Rhythm Bots (2024): A Sensitive Improvisational Environment

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Rhythm Bots [1] is an actively controlled kinetic sculpture and art-making exploration of research on collective intelligence and collective behavior, translating into design principles what we understand about neural network behavior, animal behavior (e.g., flocking and schooling), and social behavior. The work is inspired by *Rhythm Bath* [2], a dance installation by Susan Marshall that explores rhythmic entrainment of an audience who are invited into a performance space with the dancers. *Rhythm Bots* extends this inquiry to consider how the rhythmic movement of robots can induce a similar kind of entrainment and whether the synchronized movement of a robot group can create a calming and meditative public space [3]. In designing a playground for human-robot interaction, we considered how human agency should impact the exhibit's rhythms and how to make the robots' behavior interpretable to the audience. The product is a group of gentle, rhythmically rotating robots that propagate movement changes across a network in response to one another and to human audience members who sit or move around them. The piece draws on expressiveness of the underlying dynamics model to encourage exploration of ambiguity in the human-robot feedback loop.

Our design is inspired by the rich body of prior work by kinetic artists such as Alexander Calder, Panagiotis 'Takis' Vassilakis, Jean Tinguely, and studio DRIFT. Each rhythm bot features a slender carbon fiber torso topped with a colorful head, all elegantly balanced on a circular base frame. While the shapes and colors of the heads share a unified visual language, their diverse hues and varying sizes convey individuality within the synchronized movements of the collective. The torso is suspended at a pivot point low to the ground to allow it to move in cyclic 3D patterns as the upward extension of a spherical pendulum. Three independently controlled horizontal linear actuators, positioned uniformly around the bot's base, connect to the bottom of the torso through springs. Rhythmic choreography of the torso emerges through anti-synchronized oscillations of the actuators. The springs add uncertainty and surprising resonances, enhancing ambiguity associated with the bot's agency.

In May 2024 at Princeton University's Wallace Theater, we created an emergent environment, sensitive to stimuli, comprised of twelve rhythm bots and human audience members. Each bot was equipped with network communications with other bots, computer-vision-enabled observations of audience members, a microcomputer to translate its "opinion" states to control of its actuators, and the ability to activate lights and sound according to its actuator control signals. Mics on the bots captured the actuator motors' clicking sounds, which were filtered and broadcast across the space.

Collective artificial intelligence was implemented through a distributed, decision-making model known as nonlinear opinion dynamics (NOD) [4], which have been successfully used to study complex social behavior. Resembling recurrent neural network (RNN) dynamics, NOD define opinion updates over time for decision-makers that exchange opinions over a network. Nonlinearity allows the model to capture deadlock-breaking, opinion asymmetry, polarization, cascades, oscillations, and more, not possible with linear models. NOD also provide tunable sensitivity to stimulus. This means that conditions for a stimulus to trigger a cascade of opinions can be modulated by explicit parameters, such as how much attention decision-makers pay to one another. The properties of NOD can be analytically predicted based on network topology.

Every bot was a decision-maker with three evolving opinion states, each controlling the position of an actuator and activating its associated movement, light, and sound. Our creative exploration of light - of how light influences human behavior and sensory experience - draws on the work of visual artists such as James Turrell, Mary Corse and Olaffur Eliasson, as well as on a rich theatrical tradition exploring the relationship between changing lighting states and audience responses (a tradition that travels through a lineage of theatrical artists from Jean Rosenthal through Tharon Musser and Jennifer Tipton). The more narrative-informed exploration - of how light can make robot behavior more visible to humans - involves an ongoing exploration of the capabilities of lighting control systems in collaboration with engineers from the leading global company ETC.

Sonically, our aim was to magnify and transform the inherently engaging, if quiet, mechanical sounds of the bots themselves, giving them a voice and an environment both at once. Older immersive and contrasting work of Brian Eno and Pauline Oliveros, and more contemporary work by sound artists such as Camille Norment and Seth Cluett, were points of reference. By mic'ing and filtering the sounds of the bots themselves, and controlling those transformations with data also coming directly from the network of bots, the real-time sound system is an outgrowth of the bot's internal machinations, extending their reach in tandem with the lighting system.

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To control the bots' movements, light, and sound, the NOD were designed over two networks: one on-board network for anti-synchronous oscillations among each bot's three opinion states and one communication network for synchrony of all twelve bots [5]. Yolov3 [6] and Deep SORT [7] were used to detect and track individual humans who were sitting or moving. The detected human presence "excited" the NOD attention parameters of nearby bots, which sped up neuron-like dispersion of signals across the communication network. Audience members were naturally motivated to learn the boundaries of what emergent patterns they could induce, developing their own notions of "real" and "non-real" influence on the environment.

