Crafting the Computational: Artistic Production, Generative Systems, and Digital Fabrication

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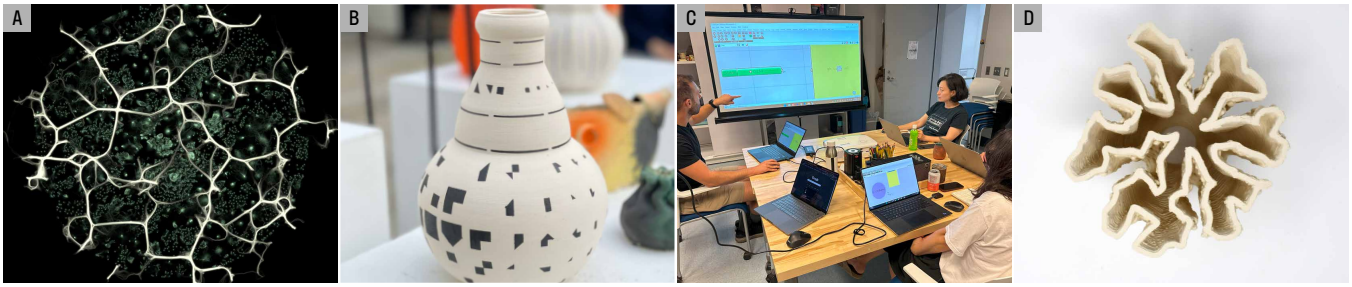


Figure 1: This dissertation aims to support digital and physical artistic production through collaborations, generative system design, and digital fabrication workflows. (A) A 2D mixed simulation containing three generative systems. (B) A generative pattern application on the ceramic vessel's surface. (C) Close collaborations with artists informed practice-driven software development methodology for digital fabrication. (D) A generative coral-like ceramic object prototyping my ongoing project.

ABSTRACT

Digital artists use generative systems for negotiating agency and control with autonomous processes that display emergent and self-organizing behavior. Practitioners have started using these systems in material fabrication for rich sensory opportunities; however, translating digital generative designs into the physical involves significant knowledge of programming, complex workflows, physical constraints, and material properties. I aim to develop computational systems bridging generative art methods with digital fabrication techniques to support artistic practices. I seek to develop digital generative workflows that account for the complexities of real-world materials through collaborations with professional practitioners. My thesis contributes practice-based research into evolutionary algorithms for real-time digital form generation, a manual-computational workflow for artistic production that moves between digital and material pipelines, and a collaborative practice-driven software development methodology for digital fabrication. These contributions inform my next project aiming to bridge the gap between digital and physical workflows, bringing computational generative design closer to material fabrication.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → **Media arts**.

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KEYWORDS

Computational Design, Generative Systems, Artificial Life, Fabrication and Material Workflows, Artistic Practice

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1 INTRODUCTION

Since the advent of general-purpose computing, artists have used computational platforms as an expressive medium for producing novel digital artifacts, starting the field of 'computer art' [36]. The abstract nature of computers prompted artists to collaborate with engineers and scientists [21, 32, 39] and learn working with low-level representations of data and programming languages [10, 33]. Nowadays, professional digital artists develop their own software to make works with new aesthetics and functionality [23, 25].

The computational platform is uniquely positioned to simulate the behaviors of complex systems in nature that display emergent and self-organizing phenomena. Such systems can be used for *generative art*: autonomous software-based processes displaying surprising behavior after iterative application of a rule set on the system state a sufficient number of times (for complete taxonomy, see [4]). Some professional artists solely rely on generative techniques [1, 19, 26, 41], but most use them to complement their deterministic art practice as compositional elements [9, 11, 35]. They may employ generative systems to create multiple design alternatives [32], negotiating direct control with emergence [30], influencing the system's evolution over time [3], and mastering

system parameters with virtuosity [27]. These processes introduce new relationships of agency and control over the creative process [17, 31, 38].

