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A Framework for Understanding Generative Art

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Jonathan McCabe is a visual generative artist interested in processes that spontaneously produce pattern, for example reaction-diffusion or Turing patterns, particularly for use in surface design. He is currently a PhD student in the Faculty of Arts and Design at the University of Canberra, comparing generative art/design processes and trying to develop heuristics about their relative productivity. His work appears in the books *Form+Code in Design, Art, and Architecture* (Princeton Architectural Press 2010) and *Written Images* (Druckerei Dietrich AG 2011), and he was one of the winners of the *Fushionwear SV* fabric design contest (2010).

Jon McCormack is an Australian-based electronic media artist and researcher in artificial life and evolutionary music and art. His research interests include generative evolutionary systems, computational creativity, machine learning, L-systems and developmental models. He holds an Honours degree in Applied Mathematics and Computer Science from Monash University, a Graduate Diploma of Art from Swinburne University and a PhD in Computer Science from Monash University. He is currently Associate Professor in Computer Science and co-director of the Centre for Electronic Media Art (CEMA) at Monash University in Melbourne, Australia. CEMA is an interdisciplinary research centre established to explore new collaborative relationships between computing and the arts.

Gordon Monro is a digital media artist who has created digital prints, abstract videos and computer-based installations and composed musical works, both computer-generated and for acoustic instruments. Most of his work has been generative in character, using computer programs Gordon has written, and much of it relates in some way to concepts from mathematics and science. Gordon's works have been exhibited or performed in Australia, New Zealand, Europe, Asia and the Americas, and broadcast nationally in Australia. He is currently undertaking a PhD in the Faculty of Art and Design at Monash University in Melbourne, Australia, working in generative art.

Mitchell Whitelaw is an academic, writer and artist with interests in new media art and culture, especially generative systems and data-aesthetics. His work has appeared in journals including *Leonardo*, *Digital Creativity*, *Fibreculture*, and *Senses and Society*. In 2004 his work on a-life art was published in the book *Metacreation: Art and Artificial Life* (MIT Press, 2004). His current work spans generative art and design, digital materiality, and data visualisation. He is currently an Associate Professor in the Faculty of Arts and Design at the University of Canberra, where he leads the Master of Digital Design.

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Abstract

In this paper we argue that a framework for the description, analysis and comparison of generative artworks is needed. Existing ideas from kinetic art and other domains in which process description is prominent are shown to be inadequate. Therefore we propose a new framework that meets this need and facilitates the long-term aim of constructing a comprehensive taxonomy of generative art. Our framework is divided into four major components: a description of a work's entities, its processes and their environmental interactions, and lastly, the outcomes experienced by the work's audience. We describe a set of diverse generative artworks in terms of our framework, demonstrating how it can be applied in practice to compare and contrast them.

Keywords: generative art; mapping; experimental music; kinetic art; taxonomy

1 Introduction

This paper proposes a new framework to coherently describe and critique generative art, in all its media and forms. "Generative art refers to any art practice where the artist uses a system … which is set into motion with some degree of autonomy contributing to or resulting in a completed work of art" (Galanter 2003). Art more generally can be categorised according to the media employed in its production, by the issues that its presence addresses, by the period in which it is made, or perhaps by its stylistic conformity to recognised abstract concepts that can be described in terms of genres. How might we apply such existing classifications of art to generative art? To an extent, traditional approaches make some headway in this context. But what can be done when the frameworks for classifying and critiquing most art become difficult or cumbersome to apply in this context, or, at worst, completely irrelevant? We propose here that in order to theorise about generative art effectively, a new framework is required, one uniquely suited to the description and analysis of generative art's core – dynamic processes.

Generative art is neither technological, nor specifically digital, despite the recent popularity of works that are both. In various guises, generative processes have been long evident in art, far predating the current era of the digital computer. From Paleolithic ornamental art (Jablan 2002, p. 102) and hydraulically-activated automata (Hero 1st C AD) of ancient Rome, Islamic art ca. the 9th century (Lee 1987, p. 185-186), through to medieval and Renaissance clockwork figures (Rosheim 2006); then the *harmonograph* in the 19th century, and the cybernetic sculptures of Ihnatowicz (1986) and Pask (Bird and Paolo 2008) of the 1960s, all of these are examples of works with generative processes as their basis.

In the 1960s conceptual and performance art practices with a focus on process emerged. These often used generative means. Artists like Sol Le Witt and composers such as Cornelius Cardew, specified their work as algorithms to be interpreted and executed by others. E.g., *"Tune a brook by moving the stones in it"* (Cardew 1974).

The digital computer provided a new means of describing and encoding processes and an increasingly accelerated capacity to execute them (Dietrich 1985). This century, popular creative programming environments such as *Processing* (www.processing.org) have ushered forth a new generation of procedurally literate artists and designers. However while code-based approaches offer great flexibility in the creation of generative art, this is not reflected in the diversity of current practice. Much work is based on established, readymade systems and algorithms: particle systems, cellular automata, physical simulations, and so on. We recognise the pedagogical value of imitation, but we are concerned that these systems operate as "black boxes" whose internal operations are obscure to the artists and designers using them.

While the tools and infrastructure to support computational generative art have undergone rapid development and acceptance, fewer resources have been devoted to the practice's classification and critical understanding. The aim of the framework we introduce here is to address this gap in generative art theory by inviting a critical and creative literacy in generative systems. This enables artists and designers to deconstruct existing generative systems, as well as devise generative systems with new attributes.

The need for our framework originated with a desire to provide a comprehensive taxonomy of processes used in generative art. There have been a number of attempts to classify and provide taxonomies of processes in related disciplines. But, to our knowledge, a comprehensive analysis and classification of the processes employed is yet to be undertaken. We discuss related work in §3.

Our early attempts to develop such a classification found no shortage of organisational possibilities along with hundreds of different kinds of processes in active use. A significant problem was comparing different processes, particularly as generative artworks span diverse mechanisms, media and forms of specification. We realised that before a taxonomy could be created a strong descriptive framework capturing the "generative" aspect of the works was required.

2 Why a framework?

Almost all discussions around art involve frameworks, even if they are implicit. Common elements include a language-based description of the work, the media, date of execution and a work's possible meanings. Artistic statements or interpretations of the artist's circumstances and methodology are also commonly included. However, approaches to discussing art generally do not adequately capture features important for process-based works, preventing deeper and richer comparisons.

A broadly applicable framework for generative art is essential because, as described above, there is wide variation in the works themselves. Comparisons, the fundament of critique and comment in any domain, are awkward without a shared framework. For instance, how do we compare Cornelius Cardew's *The Great Learning, Paragraph 7* (a generative musical composition enacted by a group of singers) with Casey Reas' *Process 18* (a software-based line drawing system)? The medium and experience of these works appear to be quite different. Yet when we look carefully we find that the underlying generative processes are remarkably similar. A framework enables us to begin such a conversation. It often reveals previously unnoticed similarities and associations. It gives us the ability to discuss a broad range of works in a consistent way.

