from, and send values to, nodes in other modules. In this way, note attributes affect one another. For example, the output values of the nodes that comprise the ED module are determined by the values they receive from pitch, duration, and velocity module nodes. The output values of the nodes that comprise the pitch module are determined by the values they receive from ED, velocity and duration module nodes, and so on.

The timbral characteristics of the notes produced by the network can be partially controlled by mapping various network and module activities to selected synthesis parameters of the software instruments chosen by the user.

When the nodes are fully connected, that is, receiving values on all their inputs, the network architecture is scale-free; however users can prune the connectivity of the network by reducing the number of inputs to the nodes.

Rules When activated, nodes sum the last values received on their inputs and use a lookup table (LUT) to determine the value to output. The number of values (or states) that can be output by the nodes is determined by the user. Experiments have used 13 and 25 values which allows for pitch to be mapped chromatically across one and two octaves respectively, and provide the same number of equivalent scale steps for velocity, duration and entry delay. However, the user can map the output values across any desired range.

NetWorks has been designed to allow:

1. each node to have its own LUT;
2. an LUT for each module;
3. one LUT for all the nodes of the network.

LUTs are generated using a variety of methods: random, random without repetition, ratios, etc.

Relationship between Architecture and Rules Two observations can be made regarding the relationship of rules and network architecture. First, when the network is scale-free, nodes have either 4, 5, 6, 15 or 40 inputs. Each input on a node can receive a range of values, determined by the user, which are then summed to determine an output value. This means the range of output values is always less than the range of summed values. For example, if the number of values that can be output by the nodes is set to 13 (e.g. 0–12), a node with four inputs will require an LUT with an index of 48 to store values for all possible sums, a node with 5 inputs will require a LUT with an index of 60, and so on. The largest hub with 40 inputs requires a LUT with an index of 480, but can only output 13 values (0–12), resulting in a loss of "information". Put another way, the hub can distinguish between 480 inputs states, but can only respond with 13 different outputs.

Second, while hubs have a wider "sphere of influence" because their output is received by a greater number of nodes, hubs also receive input from the same nodes, which means they have an equal number of inputs that co-determine their outputs. However, the more connected the hub, the more inputs it sums, and the less able it is to respond with unique outputs. While less well-connected nodes have a smaller "sphere of influence", their ability to distinguish between their inputs with unique outputs is significantly greater.

MIDI Mapping

The number of values (or states) of the nodes is determined by the user. The MIDI Mapping layer allows users to map these output values across appropriate MIDI ranges. For example, If nodes are set to output 12 values:

1. outputs from pitch nodes can be mapped to a chromatic scale (e.g. C4–B4);
2. velocity node outputs can be mapped to 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120 MIDI values;
3. duration node outputs can be mapped to an arbitrarily chosen fixed range (e.g., 100, 150, 200, 250, 300 … 650 milliseconds) or a duration based on a subdivision of the entry delay times between notes.
4. Entry delays values between notes are scaled to an appropriate musical range in milliseconds.

In addition to generating the basic attributes of notes, NetWorks provides for mapping network activity to MIDI cc control data to control various synthesis parameters such as filters, and so forth, chosen the user. However, currently these outputs do not feedback into the network. 64 nodes, organized into four 16 node module clusters allows for 16 channels of MIDI data (Figure 1).

Rules can be constructed to favour certain output values. At the extreme, a rule table could output the same value for any input. Unless a node has only one input (and that would have to be the one from itself, otherwise the node would never "fire") they can be thought of as "funnels," always reducing the specifics of their inputs. Nodes do not care which nodes send what values to their inputs; they simply sum the last values received and pass them on after an entry delay time. As feedback happens in time, where nodes may introduce previously stored values into the current stream of activations, the network dynamic as a whole must adjust (or "adapt") to "old ideas."

There are many ways inputs can sum to the same value. Nodes with rule tables that favour certain output values are less discriminating (lower resolution). Hubs are always less discriminating since they have more inputs, but the same vocabulary (number of possible output values). Nodes with fewer inputs and an equal distribution of output values across input sums are more discriminating (higher resolution). The interaction between nodes almost always results in an open-ended (endless) stream.

