# Physecology: A Conceptual Framework to describe Data Physicalizations in their Real-World Context

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The standard definition for 'physicalizations' is *"a physical artifact whose geometry or material properties encode data"* [47]. While this working definition provides the fundamental groundwork for conceptualizing physicalization, in practice many physicalization systems go beyond the scope of this definition as they consist of distributed physical and digital elements that involve complex interaction mechanisms. In this paper, we examine how 'physicalization' is part of a broader ecology — the 'physecology' — with properties that go beyond the scope of the working definition. Through analyzing 60 representative physicalization papers, we derived six design dimensions of a physecology: (i) represented data type, (ii) way of information communication, (iii) interaction mechanisms, (iv) spatial input-output coupling, (v) physical setup, and (vi) audiences involved. Our contribution is the extension of the definition of physicalization to the broader concept of 'physecology', to provide conceptual clarity on the design of physicalizations for future work.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**.

Additional Key Words and Phrases: Data Physicalization, Physical Visualization, Physecology, Conceptual Framework

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## 1 INTRODUCTION

Data physicalization as a research area is most closely related to work on information visualization [71, 72], tangible user interfaces [27, 89], shape-changing interfaces [2, 82], and ambient information displays [77]; but has emerged as its own field of inquiry over the past ten years. In 2015, Jansen et al. [47] proposed the working definition for *data physicalizations*, or simply *physicalizations*, as *"a physical artifact whose geometry or material properties encode data"*. While this definition accurately describes the fundamental idea of the physicalization of data – it can also be interpreted and operationalized across a range of different forms, representations, audiences, and contexts [21, 22, 47]. Hence, the definition crystallizes the immediate properties of physicalizations, but the wider context is less well described. Research in this area can also tend towards being device-centric, focusing on enabling the design through specific interaction techniques or actuation mechanisms [2, 47], and does not further incorporate or consider the surrounding physical world and broader context when investigating physicalizations.

Physicalization research evidences many ways in which physicalizations (and related artifacts) are described, including *data sculptures* [106], *casual information visualizations* [78], *constructive*

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*visualizations* [41], *embedded data representations* [105], and *dynamic composite data physicalizations* [61]. Additionally, there are various interaction forms possible, such as using gestures [96], the manual re-arrangement of data objects [42, 46], or the pushing/pulling of physical bar charts [97]. The limited conceptualization of the context of use in physicalizations is also increasingly reflected in empirical research, as exemplar physicalization designs have shown to be ambiguous in how they were perceived [46, 87], and therefore interacted with [88]. Furthermore, design explorations [24, 61, 96] and field studies [39, 84, 85] outline the challenges of using physicalizations as mediators for complex tasks, and the importance of making them intuitive and context-sensitive interfaces for interaction with data. Lastly, research outside the field of physicalization has previously shown that context is as important as the artifact or device itself [1, 20]. For example, Fishkin's framework [27] on tangible user interfaces (TUIs) illustrates how users can have different forms of embodied relations to the physical interface. Likewise, work on *proxemic interaction* [3] shows the intricate relations that exist between people, digital devices, and the surrounding environment. This raises questions on how this knowledge transfers to the use of physicalizations in the real-world.

The physical and tangible nature of physicalizations inherently makes them susceptible to their surrounding audience and context, and all interactions that can exist within and around them. Therefore, we base our inquiry around building and exploring the definition and construction of the 'ecologies' that make up data physicalization research. Based on our reflections on physicalization and a selection of related literature, we introduce *physecology* (a neologism of 'physicalization' [47] and 'ecology' [31] – see Section 5) as unit of analysis that considers this important wider context surrounding physicalizations, and unites it through six design dimensions: (i) data type represented; (ii) method of information communication; (iii) interaction mechanisms; (iv) spatial coupling of input/output; (v) physical setup; and, (vi) type of audience. We build directly on the broadly accepted definition of 'physicalization' [47], and extend it with these intertwined dimensions to provide a further conceptual understanding of how physicalizations are used in real-world scenarios. To evidence our thinking, we describe a selection of existing research on physicalizations through these six lenses, illustrating how their properties go beyond the scope of the current working definition of physicalization. Based on the review of these dimensions of the conceptual framework, we discuss existing archetypes and opportunities for further research and design implications.

With this work we aim to expand the working definition of data physicalization, considering the complete 'ecology' [31, 50] that makes a physicalization, and introduce the term *physecology* to encompass the relationship between all design elements – physical and digital – surrounding a physicalization. Further, we contribute an overview of the design dimensions of a physecology, to provide conceptual clarity on the design space of physicalizations, and outline possible future work in this area.

## 2 BACKGROUND

To clarify how our work builds on prior ideas and concepts around 'physicalization', we briefly present the background of data physicalization as a research area, discuss previously developed conceptual models, reflect on insights from related research fields, and finally, introduce the concept of physecology.

### 2.1 Data Physicalization

Whereas people have been creating physical depictions of data for centuries [21], only more recently has this been identified as an emerging research area [47, 106]. In 2008, Zhao and Vande Moere [106] introduced the term *data sculpture* as *"a data-based physical artifact, possessing both artistic and functional qualities, that aims to augment a nearby audience's understanding of understanding of data insights and any socially relevant issues that underlie it"*. This term put emphasis on the artistic and social nature of physical depictions of data. Later in 2015 Jansen et al. [47] defined *data physicalization* or *physicalization* as *"a physical artifact whose geometry or material properties encode data"* [47], which is now commonly used to describe physical depictions of data.