3 Related work

There have been a number of important attempts at developing "process taxonomies" in different disciplines, most notably from biology, the kinetic and time-based arts, and computer science. Table I summarises a few.

Author	**Inspired by ... Applied to ...**	**Features**	**Example classifications**
(Thompson 1917)	Biology.	Description of form from a physical and biological perspective. Focus on physical processes that generate shape and form.	Animal morphology; minimal surfaces; parameterised structural relationships of shells and horns.
(Stevens 1979)	Nature and natural processes, architecture.	Decomposition of all structural form to five basic process types.	Spirals, meanders, branches, explosions, non-linear packing and cracking, flows, minimal surfaces.
(Volk 1995)	Space, time and mind.	Discusses reappearance of meta-patterns across a variety of physical and conceptual systems.	Sheets, tubes, spheres, arrows, breaks, cycles, layers.
(Ball 2001)	Biology, chemistry, physics, morphology.	A broad survey of pattern-generating systems in the physical sciences.	Shapes, flows, branches.
(Hayter 1965)	Kinetic art.	A reductive approach to understanding motion, breaking it into components.	Orientation (with respect to a spectator), direction (where the spectator or their eye moves, for instance, across a picture plane), cheirality [sic] (handedness), velocity and rhythm.
(Rickey 1965)	Kinetic art.	A classification of techniques by which an artist introduces elements of movement into their work.	Optical phenomena; transformations where movement seems to dematerialise an object; movable works where the spectator rearranges the elements; machines; light play dependent on movement; movement itself.
(Popper 1968)	Kinetic art.	A *typology of movement* classified according to "procedures" employed by the artist.	The means of figuration of movement; methods for movement's representation; photographic or filmic techniques employed; movement expressed by movement itself.
(Nyman 1999)	Experimental music.	Categorises works according to how an artist outlines a *situation* in which sounds may occur,	Chance determination processes, people processes, contextual processes (dependent on unpredictable conditions, such as the selection of new pitches in

		a *process* of generating action.	Cardew's *The Great Learning*, *Paragraph 7*, see below), repetition processes, and lastly, electronic processes.
(Dorin 1999)	Kinetic art.	An attempt to categorise process types and their elements at a high level of abstraction.	A pulse, stream, continuum, increase, decrease and complex processes.
(Galanter 2003)	Complexity, generative art.	Analyses generative processes in terms of their *effective complexity*.	Arranges works according to the order / disorder of the processes they employ and plots this against the works' complexity.
(Wooller, Brown et al. 2005)	Algorithmic music.	Two axes of description: *function* (analytic to generative) and *context* (narrow to broad).	Arranges works according to function (analytic, transformational, generative) of the processes they employ and plots this against the breadth of the works' context.
(Dodge, Weibel et al. 2008)	Dance.	Focus on patterns of movement: hierarchical taxonomy of movement primitives; temporal, spatial and spatio-temporal classifications.	Primitive, compound and behavioural movement patterns, synchronization.
(Boden and Edmonds 2009)	Electronic, digital, interactive, robotic and virtual reality art.	Classification of art forms in areas related to generative art based on the role of technology.	Electronic, Computer, Digital, Computer-Aided, Generated, Computer-Generated, Evolved, Robotic, Interactive, Computer-Interactive and Virtual Reality art.
(Gamma 1995)	Software engineering.	Classification of mid-level program designs into common patterns of reuse. Inspired by Alexander's *A Pattern Language*.	Composition, model-view-controller, delegate, factory, singleton.
(Havemann and Fellner 2009)	Computer graphics.	Methods for building 3D shapes with computers; all shape design is based on a small number of general rules or design patterns.	Design patterns such as repetition, symmetry, erosion, extrusion, lathing, composition / decomposition;
(Roy and Haridi 2004)	Computer programming.	Methods for setting out data and procedures in software.	Object-oriented programming: objects with associated data members and behaviours. Imperative programming: data-structures and procedures that act upon them.

Table I. Some process taxonomies from biology, the kinetic and time-based arts, and computer science.

D'Arcy Thompson's, *On Growth and Form* (1917), examined shape and form in biology from the perspective of the processes used to generate them.[1] It found common mathematical descriptions were applicable to recurring shapes and forms and that these appeared in organisms not closely related by Linnaean taxonomy. The approach adopted in his study might be applicable to generative art works when common forms can be identified. But should we wish to describe the processes themselves, the approach is not

[1] A number of Thompson's process descriptions published in the first edition turned out to be incorrect, highlighting the difficulty of the problem – albeit from a biological perspective – in Thompson's time.

sufficiently tailored to art to be acute, nor is it sufficiently broad as to encompass all of the approaches an artist might adopt.

Similarly, Stevens (1979), Volk (1995) and Ball (2001), focused on physical processes and natural patterns, many of which have served as inspiration for generative art. Whilst providing some basis for describing generative art, these taxonomies do not typically address conceptual or artificial processes, leaving a significant portion of our context untouched.

Rickey (1965), Hayter (1965) and Popper (1968, p. 215-223) all classified processes for producing kinetic art, each adopting a unique approach as outline in Table I. Popper considered a variety of organisational approaches, dismissing a classification of types of movement (linear, circular, whirling etc.) as too general to be usefully applied to art. He also considered a classification based upon the "universes" of movement (physical (visible or invisible), mechanical, human physical, human psycho physiological, ludic, imaginary etc.) and one based upon the plastic elements employed in a work (colours, lines, volumes, textures etc.). These latter approaches, he felt, would make an unnatural and unwieldy distinction between an artist's meaning and the form of their work. Popper preferred instead to classify more generally according to "procedures" employed by the artist. We adopt a similar approach, but recognise that the artist's conceptualisation is not always the most appropriate level of description in realising our aims to be inclusive of the technical, semantic and practical elements of a work.

A number of different authors (Hayter 1965; Dorin 1999; Dodge, Weibel et al. 2008), have broken dynamic behaviour into components, a reductive approach that is helpful in understanding how a work achieves its effect. By describing processes at a high level, Hayter and Dorin circumvent the problems that Popper noted might occur when attempting to detail the different types of movement at a lower level. However as a result they lack some of the nuance we might prefer if they were to be extended to generative art broadly, as is our current need. By employing a hierarchy, Dodge et al. simultaneously facilitate high-level and low level descriptions, thereby allowing for recognition of abstract similarities and differentiation between a variety of specific patterns.