Evaluation of NW Output

To date, two albums have been produced using the NetWorks system: "NetWorks 1: Could-be Music" and "Networks 2: Phase Portraits", which can be heard online:

- https://shawnbell.bandcamp.com/album/networks-1-could-be-music
- https://shawnbell.bandcamp.com/album/networks-2-phase-portraits

The most recent experiments can be found here:

- https://soundcloud.com/zomes

It is possible to modulate the output dynamics of NW from complete order (and thus repetition without change) to complete chaos (and thus no element of predictability). The musicality of the output is greatest when the system is tuned to an intermediate between these extremes, i.e., the proverbial 'edge of chaos.' At this point there is a pleasing balance between familiar, repeating patterns, and the desire for novelty and surprise. The system often generates motifs that repeat, vary, and develop into more complex melodies, as well as return to their original form.

The distribution of node LUTs output values is the determining factor in balancing uniformity and variety. Trivially, if all nodes output the same value, whatever the sum of their inputs, the MIDI output is uniformly repetitive. A random distribution of node LUT output values results in random MIDI output.

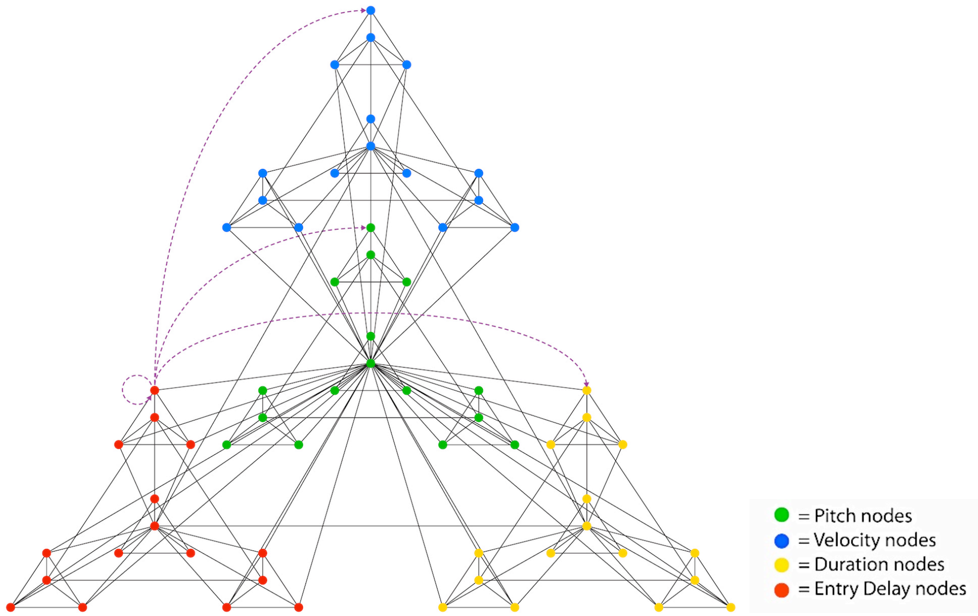

Figure 1. Schematic illustration of the different kinds of nodes and their interrelationships. Undirected edges (in black) indicate that values can be exchanged in both directions, i.e.,nodes both send values to, and receive values from, nodes to which they are connected. Directed edges (purple) show the relationship between individual nodes of the Entry Delay module and the corresponding nodes of other modules. The ED module node determines *when* it will activate itself, and the corresponding node in the duration, velocity, and pitch modules. For clarity, only one of the 16 ED nodes and its four corresponding nodes are shown.

Shannon Entropy was used to compare NW MIDI data sequences generated with rules having a random distribution of output values with MIDI data generated using node LUTs that output (mostly) the same value when activated. Entropy was also used to compare NW pieces to other genres of music to confirm subjective comparisons. Entropy is a good measure of the unpredictability / complexity in data sequences. As a simplified data sequence, music has two features: the range of notes, i.e., pitch/duration pairs, and repetitiveness of notes. Entropy values capture the degree of variety and repetitiveness of note sequences in MIDI data. Roughly speaking, high entropy indicates surprising or unpredictable musical patterns while low entropy indicates predictable, repeating musical patterns (Ren 2015).