Digital artists use pixel-based technologies to communicate their works to audiences. However, the tactility and materiality of physical media offer richer sensory experiences, real-life interaction opportunities, and novel aesthetic outcomes [6]. Some professional artists have started incorporating the affordances of generative systems in their material practices [2, 15, 28, 29, 50]. However, professional physical production often involves complex workflows that require significant knowledge of material constraints and embodied-making practices [18]. Novel computational fabrication research presents valuable insights [8, 13, 14, 47, 51] and methods [5, 34, 40, 46, 48, 49] for transforming digital forms into physical ones.

My research aims to develop computational systems bridging generative art methods with novel digital fabrication workflows to support artistic practices. I hypothesize that extending the scope of computational generative principles to physical production while remaining compatible with the existing fabrication workflows and material constraints will support established forms of artistic production and help create new media practices. I ask the following research questions: (RQ1) How can we design emergent computational workflows that can work with physical constraints of materials? and (RQ2) How can we design new computational fabrication technologies to support professional artists working with physical materials and digital generative systems?

My methodology combines computational system design, digital fabrication techniques, and collaboration with domain experts to inform art practices in digital and material domains. I implement evolutionary systems inspired by natural phenomena for digital generative forms and behaviors. To explore the applications of generative design methods to physical making, I chose ceramics as a case study. Clay is an excellent resource for studying material interactions due to its highly dynamic nature, established fabrication pipelines, and adaptability to various techniques and supplementary materials. In addition, the longstanding craft practices offer a wealth of material knowledge often missing in engineering literature [12]. In my work, collaborations with professional craftspeople contributed immensely to uncovering the material opportunities and limitations and the extent of designer control [20].

In my thesis, I present three projects investigating system development for digital and material artistic production. First, I developed the *Edge of Chaos*, a digital generative system containing a set of artificial life algorithms, to investigate the emergent and self-organizing behaviors of complex systems [42]. Second, my colleague Sam Bourgault and I created *CeramWrap*, a non-linear manual-computational workflow for ceramic surface decorations to align digital design and fabrication with established material pipelines [44]. Third, my colleague Devon Frost and I collaborated with professional ceramic artists in artist-in-residence programs, learned how they intersect computation with manual processes and developed *a practice-driven software development methodology for digital fabrication* [45].

Currently, these projects contribute design methods for digital generative form-building, a manual-computational workflow for integrating digital with traditional material practices, and a material-oriented collaborative software development methodology for digital fabrication. These contributions have led to my ongoing research project to investigate generative systems further in material fabrication. I am currently developing a fourth project, a digital fabrication system that couples real-time digital generation with embodied-making practices. An early prototype of this direction for fabricating coral-like forms is shown in Fig. 1D.