Galanter examines generative works according to the *effective complexity* of the processes they employ (Galanter 2003). He plotted different generative methods by estimating their locations on axes from order to disorder, and from simplicity to complexity. As Galanter himself notes (and Popper before him), in the context of art, a work's medium, its "content", and often the technology from which it is made, are all relevant in some cases, as are a host of other traits. Galanter's mapping does not facilitate discussion about any aspects of a work apart from order and complexity. This is insufficient when describing, analysing, comparing and critiquing works of art.

Boden and Edmonds (2009), like Galanter, deal specifically with generative art. They include a taxonomy that refines the area according to technology's application, for instance, via interaction with a human or more autonomously; in the form of robotic hardware or through evolutionary software. Their approach, like that of Galanter, allows for some comparison of different works. Boden and Edmonds' approach however operates at a high level in which the specific organisation of the processes employed is not consistently addressed, only the medium through which they are enacted. We instead prefer to give at least equal weight to the forms of the processes themselves, rather than focusing on the means by which the form is achieved. Some of Boden and Edmonds' categories permit this, for instance evolved-art relates to the process type. However most do not. For instance robotic art, digital art, computer-assisted art, virtual reality art say nothing about the processes employed by a particular robot, digital machine, computer assistant or within a VR environment.

Music composition, especially since the 1960s, has utilised many different generative techniques. Nyman (1999) for example, explains that, *"Experimental composers are by and large not concerned with prescribing a defined time-object whose materials, structuring and relationships are calculated and arranged in advance, but are more excited by the prospect of outlining a situation in which sounds may occur, a process of generating action"*. Nyman, Cardew and others emphasised the importance of describing the process employed to generate an artwork. We too include this aspect of a generative work within our framework, but go further by suggesting specific details that better capture the nature of dynamic processes.

In computer science and software engineering the description of artificial processes (in the form of computer programs) is routine. Programmers adopt a strategy embodied in a programming paradigm such as the popular *object-oriented paradigm*. Here a program consists of objects of different classes with associated state data, and behaviours or methods allowing the objects to interact with each other and to change state. An alternative approach, *imperative programming*, considers data-structures and variables as passive entities that are acted on by sequences of instructions carried out by the computer. Programming paradigms are of assistance in understanding computational processes and algorithms. Their abstract level of description, focus on computational data, and functional relationships to that data, make them ill suited to understanding processes as meaningful artefacts in the context of the arts. Perhaps these approaches could be adopted to describe the technical elements of a work, but this seems to be the level at which their utility ends.

Each approach to classification we have outlined has its own strengths and drawbacks. In all domains, the aim is to identify an appropriate framework and work within the constraints it imposes. Good choices will reveal new aspects of the subject and facilitate its analysis and description. We tailor our own framework with this in mind.

For our framework, we choose a level of description suited to the nature of the work being described and our purposes in making the explanation. For example, describing drawing software at the level of programs for Universal Turing Machines or machine-code isn't usually helpful, even though all computational processes can be completely described at these levels. A more appropriate description should mirror the "natural ontology" of the software's design, including elements such as lines, brushes and colour. Our framework uses natural language descriptions and definitions. It is not a mathematical theory with axioms, lemmas and proofs. It is simply a useful way of describing, and seeking to understand, certain aspects of a wide class of creative works. However, our description and characterisation is not arbitrary.

4 Characterisation of the generative art system

Our framework is divided into descriptions of four main components that constitute a generative art system: *entities, processes, environmental interaction* and *sensory outcomes*. We will now give a brief explanation of each. Concrete examples will follow in §5.

4.1 Entities

Using an appropriate level of description, we can identify the entities involved in a generative process. These are the subjects upon which a generative artwork's processes act. They may be real or conceptual, simulated, physical, chemical, biological or mechanical. Entities are constituents that are (conceptually) unitary and indivisible, and whose functional relationships are not typically expressed in terms of internal mechanisms. However, entities may exist in structured or hierarchical relationships with one another, leading to the creation of new composite entities.

Generative processes demonstrate a number of characteristic entity configurations. Computational generative processes such as agent-based systems often involve homogeneous populations or arrays - monocultures where all entities are formally identical, distinguished only by individual states that differ. Some systems involve more than one class of entity. For example, a diverse agent population of heterogeneous structural or behavioural types may inhabit virtual ecosystems.

Entities have characteristic properties that play a crucial role in the generative process. In computational generative systems these properties are formally defined. For example in Conway's *Game of Life* (Gardner 1970), cells can have one of two states, and occupy a fixed position in a two-dimensional grid. Typical entity properties include spatial, temporal and formal attributes (for example position, age and colour). As noted above however, there is not necessarily a direct relationship between entity properties and the perceived outcomes of a generative artwork; these properties are often perceived only via a *mapping* (§4.4). For our framework the relevant attributes of entities are those involved in the processes acting on them. For example the grains of sand in Driessens and Verstappen's work *Sandbox* (2009) (Fig. 1) might be considered its primary entities. These have innumerable attributes, but in the context of that particular work physical properties such as position, velocity, mass and friction are the most relevant.

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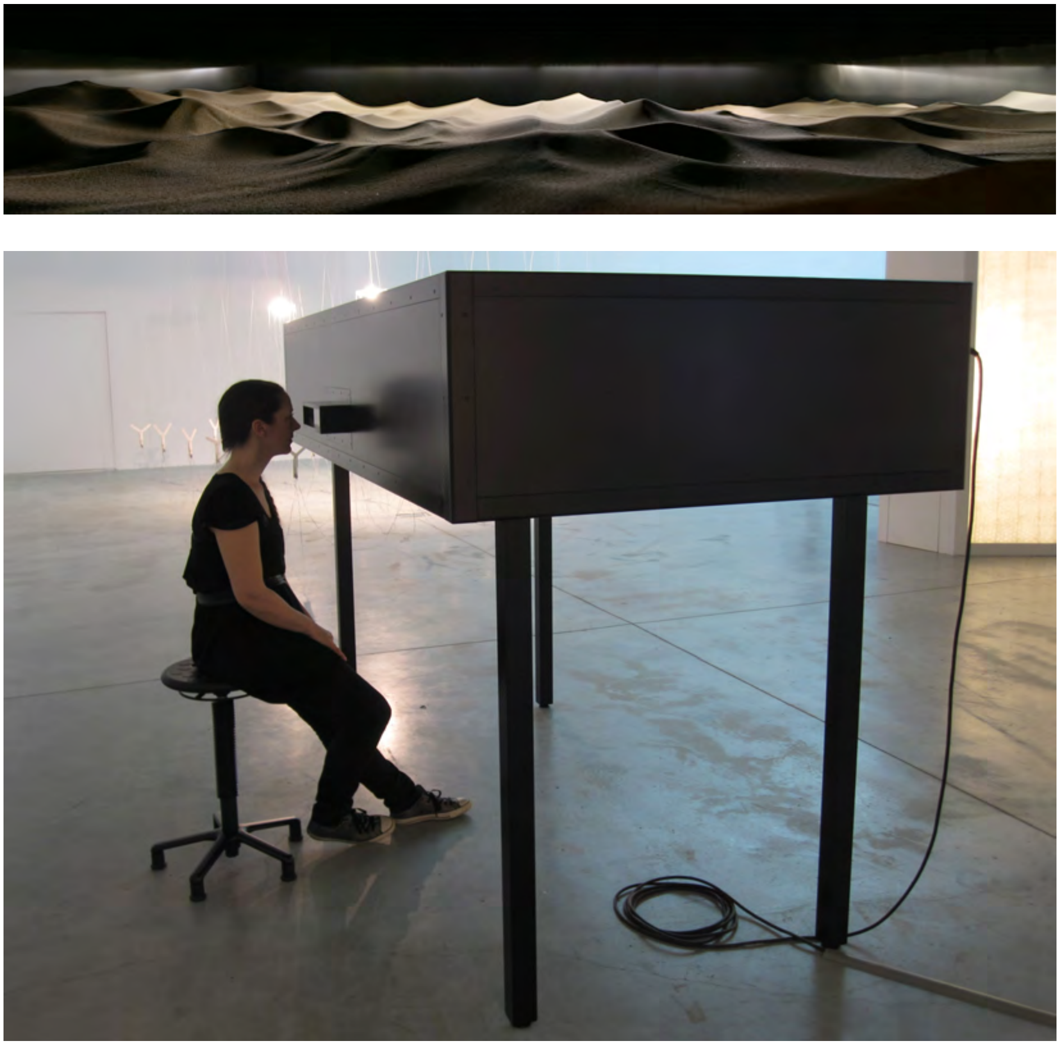