In this analysis, the entropy of a piece was calculated by counting the frequency of musical events, specifically the appearances of each note (pitch-duration pair), as well as pitch and duration separately to get the discrete distribution of those events. Equation 1 was used to calculate the information content of each note. The expectation value of the information content, defined as $-logp(x_i)$, was used to obtain the entropy. The entropy is related to the frequency of musical events in a specific range. Differences in entropy values stem from differences of (1) the underlying possibility space size, i.e. how many different types of musical events there are, and (2) how repetitive they are. Although this does not take into account the order of events it provides a general characterization useful for comparing musical sequences (Ren 2015).

$$H(X) = -\sum_i p(x_i) logp(x_i), i \in n = outcomes \quad (1)$$

In Figure 2, the entropy value of ten NW pieces (x-tick=3) is compared with Bach's chorales (x-tick=1) and with jazz tunes (x-tick=2). In terms of entropy, NW pieces are closer to jazz than to Bach, which confirms informal subjective evaluations of NW music. X-tick=4 shows the entropy value for three NW pieces generated using a random distribution of LUT output values and x-tick=5 shows the entropy values of three NWs pieces with near uniform LUTs. These values verify the relationship between NW MIDI outputs and the LUTs that generate them.

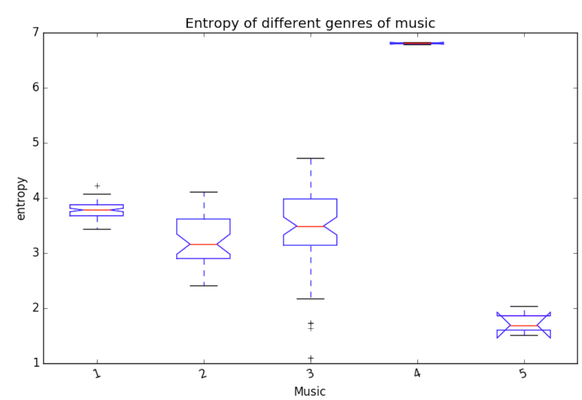

Figure 2. Comparison of entropy of ten NW pieces (x-tick=3) with Bach chorales (x-tick=1) and jazz tunes (x-tick=2).

Evaluation of NW music via social media (SoundCloud), shows an increasing interest in NW music from what is quite likely a diverse audience given the wide range of social-media groups to which NW music has been posted (e.g., classical, jazz, electronic, experimental, ambient, film music, algorithmic music, creative coding, complex systems, etc.). There has been a steady growth of "followers" over the two years (2014-2016) of posting NW pieces (28 tracks). As of the writing of this paper, NW has 307 followers. 7,418 listens, 796 downloads, 330 likes, 24 reposts, and 53 comments (all of which are positive).

As a search for "music-as-it-could-be," (e.g., new genres) a comment from SoundCloud indicates this goal may have been attained: "What can I say except I think I like it?" This suggests that the person has heard something they cannot categorize, but that sounds like good music.

How NetWorks Implements Honing Theory

We now summarize how the NetWorks (NW) architecture and outputs adhere to and implement ideas from honing theory (HT), a theory of creativity inspired by chaos theory and the theory of complex adaptive systems (CAS).

NW as Creative, Self-Organizing Structure

NW is hardwired to exhibit the key properties of real-world complex systems through it's modular, scale-free, small-world properties. NW architecture has a shallow, fractal, self-similar structure (4 node, 16 node, and 64 node modules) which allows multiple basins of attraction to form in parallel, over different timescales, and interact.

NW networks are not neural networks; they do not adapt or learn by tuning weights between nodes through experience or training, nor do they evolve; nodes simply accept input and respond. Their rules of interaction do not change, adapt, or self-organize over time, but their structure does.

Just like an experience or realization can provide the 'seed incident' that stimulates creative honing, the pseudo-randomly generated initial conditions provide 'seed incidents' that initiate NW processing. After NW receives its inputs it is a closed system that adapts to itself (self-organizes). Musical ideas sometimes unfold in an open-ended manner, producing novelty and surprise, both considered hallmarks of emergence. A diversity of asynchronous interactions (sometimes spread out in time) can push NW dynamics across different basins of attraction. Idea refinement occurs when users (1) generate and evaluate network architectures, rule-sets and mappings, and (2) orchestrate, mix, and master the most aesthetically pleasing instances of these outputs. The role of mental representation is played by notes—their basic attributes as well as attributes formed by their relationships to other notes.