2 THE *EDGE OF CHAOS*: DIGITAL EVOLUTIONARY SYSTEMS

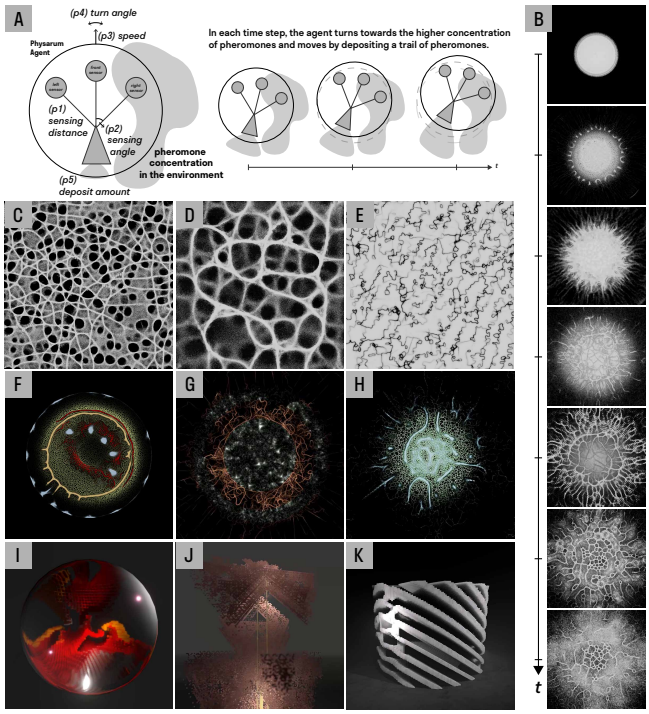


Figure 2: Visual results from the *Edge of Chaos*: (A) Diagram showing parameters of Physarum agents. The agent moves towards higher pheromone concentration based on parameters $p1...p5$. (B) One such animation unfolds over time. (C-E) Results of simulating 1m agents. (F-H) Results of simulating 5-30m agents with different types producing distinct colors. (I-K) 3D examples produced by variations of CA.

Generative algorithms define rules applied to the system state in discrete time steps. Initial conditions, input parameters, rule definitions, and update methods dictate how the system will unfold over time. In particular, artificial life (a-life) investigates biological systems' development and behaviors [52]. The *Edge of Chaos* investigates the implementation and artistic practice of visual a-life systems to uncover their emergent aesthetics and self-organizing behaviors using a practice-based research methodology [7]. Working with expert practitioners for ideation, implementation, and critique cycles for over eight months resulted in many experiments. A selection of these visual results were disseminated in group exhibitions [42, 43].

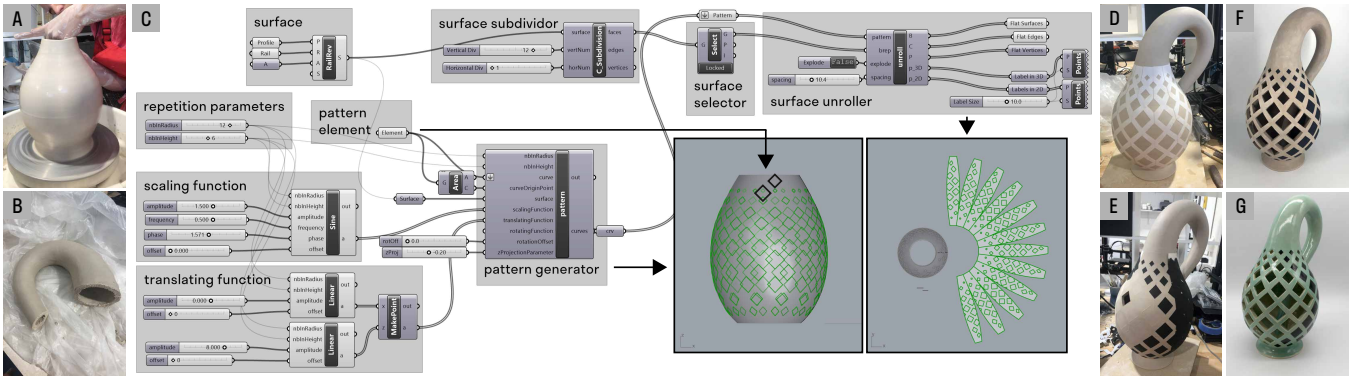


Figure 3: An example *CeramWrap* workflow for producing a decorated Klein Bottle, by Camila Friedman-Gerlicz. (A) Wheel-throwing the radially symmetric body. (B) Hand-building the ear. (C) Computational tools in Grasshopper for (left) procedural pattern generation and (right) surface unrolling: (front view) Pattern elements are repeated on the surface with a sinusoidal scaling and linear translation functions, then (top view) the patterned surface is unrolled into flat geometry. (D) Installing the laser-cut stencils. (E) Underglaze painting and carving. (F) Artifact with complete surface decorations. (G) Finished artifact.