The overall result was a peaceful, evolving environment featuring emergent synchronization modified by input and intermittently interrupted by dynamic movement, light, and sound events. Connecting lights and sound to the space and to the robot behavior made the research more visible and audible, while enhancing the meditative nature of the environment.

Rhythm Bots provides a creative platform for further art-making, novel human-machine physical interaction experiments involving movement, light, and sound, and continuing opportunities to use intelligent machines to impart positive feelings of wellbeing.

References

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Authors

Naomi Ehrich Leonard is Chair and Edwin S. Wilsey Professor of Mechanical and Aerospace Engineering at Princeton University. She studies dynamics, control, and learning for multi-agent systems on networks with application to multi-robot teams, collective animal behavior, socio-political networks, and other groups in nature, technology, and the arts. She is a MacArthur Fellow, member of the American Academy of Arts and Sciences, and recipient of the 2023 IEEE Control Systems Award and 2024 Richard E. Bellman Control Heritage Award. Past art collaborations include "FlockLogic" with choreographer Susan Marshall and "There Might Be Others" with choreographer Rebecca Lazier and composer Dan Trueman.

Jane Cox is an internationally known lighting designer working in theater, opera, dance, music and experimental practices. Her work as a designer focuses on how light, color and movement impact emotion and reveal space, relationship and narrative. She is also a long-time educator, the Director of the Program in Theater and Music Theater at Princeton since 2016 as well as a Professor of the Practice since 2021, and a creative producer. She is a four time TONY nominee and was awarded the TONY and Drama Desk for lighting in 2024.

Dan Trueman is a musician: a fiddler, a collaborator, a teacher, a developer of new instruments, a composer of music for ensembles of all shapes and sizes. He has worked with ensembles such as So Percussion, the PRISM Quartet, Eighth Blackbird, Gallicantus, the JACK Quartet, as well as individuals like scientist Naomi Leonard, choreographer Rebecca Lazier, poet Paul Muldoon, director Mark DeChiazza, fiddler Caoimhín Ó Raghallaigh, vocalist Iarla Ó Lionáird, guitarist/songwriter Monica Mugan, pianists Adam Sliwinski and Cristina Altamura, and many others. Dan's work has been recognized by fellowships, grants, commissions, and awards from the Guggenheim Foundation, the Barlow Endowment, the Bessies, the Fulbright Commission, the American Composers Forum, the MacArthur Foundation, the American Council of Learned Societies, Meet the Composer, among others. He is Professor and Chair, Department of Music at Princeton University.

María Santos is a core team researcher at H Company, Paris, France. She received the B.S. and M.S. degrees in industrial engineering from the University of Vigo, Vigo, Spain, in 2013 and the M.S. and Ph.D. degrees in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 2016 and 2020, respectively. From 2020 to 2024 she was a postdoctoral research associate with the Department of Mechanical and Aerospace Engineering at Princeton University, Princeton, NJ, USA. She is interested in agentic approaches to artificial intelligence, with a focus on multiagent systems. Dr. Santos was the recipient of a Fulbright Scholarship in 2014 and of "la Caixa" Foundation Fellowship in 2017.

Kathryn Wantlin is a Ph.D. student in Computer Science at Princeton University. She also completed her undergraduate degree at Harvard and an M.S.E. at Princeton, all in computer science. Her research interests center around the design of algorithms for machine learning and multi-agent systems, and her Master's thesis modeled decentralized morphogenesis with statistical point processes. She is currently interested in questions surrounding joint evolution of control and morphology in nature and reproducing these properties in engineered systems.

Isla Xi Han is a Ph.D. candidate in architectural technology and materials science at Princeton University. Her work delves into the collaborative potential of human-robot interaction within architectural contexts, ranging from design to computation to implementation. Her creative construction work has won the 2021 R+D Award for Robotic Construction and the MUSE Creative Silver Awards 2024 for Architectural Design - Pop-Ups & Temporary.

Sarah Witzman graduated from Princeton University with an M.Eng and B.S.E. in Mechanical and Aerospace Engineering. She is especially interested in robotics and their applications within the arts, and she spent her independent research and senior thesis exploring human-robot interaction and robotic design with the Rhythm Bots project.

Tess James (she/hers) is a freelance Lighting Designer. Her recent projects as a designer include *The Song of the Nightengale* for OnSite Opera, *Assassins* and *The Cradle Will Rock* at Classic Stage Company, and *The Running Show* with Monica Bill Barnes & Company. As an associate designer her work has included *Appropriate*, *Macbeth*, *True West*, and *King Lear* on Broadway. She is a full-time Lecturer at Princeton University and a Master Teaching Artist with Education at Roundabout.