Cellular Automata-like Behavioral Classes NW nodes have a significantly different topology from Cellular Automata (CA). While CA have a regular lattice geometry, NW has a hierarchical (modular), scale-free, small-world structure. Moreover, unlike CAs, NW is updated asynchronously. However, similar to CA, NW exhibits Wolfram's class one (homogenous), class two (periodic), class three (chaotic), and class four (complex) behaviour, and—rather than converging to a steady state—tends to oscillate between them. This is because the nested architecture of NW allow multiple basins of attraction to form in parallel and over different timescales. Pruning the scale-free architecture by reducing the inputs to hubs insulates clusters and modules from one another, reducing their interactions. Network dynamics within a basin of attraction can get pushed out of the basin by delayed values entering the system. In other words, because in the context of the current pattern an "old ideas" can push the dynamics to a different basin, the system exhibits "self-mending" behavior. This can result in musical transitions that lead to the emergence of new patterns and textures.

Representational Redescription The network "makes sense" of its present in terms of its past by adapting to delayed values or "old ideas" entering the current pattern of activations. NW nodes hone by integrating and simplifying inputs from multiple sources, and returning a particular value. In NW, a catalyst or "catalytic value" is one that needs to be received on the inputs of one or more nodes to maintain one or more periodic structure (perhaps playing a different role in each). As NW strings notes together (often in parallel) in a stream of music, its nodes act on and react to both the nodes in their cluster, and to other clusters, via their hubs. Bottom-up and top-down feedback and time-delayed interactions are essential for an open-ended communal evolution of creative novelty.

Periodic structures are often disrupted (stopped or modified) by the introduction of a new (delayed) value, although sometimes this does not affect output. As interactions between nodes occur through entry delays, periodic musical structures unfold at different timescales. Slowly evolving periodic structures can be difficult to hear (due to intervening events) but can have a "guiding" effect on the output stream, i.e., they affect what Bimbot, Deruty, Sargent, and Vincent (2011) refer to as the "semiotic" or high-level structure of the music emerging from long term regularities and relationships between its successive parts.

NW creates musical "ideas" that become the context for their further unfolding. Asynchrony, achieved by the (dynamically changing) values of the nodes in Entry Delay Module allow previously calculated node values (including their own) to be output later in time. NW outputs both manifests the dynamics of the network, and in turn generate the dynamics. As with the autopoietic structure of a creative mind, NW is a complex system composed of mutually interdependent parts.

Let us examine how this applies to the process by which the dynamics of a NW network could be said to like a creative mind, become autocatalytically closed. The nodes collectively act as a memory in the following sense. When a node is activated, it sums the last values received on its inputs and uses the sum to output the stored value (which is then delayed before being sent to receiving nodes). Nodes are programmed so that their individual inputs can only store or "remember" the last value received. However, because nodes have 3, 4, 5, 14 and 39 inputs (excluding their own), and the network is asynchronous, a node (as a whole) can "remember" values spread out over time. How long a node can remember depends on its own ED value and the ED values of the nodes that participate in co-determining its output. It is important to note, however, that nodes can also "forget" much of the information they receive, if, for example, it receives a number of different values on the same inputs since only the last ones are used when the node is activated. Again, how much they forget depends on its own ED value and the ED values of the nodes to which it is linked.

These NW memory patterns are distributed across the network. They are self-organizing because they can recur with variation, such that the whole is constantly revising itself. NW chains items together into a stream of related notes / note attributes. As NW strings notes together in a stream of music, its nodes are acting on and reacting to (feeding-back and feeding-forward information) to and from both the nodes in their cluster and to other clusters via their hubs. It would seem that bottom-up, top-down and time-based interaction / feedback are essential for an open-ended communal evolution of creative novelty.

There are many ways inputs can sum to the same value. Nodes with rule tables that favour certain output values are less discriminating (lower resolution). Hubs are always less discriminating since they have more inputs, but the same vocabulary (number of possible output values). Nodes with fewer inputs and an equal distribution of output values across input sums are more discriminating (higher resolution). The interaction between nodes (individuals) almost always results in an open-ended (endless) stream.