The *Edge of Chaos* contains system implementations of CA variations [16, 24], agent-simulations with direct-communication [37] and stigmergy [22] paradigms in Unity. Using compute shaders allowed for simulating millions of components and their interactions without compromising real-time interactivity. This ability to simulate more components resulted in a higher chance for increased emergence and self-organization (Fig. 2). In addition, custom environments containing a mixture of these systems modulating each other's parameters contributed an additional behavioral complexity to the visual outcomes (Fig. 1A).

The combination of the input parameters and probabilistic evolution makes the space of possible outcomes vast, but not all regions of this space lead to visually interesting results. Collaborations with two expert practitioners in computational image-making and electroacoustic multimedia composition revealed insights for creatively exploring this output space. Discussions with the expert composer revealed that parameter space exploration is similar to playing a musical instrument, requiring mastery over the system configurations to find desirable visual results. Discussions with the expert image-maker revealed the use of mixed simulations to create visual balance. In addition, algorithmic parameter space exploration methods provided useful results. Langton's research on CA behaviors [24] not only inspired this project's name but also motivated me to algorithmically explore global parameters that affect future iteration's 'survival rate.' This aids artists in finding desirable results quicker, allowing for deeper exploration with less frustration.

In summary, the *Edge of Chaos* partially addresses RQ1 by demonstrating key aspects of using emergence in digital art practices:

- Digital generative systems can exhibit self-organization and complex visual behavior: The *Edge of Chaos* used massively parallel computation to increase visual complexity without compromising real-time interactivity.
- Exploring the parameter space is an artistic act that requires time and labor investment to find desirable results: Using the system becomes similar to playing an instrument that requires mastering the system's affordances and constraints.

3 *CERAMWRAP*: MANUAL-COMPUTATIONAL FABRICATION WORKFLOWS

Digital generative systems offer emergent qualities that are hard to design manually. However, translating these designs into physical is challenging due to the complex workflows required for material production. In *CeramWrap*, we studied challenges around material properties and fabrication workflows using ceramic surface decoration as a case study [44]. Transforming wet clay into finished ceramics involves long drying times and kiln firings that alter the clay's chemistry. Throughout this pipeline, clay undergoes unpredictable deformations and non-uniform shrinkage across vessel geometry. Since surface decorations can be applied at different stages of this pipeline using various additive or subtractive methods, skilled craftspeople adapt their designs and techniques to the dynamic state of the material.

To create computational workflows compatible with established methods, it is essential to develop flexible strategies that allow for rapid modifications. To achieve this, my colleague Sam Bourgault and I collaborated with an expert craftsperson, studied how ceramicists work with surface decorations, and developed *CeramWrap*, an adaptable manual-computational workflow that facilitates the computational design and rapid fabrication of patterned stencils. *CeramWrap* contains two computational steps for designing decoration elements on the digital surface of a radially symmetric vessel and for unrolling the digital surface into flat stencils (Fig. 3C). The rapid iteration of computational design and digital fabrication provides adaptability to dynamic material states that can work with established manual methods. These computational steps are designed for manual form-building and surface decoration techniques.

In summary, *CeramWrap* partially addresses RQ1 and RQ2 by demonstrating key aspects of adaptable manual-computational workflows:

- Computational design, digital fabrication, and manual craft practices can be integrated into the same workflow: Surface decorations were digitally designed, fabricated, and applied using various techniques (underglaze brushing, drilling, sgraffito) on vessels fabricated with multiple methods (slab building, wheel throwing, clay 3D printing).
- Manual-computational workflows can adapt to the evolving nature of materials: By rapidly propagating changes in the pattern design and generation of stencils, we could adapt to the shrinkage and distortion of ceramic vessels.
- Manual-computational workflows can be tailored to meet different technical requirements: *CeramWrap* can accommodate different alignment tolerances between the stencils and the vessel, depending on the ornamentation techniques used.

