NodeBots: Physicalizing Network-Based Data with SwarmUIs

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Abstract

Data Physicalization is an emerging area of data representation that uses a wide variety of physical mediums and data sources. We propose 'NodeBots', a novel approach that integrates Swarm User Interfaces (SwarmUIs) with Network Visualizations to create an interactive, swarm-based physicalization of network graphs. NodeBots allows users to physically interact with the nodes of network graphs, creating physical metaphors for embodied graph interactions through the rich affordances of SwarmUIs. In this paper, we explore NodeBots' interaction space and its applied interactions, such as sparse cuts and shortest paths.

CCS Concepts

• **Human-centered computing → Interaction devices**.

Keywords

Actuated Tangible User Interface, Embodied Interaction, SwarmUIs, Network Graphs

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1 Introduction

Researchers in HCI have previously explored how embodied concreteness can improve the ability to grasp abstract mathematics [1]. Similarly, researchers have surveyed the applications of SwarmUIs in education [5], physics simulation [8], and interaction with spatial and composite information [7, 11]. Researchers have also experimented with transforming abstract and complex tasks into physical constraints [9] and static network physicalizations [2, 6, 10]. While previous HCI research has explored static network physicalization and SwarmUIs for data physicalization, there is a gap in research on dynamic graph physicalizations. NodeBots presents a novel platform that explores this gap by marrying an Eades Force-Directed graph [3] with embodied interactions.

2 NodeBots

NodeBots expresses the connections between data nodes, where more connected nodes are pulled closer, while unconnected nodes are pushed apart. The simulation reaches equilibrium at an ideal state, where all attractive and repulsive forces are balanced. Previous force simulations for network graphs have only been manipulable through touchscreens and mouse and keyboard. NodeBots extends this functionality through the rich affordances of SwarmUIs.

2.1 Interaction Space

The NodeBots interaction space explores *Network Perception*, *Network Interaction*, and *Network Exploration* (Figure 1).

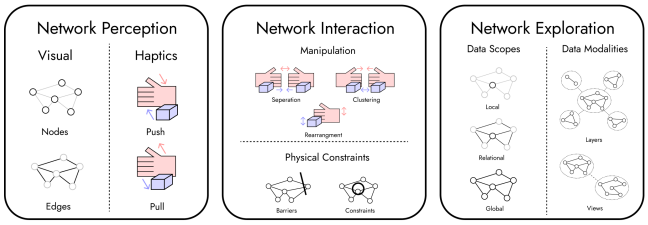


Figure 1: Interaction Space

2.1.1 Network Perception. NodeBots facilitates new forms of Network Perception through **Haptic Feedback**, such as feeling the force applied to a node, and **Visual Feedback**, such as seeing how nodes respond within the projected simulation. Haptic feedback occurs through *Pushing* and *Pulling*, which let users directly apply force to the nodes and feel the network resist as the nodes attempt to return to an ideal state. Visual feedback is provided through imagery and text projected onto the space, offering context about the *Nodes* and *Edges*, including node icons, edge weights, and details such as names and properties.

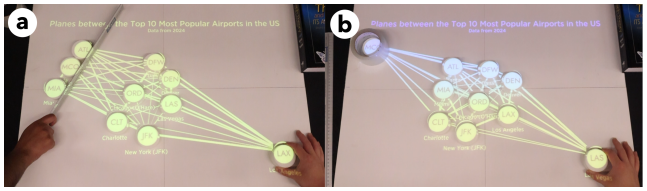


Figure 2: Physical Constraints: (a) Barriers and (b) Constraints

2.1.2 Network Interaction. NodeBots is uniquely capable of physicalized Network Interaction through **Manipulation** and **Physical Constraints**. Users can interact with multiple nodes simultaneously, enabling them to perform multiple tasks at once, or use them to perform other tasks, such as sorting or searching.

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Manipulation enables users to directly modify the graph and feel force feedback. *Separation* pulls nodes away from the larger network. *Clustering* pushes multiple nodes together into a collective group. *Rearrangement* transforms the network's topography by moving nodes to new positions.

Physical Constraints can take the form of *Barriers* or *Constraints*. Barriers completely partition an individual node or a group of nodes from the larger overall graph (Figure 2a). Constraints limit the range of motion of individual nodes (Figure 2b). These constraints are carried into the simulation, converting the physical constraints into 'computational constraints'.

2.1.3 Network Exploration. Through its physicalized network perception and interaction, NodeBots allows a more concrete understanding of a network graph at different **Data Scopes**. At the *Local* level, users can understand details about specific nodes, such as their names and any visuals. At the *Relational* level, users can understand the relationships between nodes and their immediate neighbors, such as whether two nodes are connected and to what degree. On the *Global* level, they can understand the overall topography of the network, such as its overall density and shape, which can reveal features such as clusters or isolated nodes.