Contextual Focus

Some of NW's music sounds uninspired; it contains no surprising pattern development (e.g., a sudden transition or gradually modulated transition in texture, mood, or tempo), and/or the patterns do not elicit innovative variations. To minimize this problem, NW uses an architecture that, in its own way, implements contextual focus. Clusters of nodes that are more interlinked and share a similar rule tables process in a more analytic mode. Hubs, which connect clusters into a small-world network and merge more distantly related musical ideas, process in a more associative mode. Because clusters have fewer inputs than hubs they are more discriminating than hubs. Hubs act as funnels, summarizing or simplifying the information its receives from multiple sources. Thus NW is hardwired to shift between analytic and associative modes by modulating the relative influence of top-down and bottom up processing.

Edge of Chaos

NW structures transform as they propagate in time, and as mentioned above, all four behavior classes have been observed. Class one and two dynamics do not change unless disrupted. When NW exhibits analytic processing, output streams flows toward class two behaviour. When NW exhibits associative processing it flows toward Class three (deterministic chaos) which does not repeat if unbounded. Class four (edge of chaos) balances change and continuity.

Network dynamics often sound chaotic at the beginning of a piece–set in motion from an arbitrary, initial configuration ('seed incident'). Repetition and development of motivic materials and/or melodic lines then moves the system toward one or more attractor(s) (or "grooves"), resulting in a more stable, organized musical texture. Nodes with different rules of interaction are apt to disturb the system, pushing it into another basin. If it returns to a basin, a similar texture returns. When tuned to midway between order and chaos, the global stable dynamics are repeatedly disturbed. This pushes it either (1) into another basin, creating a transition to contrasting musical material, or (2) further from the attractor, to which it tries to return. NW exhibits something akin to goal seeking behaviour in how it moves toward or away from an attractor by keeping within a range of "desirable" values. This is similar to the use of functional tonality in western music, in which a piece departs and returns to its tonal center. Quasi-periodic dynamics provide a sense of organization through cycling musical textures, or a loose theme and variation structure. These disturbances may be caused by nodes with different rules of interaction, or by delayed values entering the stream. One factor that affects the aesthetic quality of the output is the mapping of the node output values to a specific ED scale (mapped values are used to delay node outputs). This appears to produce a balance between current events and older ones that is at the proverbial edge of chaos.

Conclusions and Future Directions

NW's unique architecture—in particular, its scale-free network architecture and transparent relationship between rules of interaction (LUTs) and MIDI output—was inspired by the science of complex adaptive systems as advocated by the honing theory of creativity. The number of possible LUTs that can generate "edge of chaos' dynamics, however, is extremely large and "by hand" rule design and "by ear" verification of the results should be augmented by evolutionary programming techniques guided by quantitative analyses. NW will also continue incorporating principles of HT. In turn, grounding the theory using NW is inspiring new developments in the understanding of creativity.

Acknowledgements

Many thanks to Iris Yuping Ren for providing the entropy analysis of NetWorks music, Bach chorales and jazz tunes.

This research was supported by a grant from the Natural Sciences and Engineering Research Council of Canada.

References

Abraham, F. D. 1996. The dynamics of creativity and the courage to be. In W. Sulis & A. Combs (Eds.), *Nonlinear dynamics in human behavior*. River Edge, NJ: World Scientific, 364-400.

Ashby, W. 1947. Principles of the self-organizing dynamic system. *Journal of General Psychology* 37:125-128.

Bak, P., Tang, C., and Weisenfeld, K. 1988. Self-organized criticality. *Physical Review A* 38:364.

Barábasi, A. L. 2002. *Linked: The New Science of Networks.* New York: Perseus.

Bell, S. 1998. *Emergent Music I: Voices From The Edge of Chaos.* Polycarpe Studios: EM001.

Beyls, P. 1989. The musical universe of cellular automata. In Wells, T. & Butler, D., eds., *Proceedings of the International Computer Music Conferenc*e, 34–41.

Beyls, P. 1990. Musical morphologies from self-organizing systems. *Interface: Journal of New Music Research* 19(2-3): 205–218.

Beyls, P. 1991. Self-organizing control structures using multiple cellular automata. *Proc Intnl Computer Music Conf*. Montreal: Intnl Computer Music Assoc. 254–257.