4 PRACTICE-DRIVEN SOFTWARE DEVELOPMENT METHODOLOGY FOR DIGITAL FABRICATION

Developing software tools for artistic production presents an inherent tension between building software and making art. Especially tool development for digital fabrication must balance the implementation with producing physical objects for testing due to the shortcomings of simulating full material complexity. In the case of domain-specific software that interfaces with complex material pipelines, professional craftspeople's experience and real-world needs can provide crucial insights into ideation, implementation, fabrication, and debugging steps of software development. To study these challenges further, we organized two summer-long artist-in-residence programs hosted in our lab. This brought together HCI researchers and skilled craftspeople for in-depth collaboration and knowledge sharing for an extended duration.

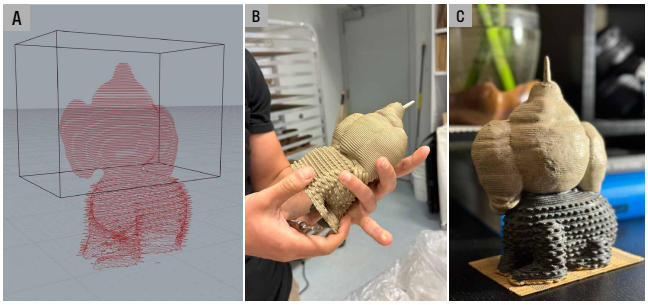


Figure 4: The second component in *ClayToolkit* was targeted for the real-world needs of residents. It allows the slicing of a 3D model and further modifying the toolpath with surface details. (A) Eun-ha Paek's signature poodle model was converted into a surface-textured toolpath. Head vertices (inside the box) are excluded from texturing. (B) Trimming the leather hard object. (C) Glazed ceramic object.

In this article, my colleague Devon Frost and I summarized findings regarding the software development for material workflows by analyzing five tools developed throughout the residencies [45]. We present similarities with software development workflows for digital production and highlight key differences emerging from the manual practices of working with clay. For example, we found that the physical objects acted as a common ground for discussions that drive the implementation and debugging cycles. My interactions with craftspeople led me to create *ClayToolkit*, a CAM-based design and utility software containing three components: The first component allows for designing radially symmetric toolpaths based on an input profile curve and controlling the surface details by mapping predefined patterns, geometry, or images. The second component converts an input geometry into a toolpath representation and allows for surface modifications (Fig. 4). The third component converts a GCode file back into an editable toolpath, providing interoperability between various machines and software developed during the residency.

In summary, this project partially addresses RQ1 and RQ2 by studying collaborative software development strategies for digital clay fabrication:

- Digital fabrication can involve dynamic craft materials, which require extensive embodied practice to master: Our methodology was derived from collaborating with professional craftspeople in artist-in-residence programs that fostered bidirectional knowledge exchange.
- Developing software for physical workflows requires iterating between programming and fabricating, resulting in increased time and labor spent on software development: Developing targeted software for the real-world needs of professional artists can provide mutual benefit to system research and artistic practice.
- The constraints of physical materials and machinery can limit the output possibilities of software for digital fabrication: Manual material interventions can partially address the limitations of software tools.

5 MODULAR GENERATIVE FABRICATION TOOLKIT (WORK-IN-PROGRESS)

While the projects described above contribute insights and components into the physical production and digital generative systems, an explicit bridge is needed. One major challenge remaining in this intersection is incorporating the material constraints into the generative system.

I'm developing a fourth project, an interactive fabrication interface that contains essential digital form-building operations as CAM-based modules. These modules can be assembled in various ways to design larger-scale structures. Modules range from elementary toolpath operations to a-life algorithms with parameters for controlling growth. An early prototype of this direction for fabricating coral-like forms is shown in Fig. 1D. I aim to develop this interface further in Javascript/WebGPU so that the generative algorithms can produce real-time results in response to parameter modifications.

This project aims to fully address my research question bridge the gap between digital and material workflows, promoting a more responsive and playful design practice for digital fabrication. Experimenting with multiple materials would provide additional benefits in differentiating one medium from another.