Additionally, there are many more ways in which physicalizations (and related artifacts) have been described. *Casual information visualization* [78] acknowledged there are motivations beyond information retrieval such as more ambient, social or artistic depictions of data for it to be used in everyday life. Others have focused on the reconfigurable nature of physicalizations, such as *constructive visualizations* [41] which focus on manual reconfiguration of physical tokens as an infovis authoring tool, or *dynamic composite data physicalizations* [61] which further characterize the manual and/or actuated reconfiguration of a collection of physical objects to depict data. Lastly, *embedded data representations* [105] focus on the integration of visual and physical representations of data in physical spaces. Hence, there are a variety of ways to describe physical depictions of data, and these definitions have different vocal points or topics of inquiry.

## 2.2 Study and Use of Physicalizations

Research contributions in the area of physicalization tend to be primarily *device-centric,* such as specific interaction techniques or actuation mechanisms [2, 47] to advance the design of physicalizations. These contributions are mainly concerned with the physicalization itself, isolated from the surrounding physical world it exists within. Looking at empirical research in the area, exemplar studies on the fundamentals of physicalization design illustrate different perceptions of size across physical shapes [46], ambiguity in perception of physical information across perspectives [87], and variety in people's strategies when organizing physical information [88]. Lastly, design [24, 61, 96] and field studies [39, 84, 85] show the myriad of different ways in which system infrastructures are designed and how they are used and appropriated in context. To give some examples, the design explorations of PolySurface [24] and Zooids [61] both aim to demonstrate the variety of their possible domain applications, but use different implementations and interaction mechanisms to do so. PolySurface [24] combines on-surface projection and a grid of individually actuated pins which can be controlled through interactive buttons, whereas Zooids [61] makes use of a collection of wheeled micro-robots that can be controlled through both direct (touch) and indirect (tablet) interaction. Regarding field studies, we observed different appropriations and deployment methods, for example Physikit [39] was under shared responsibility and control of a household to visualize environmental data in their home through an interactive tablet interface, whereas LOOP [85] independently visualized personal data from an individual (without user intervention) for it to be observed by the household.

Summarizing, fundamental empirical work illustrates the challenges of implementing physicalizations in physical 3D space, as their physicality and tangibility makes them inherently susceptible to their surroundings. Moreover, design and field studies show the variety of ways physicalizations can be implemented and interacted with in context. Therefore, there is a need to expand the focus of physicalization research from device-centric towards treating them as part of a larger ecology, and describe and study them in relation to their surrounding context and audience.

## 2.3 Surveys and Conceptual Models

Together with introducing the working definition for physicalization in 2015, Jansen et al. [47] also laid out a research agenda for the field of physicalization. Herein, they acknowledged the challenges of translating established concepts from information visualization into the field of physicalization. For example, they discuss the research challenge of identifying *physical variables* (additional to *visual variables* [5]) as physicality can go beyond solely visual concepts, and we need to identify these to understand the design space of physicalization. In 2020, Dragicevic et al. [22] provided a further overview of the research area of data physicalization, categorized by different motivations to create and use them.

Moreover, different conceptual models have been introduced to expand our understanding of physicalizations and provide new ways of describing them. Examples are conceptual models such as the *extended infovis pipeline model* [45] – which describes the complete process from raw data to a visualization rendered in the physical world – and the *physical rendering process* [18] – which unpacks the 'rendering' process of the prior model in further detail.

These prior surveys and models shaped the scope and agenda of data physicalization as a research area, and provide important insights on how to bring physicalizations into existence within the physical world. However, this could be expanded with further reflections on how physicalizations coexist with their surroundings beyond the realization of the physical representation.

### 2.4 Insights from Related Research Areas

Research on data physicalization shows close relation with the research areas of information visualization [71, 72], tangible user interfaces [27, 89], ambient information displays [77] and shape-changing interfaces [2, 82]. In contrast to physicalization research, research outside the field has focused more on the role of context, showing it is as important as the artifact or device itself [1, 8, 20]. Knowledge in these areas is transferable to physicalizations, such as insights on the directness of interaction [82]; the coupling between user and system [27]; the intricate relations between people, devices, and their surroundings [3]; as well as the situatedness of visualizations in their physical context [9].

### 2.5 Introducing Physecology

To conclude, the working definition for physicalization could benefit from expansion as prior work shows a variety of ways to describe, operationalize and deploy example systems, beyond the scope of the current working definition. Moreover, contributions in the research area tend to be device-centric and would benefit from considering a further context. Conceptual models have been proposed inside and outside the field that already expand on this device-centric view, but so far no attempt has been done to synthesize these concepts specifically tailored for the field of physicalization. Hence, we propose to consider a physicalization together with its surrounding context of use – the 'physicalization ecology' or *physecology* – and discuss them together to expand our vocabulary for and understanding of physicalizations in the real-world.

## 3 MOTIVATION & CASE STUDIES

To motivate our work we discuss five case studies, using varied examples from related work, to illustrate how the current definition of physicalization is wider than just its physical or material properties, and how it does not provide a further explanation or dissection of all the different features of these systems. For each of the examples we reflect upon (i) what information is represented, (ii) how this information is represented, (iii) how the information can be changed and/or interacted with, (iv) what the input/output mapping is, (v) what the physicalization setup consists of, and lastly (vi) who is engaging with the physicalization in what way.