NodeBots also provides exploratory structures in the form of **Data Modalities**. *Data Layers* allow for exploring individual aspects in greater detail, such as focusing on a subgraph within a larger graph. For example, Figure 3a shows two layers of network data: The top layer shows the connections between different research areas at the University of Chicago, while the bottom layer shows the connections among researchers within the Human-Computer Interaction research area. *Data Views* present different perspectives of the same network, such as different connections between the same set of nodes. Figure 3b shows two views of the same data: The first view shows the number of planes flying between the top ten U.S. airports, and the second view shows the number of buses between their corresponding cities. These data modalities allow users to feel and explore the difference between sets of connections.

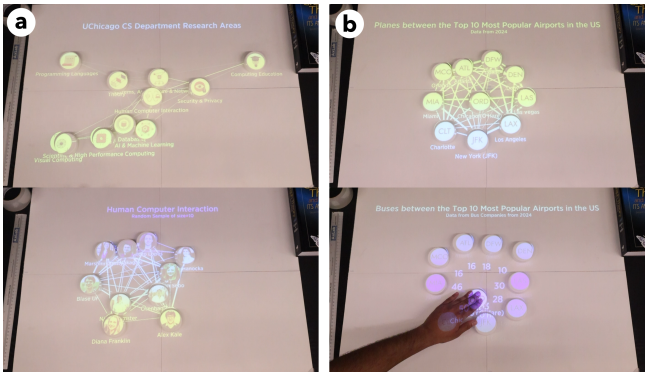


Figure 3: Data Modalities: (a) Swapping between UChicago Research Areas and UChicago researchers with Data Layers and (b) Swapping between planes and buses between the most popular U.S. airports with Data Views

2.2 Technical Implementation

The NodeBots simulation loads a set of nodes and edge weights into an Eades Force-Directed node simulation. Each node a exerts a repulsive force on each other node b with a strength of:

$$\frac{c_{rep}}{||a-b||^2} \cdot \overrightarrow{ab}$$

Each edge between nodes a and b with an ideal distance $l_{a,b}$ exerts a force of:

$$c_{attr} \cdot \log \frac{||a-b||}{l_{a,b}} \cdot \overrightarrow{ab}$$

where c_{rep} and c_{attr} are the repulsion and attraction parameters used to scale the simulation, and each ideal distance is derived from context-dependent edge weights (stored in a .csv file).

This simulation runs continuously, communicating with the robots to receive their live position and send commands, enabling users to intervene and interact in real time. Building on the velocity-targeting system from Physica [8], in which the robots travel along a smooth path to their target, NodeBots targets a node's corresponding virtual position. The simulation is then projected onto the nodes. As users pull or push on the nodes, they will feel the haptic feedback from the network and see the visual feedback from the real-time projection. As users place physical constraints, the simulation will be similarly constrained. Users can also interact with the nodes by pressing them with short or long presses, which can trigger context-specific interactions.

2.3 Hardware

NodeBots uses toio robots [4], which are cube-shaped robots that contain an infrared light and an on-board button, allowing position tracking on specialized toio mats and registering button presses from users. A single computer can connect up to 10-12 toios at once. We 3D-printed custom shells to allow an overhead projector to display visuals cleanly on each node.

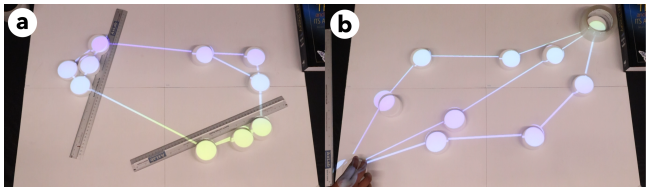


Figure 4: Applied Examples: (a) Sparse Cuts and (b) Shortest Path

3 Examples

3.1 Applied Examples

NodeBots' tangible interactions enable users to physically apply graph algorithms for an embodied learning and understanding when interacting with network graphs.

For example, NodeBots enables users to explore approximation algorithms. The system enables users to physically solve problems such as *Sparse Cuts*, which partition a network graph into smaller

subgraphs (Figure 4a). Through physical network interaction, the user can explore different cuts to find the optimal solution.

Similarly, NodeBots also enables users to physically explore and solve for *Shortest Paths*. As a user pulls apart two selected nodes, the tension in the graph will pull the shortest path "taut", intuitively revealing it (Figure 4b).

3.2 Other Examples

There are other potential applications not explored in this paper. Some notable examples of data that could be physicalized by NodeBots include:

- Research Papers: Overlapping citations between related research papers can serve as the basis of a network, with edge weights representing co-citation.
- Social Media: Connections between individuals on social platforms such as "Facebook", "LinkedIn", or "Venmo" can be expressed as networks.
- Evolutionary Trees: Branching species on the evolutionary tree can be expressed as tree graphs.
- Financial Connections: Financial Institutions such as banks form a network of capital and money flow, with edge weights representing monetary value.

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