Figure 1. *Sandbox* panoramic still, and *Sandbox*. Erwin Driessens and Maria Verstappen 2009. Courtesy gallery Vous Etes Ici, Amsterdam.

4.2 Processes

Processes are the mechanisms of change that occur within a generative system; they necessarily involve entities that perform operations on, or interact with each other. Processes can be enacted by a system that may be physical, mechanical, computational, under human control or even the result of several of these operating in concert. Processes may or may not be directly apparent to the viewer of a work. Like entities, processes may involve hierarchical relationships where a global or macroscopic process is composed of many micro processes.

We can be more specific in our characterisation by describing basic features of a process. These include *initial conditions* – the state and configuration of the entities before the process begins, or *initialisation procedures* – the actions or conditions

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necessary to start the process. All processes begin; many also end. We can describe the conditions or events that trigger the process to terminate. We can also articulate what enables the process to continue.

We can identify constituent micro-events and the relationships between micro-events within a macro process. In one common example, a series of events may form a causal chain – a chain reaction or "domino effect". A more complex balance of negative and positive feedback relationships may result in a state of self-organised criticality (Bak, Tang et al. 1988). In Conway's *Game of Life* (Gardner 1970), the formation known as a *glider* is a persistent macro-process made up of the interacting micro-processes of its constituent cells (Fig. 2). We can also characterise a process using macroscopic descriptions of the system's behavior, for example, stochastic behaviours such as random walks or turbulence; and dynamic tendencies or trends such as growth, decay, stasis or instability.

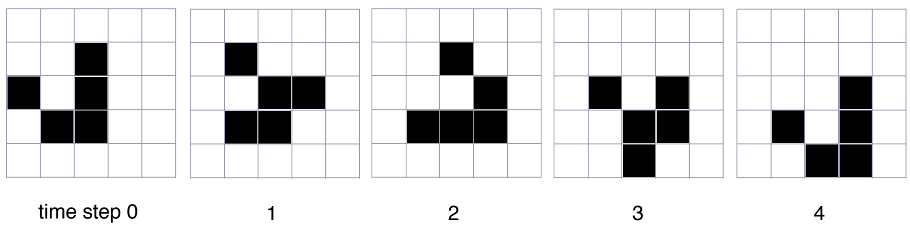

Figure 2. Subsequent stages of the *glider* pattern on Conway's *Game of Life* cellular automaton grid.

4.3 Environmental interaction

All generative systems operate within a wider environment from which they may draw information or input upon which to act. The Environmental Interaction component of our framework describes flows of information between the generative processes (§4.2) and their operating environment. Information flow may occur in discrete events, or be continuous. It may specify only initial conditions, for example configuring the states of cells on a cellular automata grid or generating an initial population of agents in a simulation. Incoming information might also set or change parameter values during execution.

Processes may also draw on information continuously through sensors of the physical world or from other devices that detect and transduce human interaction. Following Laurel (1993, p. 21), we can characterise these interactions in terms of their *frequency* (how often they occur), *range* (the range of possible interactions, or amount of information conveyed) and *significance* (the impact of the information acquired from the interaction on the generative system).

Continuous processes often involve cycles of information flow, where the output of the generative system influences (or even entirely constitutes) subsequent inputs. These cycles can also be characterised using Laurel's categories. A system that responds in real-time to user interaction has a cycle of high frequency, though its significance may still be highly constrained (limited to a single parameter for example). Conversely an interactive

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genetic algorithm may involve low frequency and low range interactions (where the artist or viewer selects one image from a set) that have high significance for the final outcome.

This description can also extend to higher-order interactions involving the artist or designer. Interactions between artist and work are of course central to both generative and traditional art and design practices. The difference for generative practice is that the creator typically manipulates the outcomes through the intermediate layer of the generative system. The creator will often adjust parameters of the system based on ongoing observation and evaluation of its outputs. These interactions constrain the subsequent outcomes of the system. Similarly, the designer may select outputs from a large set of candidates to become final "works". In each case this interaction can be characterised as *filtering* – selecting or constraining the outcomes of a process. In a more complex but equally common higher-order interaction, the creator interactively modifies the system itself in response to its outputs. The system's output informs the creator's iterative redesign of the system and underlying processes, resulting in changes to its entities, interactions and outcomes. This tweaking often, but not always, takes place behind the scenes during the development of the generative systems. In live-coding, performance tweaking becomes a focal point of the work.

4.4 Sensory outcomes

We refer to the experienced aspects of a generative work as its *sensory outcomes* or simply *outcomes*. Here we describe these and examine their relationship to perception, process and entities.