We have chosen these five case studies to give a sense of the breadth of the existing work in data physicalization, and how research in this field differs by approach and deployment. The justification for the selection of these five particular works is to create a complementary set of representative examples that illustrate the variety in features of existing systems beyond the scope of the working definition. Table 1 shows the direct comparison of the case studies based on the factors above (i-vi).


| | Physikit [39] | Econundrum [84] | PARM [79] | Mill Road [57] | EMERGE [97] |
|---|---|---|---|---|---|
| **What information is represented?** | Real-time online environmental data | Real-time online personal data on climate impact of dietary choices | Terrain data of national park from static file | Community voting data from static file | UK rainfall data and survey data from static file |
| **How is this information represented?** | Movement, light, sound, and vibration | Height change (from ceiling) and colored LED lights | Set of projections | Chalk spray stencils | Height change and colored LED lights |
| **How can the information be changed and/or interacted with?** | Reconfiguration of the cubes via touch interface | Submission of input data via mobile application | No interaction | Submission of input data via button system | Exploration of data via the physical bars and surrounding displays |
| **What is the I/O mapping?** | Interaction via medium surrounding the physicalization | Interaction via medium surrounding the physicalization | No mapping | Interaction via medium at a distance from the physicalization | Interaction with physicalization and via surrounding medium |
| **What does the physicalization setup consist of?** | Physicalization and tablet | Physicalization and mobile application | Physicalization, projection and display | Physicalization and button voting system | Physicalization and four tablets |
| **Who is engaging with the physicalization and in what way?** | Household interaction, visitors to home can spectate | Employees own and interact, visitors to workspace can spectate | Visitors to pub can spectate | Members of the public can interact and spectate | Open-ended user engagement |

Table 1. An overview of the case studies illustrating how their differing features go beyond the physical properties of a physicalization and include a wider interaction context.

### 3.1 Case Study 1: Physikit

Physikit [39] is a system consisting of a digital screen-based touch interface to control physical cubes (PhysiCubes) containing different physical properties (such as light, vibration, and movement), for members of a household to visualize real-time environmental data (for example air quality, temperature and humidity) in their home environment. Hence, the physicalization of Physikit is not solely a physical data embodiment, but includes an input interface to control the output visualization (PhysiCubes). The user interaction is meant to reconfigure the settings for the cubes, whereas the input comes from an online database. Moreover, the cubes can be moved around and appropriated in the home environment, so input and output can happen in different locations and at different times. Additionally, beyond the physical form or material properties of the PhysiCubes, their multimodal output (such as vibration, airflow, and light) is the actual method of communicating the data visualization. Lastly, multiple users within the household can interact with the digital touch interface and appropriate the PhysiCubes in their home, which has implications for different user roles and social interactions with the system. In contrast, visitors to the home would be mere spectators of the visualization (Physicubes).

### 3.2 Case study 2: Econundrum

Econundrum [84] is a ceiling mounted physical display which maps users' dietary choices to carbon emissions to encourage food habits that might produce lower environmental impact. The installation collects personal data on food consumption via a simplified mapping of 10 food types over four meals, and three portion sizes. This input data updates in real time and provides categorical and quantitative information, respectively shown via colored LED lights and icons, and height change (distance from ceiling) showing changes in the overall level of climate impact of each user. Users could input their data via a mobile application, either in close proximity to the physicalization situated in their shared workspace, or remotely. The audience comprised of those working in the shared workspace and providing input to the system, although visiting spectators from the university building could view and discuss the data as well.

### 3.3 Case Study 3: PARM

Projection Augmented Relief Models or PARM [79, 80], represents a technique used to map digital information to a physical display in a semi-public space. In the case of a more recent study [79], the physicalization presented a Digital Surface Model (DSM) of terrain data in the English Lake District national park. Digital imagery is projected from above onto an accurate 3D model of the park, and cycles through a set number of projections, highlighting places of interest, footpaths, and environmental conditions amongst others. Although users can touch the surface, it provides no interactive capabilities. The setup uses a display to extend the spatial model and provide extra information to the spectators, made up of visitors to the Sticklebarn pub (situated in a valley in the heart of the English Lake District).

### 3.4 Case Study 4: Mill Road

Mill Road [57, 58] was an urban visualization project consisting of voting systems placed in local shops and chalk images stencilled onto the roads of the street used to engage the local community. The research collected communal data consisting of perceived differences about the two ends of the same road (such as feeling of safety, wellness) which was voted upon by members of the public. The data was input using three buttons with icons, for example, wellness on a three-point scale represented by a sad, neutral, or happy face. The collected data was stencilled onto the pavement outside each voting station every other day using colored chalk spray in an isotype-inspired [74] visualization of 10 human-like figures categorized by three colors, each one representing 10% of the votes. A comparative piece was placed at the railway bridge dividing each end of the road. Members of the public indirectly influenced the visualizations using the voting boxes in the local shops and cafes, and could see the aggregated data the following day on the pavement. Those who had not voted inside the shops were also able to view and comment on the data, and engage in open discussions with the local community.