Bimbot, F.; Deruty, E.; Sargent, G.; and Vincent, E. 2011. Methodology and resources for a structural segmentation of music pieces into autonomous and comparable blocks. *Proc Intl Soc Music Information Retrieval Conf* 287–292.

Bowcott, P. 1989. Cellular Automata as a means of high level control of granular synthesis. In Wells, T. & Butler, D., eds., *Proc Intl Comp Music Conf*. San Francisco: ICMA. 55–57.

Carver, C., and Scheier, M. 2002. Control processes and self organization as complementary principles underlying behavior. *Personality and Social Psych Review* 6:304–315.

Chareyron, J. 1990. Digital synthesis of self-modifying waveforms by means of linear automata. *Computer Music Journal, 14*(4):25–41.

Evans J. St. B. 2003. In two minds: dual process accounts of reasoning. *Trends in Cognitive Science* 7: 454-59.

Gabora, L. 1998. Autocatalytic closure in a cognitive system: A tentative scenario for the origin of culture. *Psycoloquy, 9*(67). [adap-org/9901002]

Gabora, L. 2010. Revenge of the 'neurds': Characterizing creative thought in terms of the structure and dynamics of human memory. *Creativity Research Journal* 22:1–13.

Gabora, L. (in press). Honing theory: A complex systems framework for creativity. *Nonlinear Dynamics, Psychology, and Life Sciences*.

Goertzel, B. 1997. *From complexity to creativity*. New York: Plenum Press.

Guastello, S. J. 1998. Creative problem solving at the edge of chaos. *Journal of Creative Behavior* 32:38–57.

Horner, A. & Goldberg, D. E. 1991. Computer-Assisted composition. *Fourth International Conference on Genetic Algorithms*. University of California, San Diego, CA.

Horowitz, D. 1994. Generating rhythms with genetic algorithms. *Proceedings of the International Computer Music Conference.* Aarhus, Denmark.

Kitzbichler, M. G., Smith, M. L., Christensen, S. R., and Bullmore, E. 2009. Broadband criticality of human brain network synchronization. PLoS Computational Biology, 5.

Liu, X. F, Tse, C. K., and Small, M. 2010. Complex network structure of musical compositions: Algorithmic generation of appealing music. Physica A 38: 126–132.

McCormack, J & d'Inverno, M. 2014. On the Future of Computers and Creativity. Symposium on Computational Creativity, AISB: Goldsmiths, University of London.

Millen, D. 1992. Generation of formal patterns for music composition by means of cellular automata. In Strange, A., ed., Proc Intl Comp Music Conf. San Francisco: ICMA, 398–399.

Miranda, E. R. 1995. Granular synthesis of sounds by means of a cellular automaton. Leonardo 28(4):297–300.

Mitchell, M. 2006. Complex systems: Network thinking. Artificial Intelligence, 170(18): 1194–1212.

Nelson, D. L., McEvoy, C. L., & Schreiber, T. A. 2004. The University of South Florida free association, rhyme, and word fragment norms Behavior Research Methods, Instruments, & Computers 36(3):402–407.

Pribram K.H. 1994. Origins: brain and self-organization. Hillsdale NJ: Lawrence Erlbaum.

Prigogine, I., & Nicolis, G. 1977. *Self-organization in non-equilibrium systems*. New York: Wiley.

Ren, I Y. 2014. Complexity of Musical Patterns. University of Warwick.

Ren, I Y. 2015. Using Shannon Entropy to evaluate automatic music generation systems: A Case Study of Bach's Chorales. ECE Department, University of Rochester.

Runco, M. 2010. Divergent thinking, creativity, and ideation. In J. Kaufman and R. Sternberg, (Eds.), The Cambridge handbook of creativity. Cambridge UK: Cambridge University Press, 414–446.

Sowden, P., Pringle, A., and Gabora, L. 2015. The shifting sands of creative thinking: Connections to dual process theory. *Thinking & Reasoning* 21:40–60.

Steyvers, M., and Tenenbaum, J. B. 2005. The large-scale structure of semantic networks: Statistical analyses and a model of semantic growth. *Cognitive Science* 29:4–78.

Todd, P. M. and Loy, G., eds. 1991. *Music and Connectionism*. MIT Press.