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REFERENCES

[1] Refik Anadol. 2024. *Projects.* Refik Anadol Studio, LLC. https://refikanadol.com/works/
[2] Alexis André. 2024. *Navette.* TRAME Paris. https://trameparis.com/collections/navette-by-alexis-andre
[3] Margaret A. Boden. 2010. *Creativity and Art: Three Roads to Surprise.* Oxford University Press, Oxford ; New York.
[4] Margaret A. Boden and Ernest A. Edmonds. 2009. What Is Generative Art? *Digital Creativity* 20, 1-2 (2009), 21–46. https://doi.org/10.1080/14626260902867915
[5] Samuelle Bourgault, Pilar Wiley, Avi Farber, and Jennifer Jacobs. 2023. CoilCAM: Enabling Parametric Design for Clay 3D Printing Through an Action-Oriented Toolpath Programming System. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23).* Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3544548.3580745
[6] Leah Buechley, Alyshia Bustos, Eleonora Edreva, Tyler Fenske, Reuben Fresquez, Samuel Hafer, Aislinn Handey, Michelle Louie, John Ng, Alan Shen, Randi Smith, Amber Sustaita, Michael Truong, Kai Vallon, and Kage Micaiah Weiss. 2022. A Computational Fabrication Course: Exploring Philosophical Reflection, Real-World Use, Personal Expression, and Social Connection. In *Proceedings of the 7th Annual ACM Symposium on Computational Fabrication (SCF '22).* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3559400.3562006
[7] Linda Candy and Ernest A. Edmonds. 2018. Practice-Based Research in the Creative Arts. *Leonardo* 51, 2 (2018), 111–117. https://doi.org/10.1162/LEON_a_01471
[8] Amy Cheatle and Steven J. Jackson. 2015. Digital Entanglements: Craft, Computation and Collaboration in Fine Art Furniture Production. *CSCW 2015 - Proceedings of the 2015 ACM International Conference on Computer-Supported Cooperative Work and Social Computing* (2015), 958–968. https://doi.org/10.1145/2675133.2675291
[9] Sougwen Chung. 2024. *Projects.* Sougwen Chung. https://sougwen.com/projects
[10] Harold Cohen. 1995. The Further Exploits of AARON, Painter. *Stanford Humanities Review* 4, 2 (1995), 141–158.
[11] Max Cooper. 2024. *Works.* Max Cooper. https://maxcooper.net/work
[12] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20).* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376820
[13] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. *Conference on Human Factors in Computing Systems - Proceedings* 2015-April (2015), 2477–2486. https://doi.org/10.1145/2702123.2702547
[14] Kristin N. Dew and Daniela K. Rosner. 2018. Lessons from the Woodshop: Cultivating Design with Living Materials. *Conference on Human Factors in Computing Systems - Proceedings* 2018-April (2018), 1–12. https://doi.org/10.1145/3173574.3174159
[15] Jorge Duro-Royo, Josh Van Zak, Andrea Ling, Yen-Ju Tai, Nicolas Hogan, Barrak Darweesh, and Neri Oxman. 2018. Designing a Tree: Fabrication Informed Digital Design and Fabrication of Hierarchical Structures. In *Proceedings of the IASS Symposium 2018.* Boston, MA.
[16] Robert Fisch, Janko Gravnar, and David Griffeath. 1991. *Threshold-Range Scaling of Cellular Automata Excitable.* Technical Report.
[17] Philip Galanter. 2003. What Is Generative Art? Complexity Theory as a Context for Art Theory. *6th Generative Art Conference* (2003), 21–21.
[18] Mare Hirsch, Gabrielle Benabdallah, Jennifer Jacobs, and Nadya Peek. 2023. Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Extruding, Milling, and Machines. *ACM Transactions on Computer-Human Interaction* (July 2023). https://doi.org/10.1145/3609328
[19] Anders Hoff. 2024. *inconvergent.* Anders Hoff. https://img.inconvergent.net/plot/
[20] Tim Ingold. 2009. The Textility of Making. *Cambridge Journal of Economics* 34, 1 (2009), 91–102. https://doi.org/10.1093/cje/bep042
[21] Rachel Jacobs, Steve Benford, and Ewa Luger. 2015. Behind The Scenes at HCI's Turn to the Arts. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15).* Association for Computing Machinery, New York, NY, USA, 567–578. https://doi.org/10.1145/2702613.2732513
[22] Jeff Jones. 2010. *Characteristics of Pattern Formation and Evolution in Approximations of Physarum Transport Networks.* Vol. 16. Massachusetts Institute of Technology Press (MIT Press). 153 pages. https://doi.org/10.1162/artl.2010.16.2.16202