### 3.5 Case Study 5: EMERGE

EMERGE [96, 97] is a tabletop sized interactive bar-chart driven by 100 linear actuators in a $10 \times 10$ grid, built solely to display physical data in an interactive way. The device falls into the dual remit of data physicalization but also that of shape-changing interfaces. In the published work, EMERGE displays one of two datasets – either 100 years of rainfall in the United Kingdom, or measures of 'appropriate' behavior taken from a survey of college students in the 1970s. Although these datasets are used as examples, other CSV files can be uploaded. The height of each bar represents the input value and is comparable with its neighbouring bars. Interaction occurs either directly on the physical surface (for example push, pull, and tap) or from tablets positioned on each side of the array (such as scroll and select). The bars can be highlighted or hidden, and hidden parts of the dataset can be navigated to by using the tablets to scroll left or right. The setup is a metre tall cabinet which houses the mechanisms that drive the bars, with a tablet on each side of the $10 \times 10$ grid. Each bar contains an LED array which can change color, and switch on/off, according to its programming – although the color does not communicate data directly. The current publications suggest single user input, but the tabletop nature of the device, and availability of tablets, could support up to four users or observers at one time.

### 3.6 Case Study Summary

As illustrated by the above five case studies, and as summarized in Table 1, each of the exemplar systems has a unique composition of digital and physical features – beyond mere physicalization – that together allow for the communication of, and interaction with data. To give an example, the information presented can range from a real-time online dataset, to a static file, and the information can be presented in different ways, such as change in height, projection, or even chalk spray stencils. Moreover, the change of information can be done for different reasons (for example reconfiguration, data input, or exploration) and through different means (such as indirectly via a touch interface or mobile application, or by directly touching the physicalization), which also shows in the implementation of the system setup (for example the inclusion of tablets or displays). Lastly, physicalizations can exist in different contexts (for example at home, workspace, or pub) and can have different kind of audiences (such as users and/or spectators).

## 4 METHODOLOGY

In this paper, we reflect on how physicalizations are used in context. Through a meta-review, we derive key insights, concepts, and design dimensions that characterize and expand the concept of physicalization into a wider *physecology*. The goal is to demonstrate that physicalizations are part of a wider ecology of input, output and mediating mechanisms that collectively create an effective and interactive system (physecology). We report the results of a meta-review based on an analysis of a representative set of 60 physicalization papers.

### 4.1 Selection and Corpus

Based on the insights from analyzing the case studies discussed above, we compiled a list of selected physicalizations. We used the 'List of Physical Visualizations' from Jansen et al. [21] as a starting point for our analysis, including examples from the 'Active physical visualizations' tab and excluding any submissions that included disclaimers such as 'not a physicalization'. We also conducted a systematic search in the ACM Digital Library (May 2021) to include research papers for this analysis, focusing on recent publications (from 2004 onward). We chose the ACM Digital Library as it is the primary research repository for physicalization research. Our search terms included '*physicalization*', all combinations of '*physical*' with '*(data) visualization*', '*data representation*', '*constructive visualization*', and '*data sculpture*'. A subsequent search of the IEEEXplore database (using the same keywords) resulted in an additional 3 relevant papers [60, 95, 97]. These search terms slightly broaden the scope of physicalization in an attempt to be inclusive in criteria. As a result there might be a few examples that present edge cases in relation to the core definition of physicalization.

We excluded contributions on *shape-changing interfaces*, *TUIs*, *ambient displays*, and other related artifacts that did not focus on *data physicalization* specifically. We excluded speculative or conceptual work with no technical realization or implementation of a physicalization system. Additionally, we included 4 relevant examples of *analog physicalizations* [26, 34, 42, 100] to complete the selection, as their manual reconfiguration possibilities afforded the same degrees of input as interactive physicalizations. For a complete sample list see Table 2[1].

### 4.2 Analysis

We argue that most of the current exemplar implementations of physicalizations in the real world go beyond the working definition. Therefore, for the analysis we applied an interpretive approach [81], based on (i) the researchers' own experiences and observations, (ii) the case studies as described above, and (iii) reflections on literature of physicalization research and related fields.

The analysis was performed in two iterations. First, we performed an initial labelling of all physicalizations followed by affinity diagramming [65], and constructed overarching clusters using axial coding (these clusters were the foundation for the final set of six dimensions). Afterwards, we