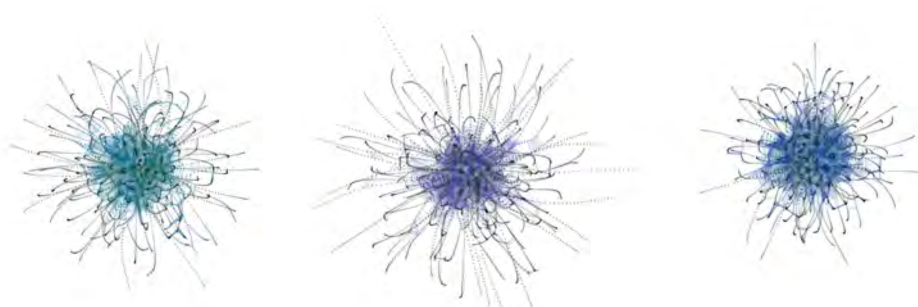

Figure 3. Still image from *Pretty Little Flocker*. Alice Eldridge 2009.

Outcomes may be artefacts (visual, sonic, musical, literary, sculptural, etc.), including static or time-based forms. Static artefacts include selective "snapshots", the final state ("endpoints"), or "accretions" of processes over time (where the outcomes are built to an end point by numerous individual contributions, as in works such as Eldridge's *You Pretty Little Flocker* (2009) (Fig. 3) or Reas' process drawings (2010) (Fig. 5)).

In some works the audience perceives the operation of the generative process live as it unfolds. Real-time interaction may be possible. Many processes generate multiple outcomes. These frequently function to demonstrate the possible variation within a process. Jared Tarbell's work *Invader Fractal* (2003) for example, illustrates the range of variation of a simple combinatorial generative system. In practice many generative processes produce several different types of outcome, either as primary "works" or secondary documentation. The relationship between process and outcome is further compounded by the use of editing, post-processing, selection, juxtaposition, or other extrinsic elements that lie outside the process. For the remainder of this section we will focus on outcomes that arise directly from the interaction of process and entity as defined in the previous sections.

There are a number of possibilities for making a generative work perceptible. The entities of an artwork may be directly available for perception, or hidden. (E.g. In the case of a clockwork machine, the gears and springs may be visible, or concealed, with animated figures the only perceptible outcomes.) In Cardew's *Paragraph 7* (1971), the audience directly perceives the entities (singers) as they enact the singing process. Artist Hubert Duprat deliberately intervenes in the developmental process of the Caddis fly larvae, substituting precious metals and jewels for the dirt and grit of their natural environment which the larvae use to build their protective casings (Duprat 1980-1996). The audience directly perceives the same process as that which occurs naturally, *but with different entities*. We describe such systems, where the entities and outcomes occupy a single perceptible layer, as *flat.*

Where the entities and processes of a system are not immediately apparent, they are rendered perceptible through a process of *mapping*: the transformation of the underlying entities and processes of the system to perceptible outcomes. In computer software for example, the interactions of the system's entities are usually mapped from imperceptible machine states to physical systems whose changing states are perceptible. The artist makes decisions about *what* should be perceived and *how* it should be mapped. Such decisions are shaped by the affordances involved, which in the case of technology may be considerable. For example the technologies of screen-based display are deeply embedded in the interfaces and protocols of modern computing, though non-screen mappings are certainly possible, and arguably increasing in prevalence (Whitelaw 2010).

A *natural mapping* is one where the structure of entities, process and outcome are closely aligned. In these cases the configuration of entities and attributes built into the process is recognisably present in the outcome; or put another way, the entities and process are designed to match the ontology of the intended outcome. For example, the process at work in Michael Hansmeyer's *Subdivided Columns* (2010) involves the recursive subdivision of polygons in a three dimensional form. Here the entities (polygons, vertices and edges) are configured with a particular perceptible outcome in mind, and there is a close alignment between the structure of entity and outcome.

In many generative systems however, there are no necessary or intrinsic relationships between the entities, processes and the material manifestation of their outcomes. Thus, creative choices around the manifestation of a process can play a crucial role in the resulting work. As an example, consider cellular automata (CA): typically 1 or 2-dimensional arrays of discrete cells with individual states and local rules determining global emergent patterns. Wide ranges of both natural and arbitrary mappings are possible. Burraston (2005) mapped cells at each time-step of a 1D CA to a variety of musical (MIDI) events; Miranda (1995) used clusters of cells in a 2D CA to control a granular synthesis algorithm.

Visual manifestations of cellular automata are more often natural mappings where the topology of the CA relationship is preserved. But even if a natural mapping is used, there is still a role for creative choice. Bill Vorn's *Evil / Live* (1997) manifests the *Game of Life* on a grid of halogen stage lights. Kristoffer Myskja's *Rule 30* implements a 1D CA rule as a kinetic sculpture that mechanically enacts the process (see below) while Camilla Fox's *CA tea-cozies* (2008) are the result of a human enactment of CA rules, through the process of knitting.

All of these examples share similar processes, yet their physical manifestations and aesthetic experiences are significantly different, making mapping central to the artistic contribution of each system. A tangible physicality may provide the essential "conceptual hinge" that joins an abstract process with a specific outcome, additionally forming a basis for critical analysis of the work. Decisions about mapping may be informed by a coherent "system story" – a narrative of ontology that defines the system (Whitelaw 2003). This may assist the artist in conceptualising suitable mappings, and the audience in better appreciating the intangible and hidden elements that give rise to the perceived outcome. Equally however, manifestations may work in counterpoint or contrast to their underlying system. In either case mapping entails a poetic: a conceptual and aesthetic juxtaposition of system, process and manifestation that is central to the generative artwork.

5 Examples

Having now outlined the framework, we will demonstrate its utility by analysing and describing a series of generative artworks with it (see table II). The works were chosen to illustrate the variety of generative art in medium and process, whilst being in no way an exhaustive catalogue. Even though the examples are diverse, they can all be described within the framework, allowing comparison and the illumination of congruence and disparity.

5.1 *Islamic star patterns* (ca. ninth century CE onwards)

The intricate abstract patterns of Islamic art may involve ten-pointed shapes that do not fit into the simple divisions of the plane into triangles, squares or hexagons (Fig. 4). They therefore require sophisticated geometric construction procedures (Lee 1987). The rules are not known with certainty, but scholars have reconstructed plausible methods that do not employ an underlying repeated grid, facilitating a greater variety of patterns (Cromwell 2009).