[23] Amy J. Ko, Robin Abraham, Laura Beckwith, Alan Blackwell, Margaret Burnett, Martin Erwig, Chris Scaffidi, Joseph Lawrance, Henry Lieberman, Brad Myers, Mary Beth Rosson, Gregg Rothermel, Mary Shaw, and Susan Wiedenbeck. 2011. The State of the Art in End-User Software Engineering. *Comput. Surveys* 43, 3 (April 2011), 21:1–21:44. https://doi.org/10.1145/1922649.1922658
[24] Chris G. Langton. 1990. Computation at the Edge of Chaos: Phase Transitions and Emergent Computation. *Physica D: Nonlinear Phenomena* 42, 1-3 (June 1990), 12–37. https://doi.org/10.1016/0167-2789(90)90064-V
[25] Jingyi Li, Sonia Hashim, and Jennifer Jacobs. 2021. What We Can Learn From Visual Artists About Software Development. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21).* Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3411764.3445682
[26] Andy Lomas. 2014. Cellular forms: an artistic exploration of morphogenesis.. In *SIGGRAPH studio (SIGGRAPH studio '14).* Association for Computing Machinery, New York, NY, USA, 1–1.
[27] Andy Lomas. 2016. Species Explorer: An Interface for Artistic Exploration of Multi-Dimensional Parameter Spaces. In *Electronic Visualisation and the Arts.* https://doi.org/10.14236/ewic/EVA2016.23
[28] Andy Lomas. 2019. Morphogenetic Vase Forms. In *ALIFE 2019: The 2019 Conference on Artificial Life.* 523–530. https://doi.org/10.1162/isal_a_00215
[29] Jesse Louis-Rosenberg and Jessica Rosenkrantz. 2024. *Projects.* Nervous System. https://n-e-r-v-o-u-s.com/projects/
[30] Jon McCormack. 2001. Art, Emergence, and the Computational Sublime. (2001), 15.
[31] Frieder Nake. 2012. Information Aesthetics: An Heroic Experiment. *Journal of Mathematics and the Arts* 6, 2-3 (June 2012), 65–75. https://doi.org/10.1080/17513472.2012.679458
[32] Frieder Nake. 2018. Someone Is Always Already There in Front of You Even Though You May Not like It. *Journal of Science and Technology of the Arts* 10, 3 Special Issue (Sept. 2018), 2–15–2–25. https://doi.org/10.7559/citarj.v10i3.569
[33] Frieder Nake. 2019. Georg Nees & Harold Cohen: Re:Tracing the Origins of Digital Media. In *Digital Art through the Looking Glass. New Strategies for Archiving, Collecting and Preserving in Digital Humanities.*
[34] Franklin Pezutti-Dyer and Leah Buechley. 2022. Extruder-Turtle: A Library for 3D Printing Delicate, Textured, and Flexible Objects. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22).* Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3490149.3501312
[35] Casey Raes. 2024. *Works.* Casey Raes. https://reas.com/
[36] Jasia Reichardt. 1971. Cybernetics, Art and Ideas: Introduction. In *Cybernetics, Art and Ideas.* New York Graphic Society, 11–17.
[37] Craig W. Reynolds. 1987. FLOCKS, HERDS, AND SCHOOLS: A DISTRIBUTED BEHAVIORAL MODEL. *Computer Graphics (ACM)* 21, 4 (Aug. 1987), 25–34. https://doi.org/10.1145/37402.37406
[38] Glenn W. Smith. 2019. An Interview with Frieder Nake. *Arts* 8, 2 (May 2019), 69–69. https://doi.org/10.3390/arts8020069
[39] Brigitte Steinheider and George Legrady. 2004. Interdisciplinary Collaboration in Digital Media Arts: A Psychological Perspective on the Production Process. *Leonardo* 37, 4 (2004), 315–321.
[40] Blair Subbaraman and Nadya Peek. 2022. P5.Fab: Direct Control of Digital Fabrication Machines from a Creative Coding Environment. In *Proceedings of the 2022 ACM Designing Interactive Systems Conference (DIS '22).* Association for Computing Machinery, New York, NY, USA, 1148–1161. https://doi.org/10.1145/3532106.3533496
[41] Jared Tarbell. 2012. *Complexification.* Jared Tarbell. http://www.complexification.net/gallery/
[42] Mert Toka. 2021. The Edge of Chaos. In *Hybrid Science Experimentation.* EXP. Experimental Photo Festival, Barcelona, Spain (online). https://www.artsteps.com/embed/61aa51b083927f0da437c43f/560/315 Group exhibition curated by Felicita Russo and Maciej Zapiór.
[43] Mert Toka. 2022. The Edge of Chaos. In *SYMADES '22.* California NanoSystems Institute, Santa Barbara, CA, USA. https://show.mat.ucsb.edu/2022 Group exhibition curated by Marko Peljhan.
[44] Mert Toka, Samuelle Bourgault, Camila Friedman-Gerlicz, and Jennifer Jacobs. 2023. An Adaptable Workflow for Manual-Computational Ceramic Surface Ornamentation. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23).* Association for Computing Machinery, New