[1]Sample list data: https://physecology.github.io/dataphys/

| | | | | | DATA TYPE | | | | | INFO COM | | | | INTERACTION | | | | | | I/O COUPLING | | | | SETUP | | | AUDIENCE | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | SAMPLE | VENUE | YEAR | REF | Static | Dynamic | Categorical | Ordinal | Quantitative | Positioning in space | Control optical properties | Control material properties | Specialized applications | No interaction | Direct interaction | Indirect interaction | Manipulation | Exploration | Configuration | Full | Nearby | Environmental | Distant | Standalone | Spatial Distribution | Logical distribution | Private | Semi-public | Public | Open-ended |
| 1 | XenoVision Mark III | | 2004 | [29] | x | | x | | x | x | x | | | | | x | | | x | | x | | | | | x | | | | x |
| 2 | Garden of Eden | | 2007 | [21] | | x | | | x | | | x | | x | | | | | | | | | | | x | | | | x | |
| 3 | Wable | | 2007 | [56] | | x | | | x | x | | | | | | x | | x | | | x | | | | | x | | x | | |
| 4 | Centograph | | 2009 | [101] | x | | | | x | x | | | | | | x | | x | | | x | | | | | x | | x | | |
| 5 | DataMorphose | | 2009 | [52] | x | | x | | x | x | x | | | x | | | | | | | | | | | x | | | | | x |
| 6 | Poly | | 2009 | [17] | | x | | x | | x | | | | x | | | | | | | | | | x | | | | x | | |
| 7 | Pulse | | 2009 | [55] | | x | | x | | x | | | | x | | | | | | | | | | x | | | | x | | |
| 8 | Virtual Gravity | | 2009 | [36] | x | | | | x | x | x | | | | | x | | x | | | x | | | | | x | | | | x |
| 9 | Clouds | UbiComp | 2010 | [83] | | x | | | x | x | | | | | | x | x | | | | | | x | x | | | | x | | |
| 10 | Dust Serenade | | 2010 | [21] | x | | | | x | | | | x | | | x | | x | | | x | | | x | | | | | | x |
| 11 | eCLOUD | | 2010 | [33] | | x | x | | x | | x | x | | x | | | | | | | | | | | x | | | | x | |
| 12 | Relief | TEI | 2010 | [62] | x | | x | | x | x | x | | | | | x | | x | | | x | | | x | | | | | | x |
| 13 | Tidy Street | Pervasive | 2010 | [6] | x | | x | | x | | x | | x | x | | | | | | | | | | | x | | | | x | |
| 14 | Recompose | CHI EA | 2011 | [7] | x | | | | x | x | x | | | | x | x | x | x | | x | x | | | x | | | | | | x |
| 16 | Emoto | | 2012 | [73] | x | | x | | | | x | | | | | x | | x | | | x | | | | | x | | | x | |
| 17 | Pulse: Tangible Line Graph | | 2012 | [69] | | x | | | x | x | | | | | | x | | | x | | x | | | x | | | x | | | |
| 18 | Chaotic Flow | | 2012 | [66] | x | | | | x | | | | x | x | | | | | | | | | | x | | | | x | | |
| 19 | Point Cloud | | 2012 | [63] | | x | | | x | x | | | | x | | | | | | | | | | x | | | | | | x |
| 20 | Season in Review | | 2013 | [59] | x | | | x | | | x | | | | | x | | x | | | x | | | | | x | | | | x |
| 21 | inFORM | UIST | 2013 | [28] | x | | x | | x | x | x | | | | x | x | x | x | | x | x | | | x | | | | | | x |
| 22 | Pneumatic Charts | | 2013 | [21] | x | | | | x | | | | x | x | | | | | | | | | | x | | | | x | | |
| 23 | Tidal Memory | | 2013 | [91] | | x | | | x | | | | x | x | | | | | | | | | | x | | | | | x | |
| 24 | SweatAtoms | CHI | 2014 | [54] | x | | | | x | | | | x | | | x | x | | | | | x | | | | x | x | | | |
| 25 | Activity Sculptures | IEEE | 2014 | [95] | x | | | | x | | | | x | | | x | x | | | | | | x | x | | | x | | | |
| 26 | Drip-by-Tweet | | 2014 | [92] | | x | | x | | | | | x | x | | | | | | | | | | x | | | | x | | |
| 27 | #Good vs. #Evil | | 2014 | [23] | | x | | x | | x | | | | x | | | | | | | | | | x | | | | | | x |
| 28 | Tangible tokens | IEEE | 2014 | [42] | x | | | | x | x | | | | | x | | | | x | x | | | | x | | | | | | x |
| 29 | x.pose | | 2014 | [13] | | x | | | x | | | x | | | | x | x | | | | | x | | x | | | | | | x |
| 30 | Mood Squeezer | CSCW | 2015 | [30] | | x | x | | | | x | | | | | x | x | | | | | | x | | | x | | x | | |
| 31 | Passim | | 2015 | [35] | x | | x | | | | x | | | x | | | | | | | | | | x | | | | | | x |
| 32 | Tempescope | | 2015 | [51] | | x | x | | | | | | x | | | x | | | x | | | x | | | | x | x | | | |
| 33 | Visualizing Mill Road | CHI | 2015 | [57] | x | | | x | | | | | x | | | x | x | | | | | | x | | | x | | | x | |
| 34 | Wage Islands | | 2015 | [43] | x | | | | x | x | | | x | | | x | | x | | | x | | | | | x | | | x | |
| 35 | Actuated Prism Map of Italy | | 2016 | [68] | x | | | | x | x | | | | | | x | | x | | | x | | | | | x | | | | x |
| 36 | Dataponics | DCS | 2016 | [12] | | x | | | x | | | x | | | | x | x | | | | | x | | | | x | x | | | |
| 37 | FizViz | | 2016 | [90] | | x | x | | x | x | x | | | | | x | | | x | | | | x | | | x | | x | | |
| 38 | Physikit | CHI | 2016 | [39] | | x | | | x | x | x | | x | | | x | | x | x | | | x | | | | x | x | | | |
| 39 | Podium | | 2016 | [44] | | x | | | x | x | | | | | | x | | | x | | x | | | | | x | | x | | |
| 40 | ShapeCanvas | CHI | 2016 | [25] | x | | x | | x | x | x | | | | | x | | | x | | x | | | | | x | | | | x |
| 41 | Squeezy Green Balls | CHI PLAY | 2016 | [48] | | x | | x | | | x | | | | | x | x | | | | x | | | | | x | | x | | |
| 42 | EMERGE | IEEE | 2017 | [97] | x | | x | | x | x | x | | | | x | x | | x | | x | x | | | | | x | | | | x |
| 43 | Microsoft Research Physical Charts | CSCW | 2017 | [64] | | x | | | x | x | | | | x | | | | | | | | | | | x | | | | x | |
| 44 | Torrent | TEI | 2017 | [76] | | x | | | x | | | | x | | | x | x | | | | | x | | x | | | | x | | |
| 45 | EdiPulse | CHI | 2017 | [53] | x | | | | x | | | | x | | | x | x | | | | | x | | | | x | x | | | |
| 46 | Cairn | DIS | 2017 | [34] | | x | | | x | x | | | | | x | | x | | | x | | | | x | | | | x | | |
| 47 | Damião's Dataphys Project | | 2017 | [15] | x | | x | | | | x | | | | | x | | x | | | x | | | | | x | | | | x |
| 48 | PolySurface | DIS | 2017 | [24] | x | | x | | x | x | x | | | | | x | | x | | | x | | | | | x | | | | x |
| 49 | Yellow Dust | | 2017 | [11] | | x | | | x | | | | x | x | | | | | | | | | | x | | | | | x | |
| 50 | Personal Physicalization Construction | CHI | 2018 | [100] | | x | | | x | x | | | | | x | | x | | | x | | | | x | | | x | | | |
| 51 | The Long Run | | 2018 | [49] | x | | | | x | x | | | | | | x | | x | | | x | | | x | | | | x | | |
| 52 | Living Map | | 2018 | [21] | x | | | | x | | | x | | x | | | | | | | | | | x | | | | | | x |
| 53 | ON BRINK | | 2018 | [93] | | x | | | x | | | | x | x | | | | | | | | | | | x | | | | | x |
| 54 | Zooids | IEEE | 2019 | [61] | x | | x | | x | x | x | | | | x | x | | x | x | x | x | | | | | x | | | | x |
| 55 | CairnFORM | TEI | 2019 | [16] | | x | | | x | x | x | | | x | | | | | | | | | | x | | | | | x | |
| 15 | PARM | Pers Ubiquit Comput | 2019 | [79] | x | | | | x | | x | | | x | | | | | | | | | | | x | | | x | | |
| 56 | CoDa | TEI | 2020 | [102] | x | | | | x | x | x | | | | x | x | | x | x | x | x | | | | | x | | x | | |
| 57 | Econundrum | DIS | 2020 | [84] | | x | x | | x | x | x | | | | | x | x | | | | | x | | | | x | | x | | |
| 58 | ProjecTable | PEARC | 2020 | [99] | x | | x | | x | | x | | | | | x | | x | | | x | | | | | x | | x | | |
| 59 | LOOP | NordiCHI | 2020 | [85] | | x | | | x | x | | | | | | x | x | | | | | x | | | | x | x | | | |
| 60 | Tactile Data Representations | ASSETS | 2020 | [26] | x | | | | x | x | | | | | x | | | | x | x | | | | x | | | | | | x |
| | TOTAL | | | | 32 | 28 | 18 | 7 | 48 | 33 | 25 | 5 | 16 | 19 | 9 | 37 | 16 | 19 | 11 | 9 | 23 | 9 | 5 | 26 | 7 | 27 | 9 | 19 | 10 | 22 |