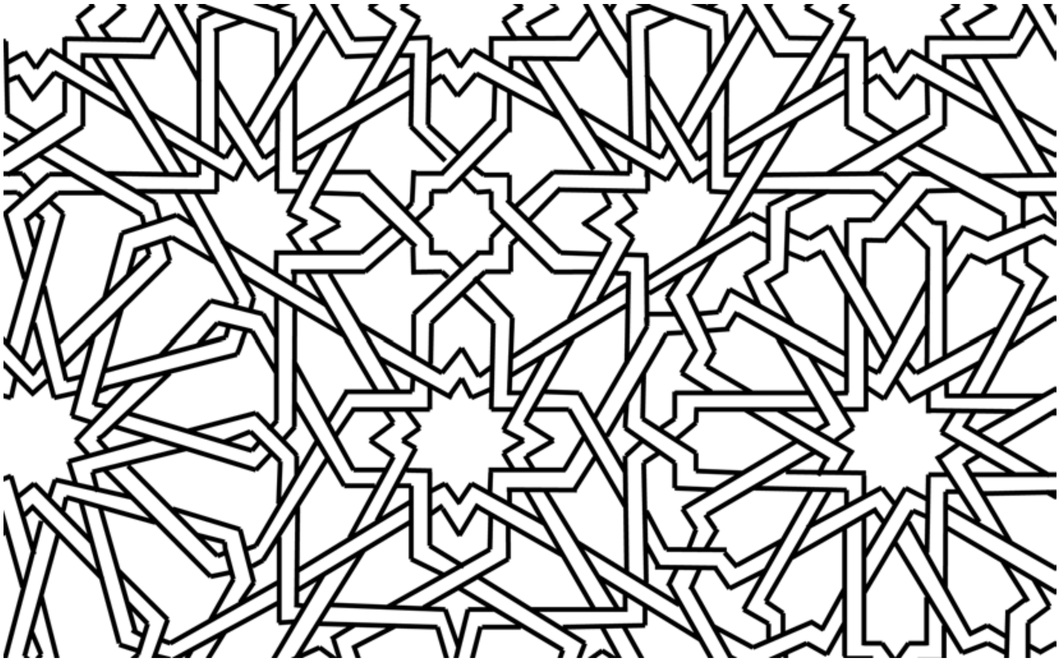

Figure 4. Islamic architectural tiling pattern. The *Alhambra*, Granada, Spain. Drawing by Gordon Monro 2012.

Our framework neatly captures the important elements of this process. It highlights that extrinsic forces minimally affect such patterns. This fact, and the use of non-random initialisation, ensures that if re-enacted the process will generate almost identical outcomes each time. In contrast to the other works shown in table II, these works are perceived entirely in terms of their final configurations, static artefacts, with no obvious reference to their method of generation.

5.2 The Great Learning, Paragraph 7 - Cornelius Cardew (1971)

Paragraph 7 is a self-organising choral work described by a written "score" of instructions. The process involves singing, humming and speaking a fixed sequence of words and phrases according to the instructions. Singers are given free reign over phrasing and disposition of syllables and allowed choice in recognising the leader's signals if they choose.[2] The process undergoes a form of random initialisation by which each singer silently chooses a starting pitch before the first note is sung. Each note is sung for the "length-of-a-breath". For subsequent notes, pitches are chosen by selecting a pitch the singer hears a neighbour singing (via environmental interaction). If the individual singer cannot find a neighbouring pitch, or is unable to reach it, or is already singing the note, then they may freely choose another. The performance continues, each singer working at their own pace, until the list of words has been completed. Performers may move about the space to more clearly hear neighbouring notes.

[2] Cardew rejected the avant-garde music of his day and wished to involve ordinary people in co-operative music-making (Taylor 1998).

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The work typically moves from a global state of disorder (due to the random initialisation) to a more ordered, but never stable state (due to the rule that forbids singers from repeating a note or from singing beyond their vocal range). A heterogeneous mix of singers' vocal ranges helps to ensure greater variation.

Using our framework, it is quite easy to see *Paragraph 7* as an agent-based, distributed model of self-organisation, similar to the flocking system devised by Reynolds (1987) in which virtual agents flock or swarm by maintaining particular relationships with their immediate neighbours. Indeed, *Paragraph 7* exhibits many of the classic features of generative systems including emergent phenomena, self-organisation, attractor states and stochastic variation in repeated performances. It is a process that has musically varying outcomes, yet these are all recognisable instances of the same work.

5.3 *Process 18* - C.E.B. Reas (2008)

In his *Process* works C.E.B. Reas suggests that, "The most important element of Process <NUMBER> is the text" (Reas 2010). The text is a high-level English description of a process intended for translation into software that, as it executes, generates a digital image for printing. (We are reminded of the *Wall Drawings* of Sol LeWitt.) For example, *Process 18* specifies how a set of lines can be moved across a plane, and, when they touch, be joined to create quadrilaterals of varying opacity (Fig. 5).

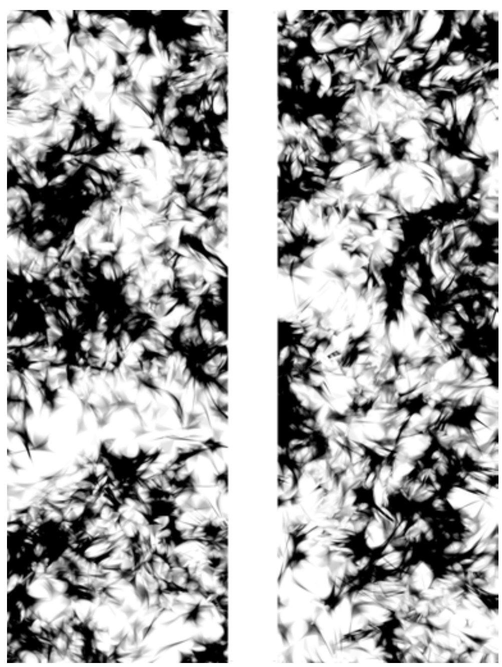

Figure 5. *Process 18* (Image 3, 4), pair of unique C prints, 36 x 12 inches each. Casey Reas 2008.

We consider the entities of *Process 18* to be individual mobile lines with a process specifying their motion and orientation. By contrast, Reas describes his process in terms of elements with behaviours ("Elements 5", pairs of touching lines that behave in particular ways). We choose to distinguish between process and entity, whereas Reas partially folds these together. The sensory outcome of the work is an accretion of quadrilaterals rendered onto the surface and documented in print form or animation, neither of which, in and of itself, is considered by the artist to constitute the whole work.

Though the high-level English language description of the generative process is positioned as core, there are many free choices to be made in its implementation (e.g. the number, size, speed, and rate of opacity change of elements). Exact specification of the entities and processes in the text would interfere with its poetic qualities such as the simplicity of describing a piece in three sentences. An idiosyncratic and brief description suits the artist's interpretation, however, our framework helps us to produce standardised and detailed descriptions for comparison with other generative works.[3]

5.4 *Tree Drawings* - Tim Knowles (2005)

Tree Drawings is a set of physical works in which the movement of wind-blown branches is used to mark a canvas (Fig 6). The wind blows the branches, causing them to move a stylus across a carefully positioned, initially blank canvas (Knowles 2005).

A found process of natural wind blowing real tree branches is used in these works. The process is driven by local environmental conditions, and, at the level of the artwork, by the positioning of the pen on branch tips and the canvas on which it draws. The resilience of the timber, the weight and other physical properties of the branch have significant effect on the drawings produced. Different species of tree produce visually discernible drawings.