York, NY, USA, 1–15. https://doi.org/10.1145/3586183.3606726

[45] Mert Toka, Devon Frost, Samuelle Bourgault, Avi Farber, Camila Friedman-Gerlicz, Raina Lee, Eun-ha Paek, Pilar Wiley, and Jennifer Jacobs. 2024. Practice-driven Software Development: A Collaborative Method for Digital Fabrication Systems Research in a Residency Program. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference (DIS '24)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3643834.3661522

[46] Jasper Tran O'Leary, Gabrielle Benabdallah, and Nadya Peek. 2023. Imprimer: Computational Notebooks for CNC Milling. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581334

[47] Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2021. Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on #PlotterTwitter. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3411764.3445653

[48] Hannah Twigg-Smith and Nadya Peek. 2023. Dynamic Toolchains: Software Infrastructure for Digital Fabrication Workflows. In *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology (UIST '23)*. Association for Computing Machinery, New York, NY, USA, 1–20. https://doi.org/10.1145/3586183.3606802

[49] Ashley Del Valle, Mert Toka, Alejandro Aponte, and Jennifer Jacobs. 2023. PunchPrint: Creating Composite Fiber-Filament Craft Artifacts by Integrating Punch Needle Embroidery and 3D Printing. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3544548.3581298

[50] Iris Van Herpen. 2024. *State-of-the-art*. Iris Van Herpen. https://www.irisvanherpen.com/state-of-the-art

[51] Ron Wakkary, Henry Lin, Shannon Mortimer, Lauren Low, Audrey Desjardins, Keith Doyle, and Philip Robbins. 2016. Productive Frictions: Moving from Digital to Material Prototyping and Low-Volume Production for Design Research. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16)*. Association for Computing Machinery, New York, NY, USA, 1258–1269. https://doi.org/10.1145/2901790.2901880

[52] Zi-Wei Wu, Huamin Qu, and Kang Zhang. 2024. A Survey of Recent Practice of Artificial Life in Visual Art. *Artificial Life* 30, 1 (Feb. 2024), 106–135. https://doi.org/10.1162/artl_a_00433