Table 2. An overview of the 60 data physicalizations included in the sample list used for the analysis, of which 29 samples are publications (indicated by venue) and 31 non-academic work. Included is an overview of how they are represented in the six key design dimensions: (i) data type, (ii) information communication, (iii) interaction mechanisms, (iv) spatial coupling, (v) physical setup, and (vi) audience. The data type dimension is subdivided in data availability (dark purple), and data attributes (light purple); the interaction mechanisms dimension is subdivided in interaction directness (dark orange), and implication (light orange).

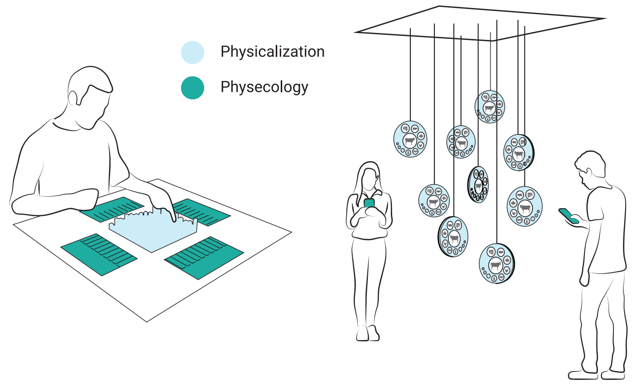



Fig. 1. Sketches of EMERGE [97] and Econundrum [84] illustrating the concepts of 'physicalization' and 'physecology'.

applied a deductive approach with the defined overarching clusters and labels to cross-reference the final categorization of the physicalizations. We used Excel to visualize trends and patterns to reveal certain archetypes of physicalizations, and populated a digital Miro board with imagery and text of the samples for mapping out the connections between the design dimensions.

The final six dimensions are inspired by existing concepts and theoretical frameworks from within and outside physicalization research. More specifically, the dimension of *Data type* follows Munzner et al.'s visualization classification [72] and *Information communication* expands on the actuation technologies as proposed by Dragicevic et al. [22]. *Interaction mechanisms* synthesizes *interaction types* – as discussed by Jansen et al. [47] – and *interaction directness* – from literature on shape-changing interfaces [82]. Lastly, *Spatial input & output coupling* and *Physical setup* are derived from a taxonomy on TUIs [27] and cross-device interactions [10], and applied in the scope of physicalization.