Similar to Reas' *Process* works we have a generative process with a specific initial condition but no intrinsic end point. The tree forms a complex ready-made, natural "transducer" that transforms wind (environmental interaction) into movement. The physical and mechanical specifics of the tree and its interactions with the environment are transformed into a functional unit. While many of the entities and processes here precede the generative system, the artist selects a portion of this ongoing process for transduction (as well as shaping the transduction with choice of stylus, canvas position, etc.).

The outcome is a set of drawings. This is often accompanied by location photographs and videos of the process that produced the drawings, highlighting the importance of including an explanation of the generative process itself.

Each drawing is a surprise, as we don't often think of trees as doing anything more than growing. To see one exhibiting its work in a gallery is novel. Like other "drawing machines" (and indeed all generative art), *Tree Drawings* calls into question ideas of

[3] Reas often exhibits the products of the generative process by themselves, without the text, somewhat weakening the suggestion that they are not artworks in their own right. The fact that the text does not uniquely specify the outputs (prints and animations) also strengthens the case that the text, software implementation, and outputs of the generative process must all be considered in any analysis of the artwork.

signature, intent and agency in art (Boden 2010). Knowles uses elegant means to condense a complex set of interactions and elements, shaped but not determined by his own authorship. As with many other generative artworks, the outcome is a static accumulation of a dynamic process. In this mapping the spatial properties of the process are represented more completely than its temporal dynamics. The drawing provides a cumulative, unique signature of the tree within its environment.

Figure 6. *Ginko on Easel #1* (detail). Ink on paper and C-type print. Tim Knowles 2011.

Applying our framework to Knowles' work highlights the need to consider where to draw the boundary between entity, process and environment. At first pass we might consider the wind an entity, although here, and in table II, we did not. We choose a suitable ontology for our system's description. What we label "wind" is the movement of air generated by a complex causal chain of meteorological and other events. More importantly, the work brings to the fore issues of place and environment. The weather conditions at the time of drawing contribute to this signature, not only in terms of the form of the drawing, but conceptually in the mind of the viewer. Thus it seems natural to consider meteorological conditions as unique to the environment that the generative process interacts with, rather than as entities that form part of the process itself.[4]

5.5 *Rule 30* - Kristoffer Myskja (2008)

In Myskja's *Rule 30* (Fig. 7), a machine made from brass and steel slowly punches

[4] We can also consider the possibility of the entities and process still producing a (simple) drawing in the absence of any wind.

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holes in a long roll of paper. As the title suggests the hole-punching machine is executing a cellular automaton rule. The punched holes show the complex triangular patterns that are the signature of a rule set identified by Stephen Wolfram as *Rule 30*; a classic example of chaotic structure arising from a simple, deterministic process (Wolfram 1984). Yet while its generative mechanism may be familiar, Myskja's implementation of that algorithm is remarkable. In creating an electromechanical machine that literally embodies *Rule 30*, Myskja reminds us that computation – or the formal, logical processes that make up *Rule 30* – can exist without computers, as we know them. In contrast to the rapid, silent flickering of the typical computer realisation of a CA, the *Rule 30* machine is slow; its cogs and gears whir and click. The artist's documentation focuses on the tactile details of the piece – the paper crackling as it is punched; the smooth engagement of gears and cams. Unlike most digital systems, the output is a tangible, persistent artefact. This is central to the logic of the machine's operation; it manipulates material in a form that it can also interpret. Thus the paper operates like the machine's metal components, as an element in an ongoing process.

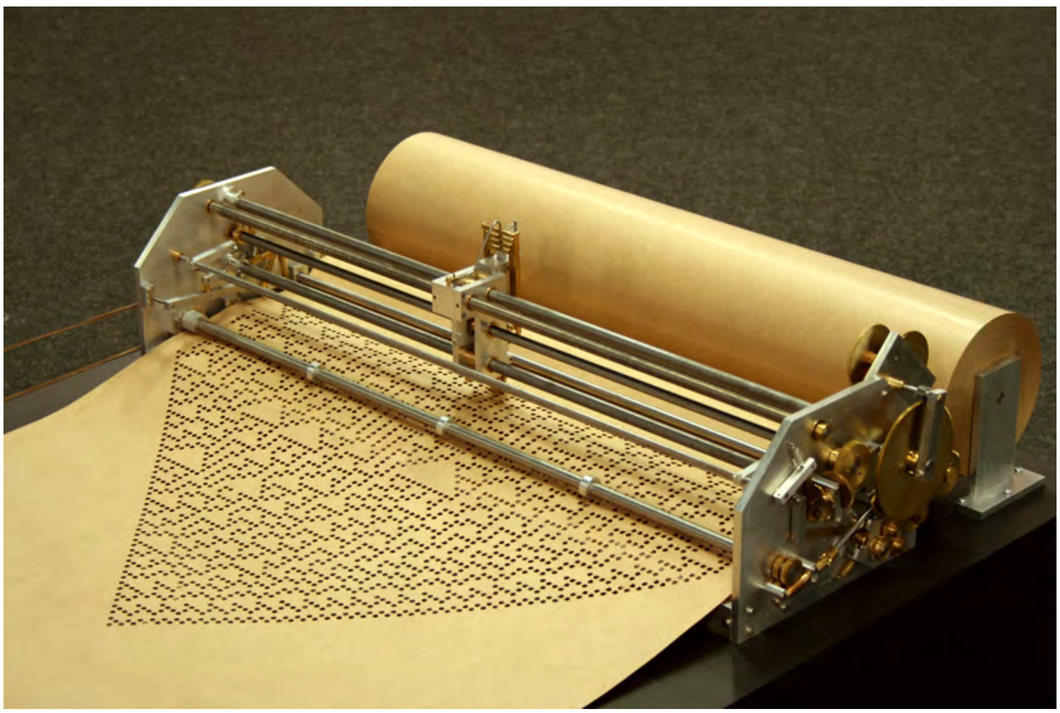

Figure 7. *Rule 30*. Kristoffer Myskja 2008.

In the work's presentation, machine and paper are granted equal emphasis in an integral whole. The work is best conceived of as including the paper, the machine, and its operation.

Rule 30 presents a number of interesting challenges for our framework. Firstly, what are the entities? In a computational CA we would readily use a level of description in which the entities are cells. In this case however the presentation of the machine requires us to shift levels, and recognise its physical elements – cogs, screws, cams, paper and holes – as the primary entities. Together these elements enact a process defined by the logic of their mechanical interactions. Except for the read/write head of the machine, much of that process is, like the entities involved, directly apparent. Like Cardew's *Paragraph 7*, and Driessens and Verstappen's *Sandbox*, there is no distinction here between entities and outcome, and thus no mapping. These systems are ontologically flat. Unlike those other works however, *Rule 30* makes a particular point of its flatness by staging the emergence of a more abstract formal system (the CA) from a physical substrate, reminding us that all computational processes may be reliably transferred between any physical/mechanical instantiation of the computer as process-enactor.