## 5 PHYSECOLOGY AS CONCEPTUAL FRAMEWORK

To discuss physicalization and its inherent properties, we introduce the term 'physicalization ecology', or *physecology*, to describe *the relations between the different design elements – physical and digital – of a physicalization, and their coupling to the audience and (physical) surroundings.* We apply the concept of *ecology* from Gibson [31], and extended by Jung et al. [50], describing the relations among interactive artifacts in people's surroundings [10, 67]. Hence, *physecology* describes how the design elements of a *physicalization* interact and/or coexist with one another, and interact with people and the surroundings. Subsequently, each *physecology* has an 'audience', which is composed of 'users' who own and actively engage with the physecology, but as a result of their physicality and spatiality, physecologies are also perceivable to a wider group of people, whom we describe as 'spectators'. This type of audience plays a more passive role, and merely observes the physecology.

To clarify the differences between the concepts of *physicalization* and *physecology*, we compare the case studies of EMERGE [96, 97] and Econundrum [84] as introduced earlier (see Figure 1). For EMERGE [96, 97], the grid of physical bar charts in the center of the system represents the *physicalization*, whereas the complete system including the digital touch interfaces and interactions around the system represents the *physecology*. Similarly, for Econundrum [84], the physical installation of disks suspended from the ceiling represents the *physicalization*, whereas the complete system

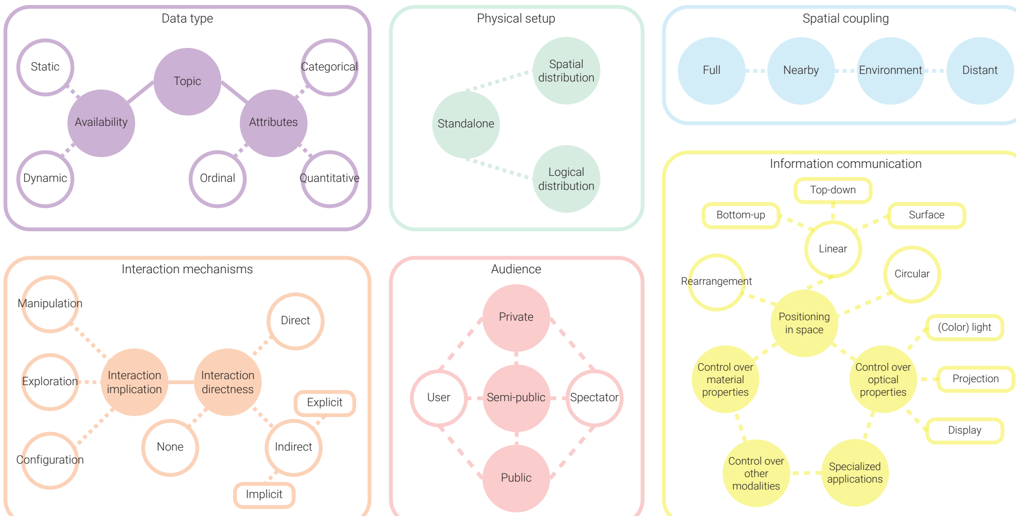



Fig. 2. An overview of six key dimensions of a physecology with a detailing of the relationships within each dimension. Within each dimension, solid circles represent main categories, and the unfilled circles – subcategories. Circles connected by solid lines are categories that are always present within the dimension, whereas circles connected by dashed lines indicate (sub)categories that are discretionary and/or non-mandatory.

(including the mobile application and interactions that occur around the installation) represents the *physecology*.

In the following sections we discuss six key design dimensions of a physecology (Figure 2) that we extracted from our analysis: (i) data type, (ii) information communication, (iii) interaction mechanisms, (iv) spatial input-output coupling, (v) physical setup, and (vi) audience. In the remainder of this section, the number of samples described are in relation to the total number of 60 samples in our corpus.

### 5.1 Data Type – What information is represented?

The fundamental goal of physicalizations is to communicate information by means of a physical representation. Hence, it is important to consider what information is actually communicated and with what purpose. Herein, we first reiterate and describe the datasets represented in the sample list, to facilitate the unpacking of the following design dimensions. *Data type* refers to how the data relates to the *users* of the physecology, which we define as the people that engage and interact with the system, either in a remote or co-located fashion. From our analysis of the sample physicalizations we observed a wide variety of (ii) data availability, (iii) data attributes, and (iii) data topics, which we will discuss below.

*5.1.1 Data Availability.* Following the visualization classification from Munzner [72], we can distinguish datasets based on their temporal nature, or in other words their *data availability* [72]. Therefore, we consider a dataset to either be *static* or *dynamic*, which also resonates with the concepts of *one-shot* versus *repeated propagation* as introduced by the extended infovis pipeline model [45].

- **Static** (*f (frequency)* = 32) refers to a dataset that is offline and/or in a static file, hence the data is over a fixed time frame and does not allow for further forward propagation after the initial file is created. From our sample list we observed that the *specialized topics* ($f$ = 9), *geospatial* data ($f$ = 4), and *configurable platforms* ($f$ = 10) are often of a static nature. For a more detailed description of the topics see Section 5.1.3.