As this analysis shows, the framework is not a mechanical tool but a critical one. This work presents us with a choice; we must decide on an appropriate level of description, and thus the entities, processes and outcomes of the system. Here we selected a level of description that is based on a specific reading of the work and its presentation. However an alternative reading focusing on the CA cells as the primary entities remains possible.

5.6 Summary of example works

Table II lists each of the example works covered in this section and provides a summary of their important components according to the framework introduced in this paper.

Work details	Entities	Initialisation, termination	Processes	Environmental interaction	Sensory outcomes
Islamic star patterns (*ca.* 9th C CE) Fig. 4	Points, lines, circles, rhombuses used in the geometric construction.	Termination determined by the boundaries of the workspace.	Geometric constructions; the exact processes are unknown. Possible rules to construct a pattern include: specify drawing of lines and placement of shapes, colouring regions, specification of which construction lines are removed after the pattern has been generated.	None after completion.	A static work on a building or manuscript page. Flat system.
Paragraph 7, Cardew (1971)	Human singers (sound-making agents).	Random initialisation; "Leader" may signal start and end of the work.	Agent state changes through interaction with neighbours; finite set of singing tasks performed by each agent. Agents move and listen to neighbours.	Room acoustics.	Self-organising choral work. Flat system.
Process 18, Reas (2008) Fig. 5	Lines with state (size, position, velocity).	A rectangular surface randomly filled with instances of lines of different sizes and grey values. No termination	Entity behaviours: move in a straight line; enter from the opposite edge after moving off the surface; orient toward the direction of the element that is touching; deviate from the current direction. Draw a quadrilateral connecting endpoints of each pair of	None.	Accretive image formed through temporal interaction. Artist-defined mapping.

		condition.	lines that are touching. Increase the opacity of the quadrilateral while the lines are touching and decrease while they are not.		
Tree Drawings, Knowles (2005) Fig. 6	Tree, pen, ink, paper, easel.	Fixed initialisation - pens attached to selected branches and placed on a blank canvas. Process end determined by artist.	Natural physical movement based on environmental conditions that cause the branches to move.	Meteorological environment - wind and weather behaviour.	Accretive image formed through temporal interaction. Flat system.
Rule 30, Myskja (2008) Fig. 7	Electromechanical machine: gears, motors, hole punches, etc.; paper roll.	Deterministic initialisation of cell states – begins with one cell "live". Process ends when machine runs out of paper or is stopped manually.	Physical, hole-punching machine implementing CA Rule 30. 1D local interaction between immediate neighbours (punched holes in the paper roll).	None.	Pattern of holes in the paper roll; the machine performing. Flat system.

Table II. A summary of properties of a diverse set of generative works explored using our framework.

6 Discussion and conclusions

We have proposed a descriptive framework for generative art composed of four primary elements: entities, processes, environmental interactions and sensory outcomes. As our examples demonstrate, the framework successfully spans media, time and physical realisation. It accommodates computational, physical, kinetic and virtual systems, allowing meaningful comparison between a wide variety of generative systems from the past, present and (we anticipate) future. It raises a number of issues regarding the conceptualisation, enactment and experience of generative art. Our hope is that it is useful and general enough to be widely adopted.

A potential criticism of our framework is its focus on features of the generative process, rather than artistic motivations. In trying to be all-inclusive have we over-generalised and missed important details? Or is our focus too mechanistic, obsessed with implementation and mechanics at the expense of other concerns? Certainly, the works we have discussed have radically and importantly different artistic motivations. For example, *Happenings* did not come about for the sake of being generative or process-focused; their origins are more strongly embedded in political and class changes in the authority and hierarchy of established art practices. Similarly for Cardew, the act of giving autonomy[5] to individual singers was an important part of his political philosophy, which in simple terms, was to resist the established musical tradition of the composer-conductor-performer hierarchy. However our framework is intended to supplement and complement such readings, rather than supersede them.

Similarly our descriptive focus on process might appear to neglect the critical analysis of generative art. Certainly this is not our aim. We propose that the framework supports critical analysis by offering a conceptual model for engaging with generative processes. It does entail a critical position based on the significance of process in understanding generative art. If process is, as argued here, a key feature of generative art and design, then an ability to describe, analyse and compare processes is essential to any adequate understanding of the practice. Again our intent is to supplement rather than supplant existing critical approaches.

As an example, author and curator Inke Arns sees generative art as being preoccupied with the "negation of intentionality", and lacking an interest in questioning the tools employed in its creation (Arns 2004). Instead, Arns prefers to characterise generative art as focused on the instrumentalisation of process in the service of results. Our framework provides an alternative view, in which outcomes are only one component of the work. An emphasis on process is supported by many of the examples in this paper in which artists take care to explain, document or expose the processes that generate their work. Often the process is exhibited along with its outcomes. In the case of what we have called *flat* systems, the process is an integral part of the sensory experience of the work.

In warning of an uncritical adoption of technological tools, Arns echoes, among others, Terry Fenton, who cautioned in 1969 that art should not become "the handmaiden of science". Fenton was responding to Jack Burnham's enthusiasm for technological, process-based, autonomous art in the 1960s – work that shares many attributes with contemporary generative art (Burnham 1968; Fenton 1969). We agree that this warning remains valid. Generative art must do more than simply implement formal systems imported from the sciences. This framework enables a clear analysis that can deal with the distinctive features of a work (as demonstrated by the discussion in the latter part of section 4.4). Our framework is neutral regarding technology. It does not require or privilege technology, but equally it is silent on the critical implications and origins of processes and their implementation. This reflects our desire for an analytical *descriptive* rather than critical framework.[6] This does not preclude a wide variety of critical positions about the framework itself and concerning what it makes possible.

Art history and theory, aesthetics, social and cultural theory and many other fields can provide valuable approaches to understanding generative art; but arguably none adequately describe and account for the processes that are at the core of this work. In

[5] Somewhat ironically, a machine can now easily implement this autonomy.
[6] We acknowledge that such a separation is problematic as our analysis of works demonstrates (§5).

focusing on process *per se*, our framework addresses the most significant limitation in current analysis of this practice, providing a means of describing and analysing generative processes and the artworks that use them. The framework offers an intuitive and flexible approach that we hope will encourage more engaged and fine-grained analyses of generative art and design.

As we have demonstrated, our framework makes clear connections that were difficult to articulate previously. With it we can describe a wide variety of works, irrespective of medium, message or form. It can form the basis for the conceptualisation of new generative art and the critical understanding and comparison of these works with their predecessors – even those from many centuries or millennia in our past.

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