Some special cases of personal and community data topics involved multiple static datasets, which were added or replaced over different time periods. The static visualization of Mill Road [57] was updated every other day by manually stencilling a static chalk visualization, using the dataset of the previous day. Similarly, Tidy Street [6] was updated on a daily and weekly basis. Both SweatAtoms [54] and Edipulse [53] involved the daily 3D printing of static data objects in the evening at home, based on the dataset of the current day. Lastly, Activity Sculptures [95] involved 3D printed static data objects that were delivered to the participants every one to three days. Still, we consider these examples one-shot propagations of data (although happening multiple times), as the changes to the data can not be reflected on the same single physical representation, but requires a new snapshot of data every time.

- **Dynamic** ($f$ = 28) refers to a dataset that is online and occurs from a dynamic stream, that can either be updated through local sensing or outside the scope of the physecology. Here, repeated propagation can take place, as changes to the data can be presented on the same single physical representation. From our sample list we observed that data topics such as *personal data* ($f$ = 7), *city & environmental data* ($f$ = 6), *community data* ($f$ = 5), and *online activity* ($f$ = 5) are often of a dynamic nature. For a more detailed description of the topics see Section 5.1.3.

The speed in which this data is updated can be immediate (real-time) such as every 30 seconds [84], or represent particular time frames (intervals) such as every half hour [83] or hourly [85, 91]. In the special case of Mood Squeezer [30], while maybe not a classic example of physicalization, the mood data of a workplace community was dynamic, and collected in real-time – but the floor display visualizing the aggregated mood by color was only activated for a two-hour period during the day.

*5.1.2 Data Attributes.* Again, based on the classification from Munzner [72], we can take a closer look at the *data attributes* that are represented in our sample list, which are defined as *"some specific property that can be measured, observed, or logged"* [72]. Herein, we distinguish between changes in categorical and ordered data attributes, resulting in three attribute types: *categorical* ($f$ = 5), *ordinal* ($f$ = 7), and *quantitative* ($f$ = 35). Lastly, we observed that for 13 samples changes in *both categorical and quantitative* data were made.

- **Categorical.** Categorical or nominal data can distinguish whether two or more things are similar or different. Of all 60 samples, 5 samples included the change of categorical data (and no ordinal or quantitative changes). Examples from the list are Tempescope [51] (weather conditions), and although not a typical physicalization example, Mood Squeezer [30], showing mood by color.
- **Ordinal.** Within ordered data attributes, the first type we discuss is ordinal data. This involves data that shows a well-defined ordering, but does not support direct mathematical comparison. Of the 60 samples, 7 samples included the change of ordinal data (and no categorical or quantitative changes). Example physicalizations are Poly [17] (polls), Drip-by-Tweet [92] (votes), and Season in Review [59] (baseball stats).
- **Quantitative.** The second type of ordered data is quantitative data, which involves a measurement that does support direct mathematical comparison. Of all 60 samples, 35 samples involved the change of quantitative data (and no categorical or ordinal changes). Example physicalizations are manifold, and could be further divided into discrete (countable) and continuous (measurable) data. Examples that visualize discrete data are Virtual Gravity [36]

(frequency of search keywords), Wable [56] (online activity), and Chaotic Flow [66] (bike traffic). Examples visualizing continuous data are Garden of Eden [21] (air pollution levels), Torrent [76] (flutists muscle tension), and Living Map [21] (rainfall).

*5.1.3 Data Topic.* Analyzing the topic of the visualized data, we observed that the relation of the user to the dataset can be discussed in order of scalability, ranging from personal to more public information. The data topics among the 60 sample physicalizations visualize are:

- **Personal data** ($f$ = 10) represents data that is directly related to the user, such as their physical activity measured by activity trackers (for example Dataponics [12], Edipulse [53], SweatAtoms [54], LOOP [85], and Activity Sculptures [95]), their daily online activity (for example x.pose [13], Wable [56], and Pulse [69]), the climate impact of personal dietary choices [84], and a myriad of manually logged topics such as mood, distractions during writing, and places visited [100].
- **Community data** ($f$ = 7) refers to accumulated data related to a particular co-located community of users. Example works include tracking the number of co-workers in an office building taking the stairs [83], or tracking their mood through choice of color [30]. Other example works include neighbourhoods, such as tracking the collective energy usage of Tidy Street [6], collecting votes on a variety of local topics on Mill Road [57], or varied data measurements on community life (such as number of passing vehicles) on Tenison Road [64]. Lastly, there are examples which investigate whether university staff and students recognize themselves in statements on sustainable behaviors [48], or collect data on the variety of practices people perform in a fabrication lab [34].
- **City & environmental data** ($f$ = 9) refers to data which is not directly connected to the user, but relates to their place of residence. Example works visualize live feeds of local weather conditions [51, 63], environmental data (for example temperature) [39], air pollution [11], daily tide levels in San Francisco [91], bicycle traffic in Copenhagen [66], and city data (for example power usage) of Palo Alto (Pneumatic Charts [21]). Other examples involve the comparison of environmental data across the world, such air pollution levels (Garden of Eden [21]) or weather conditions [33] of different global cities.
- **Online activity** ($f$ = 7) refers to accumulated data regarding online behavior, that goes beyond a single user or co-located community of people. Example works include online voting [17, 92]; frequency of emotional expressions on weblogs [55], particular twitter hashtags [23], or keyword search queries [36]; tweets during one day of the Olympics [73]; and social media rankings of brands [44].
- **Geospatial data** ($f$ = 4) refers to data that describes features of the earth's surface, such as elevation and landscape attributes (for example the XenoVision Dynamic Sand Table [29], Relief [62], PARM [79], and Projectable [99]).
- **Specialized topic** ($f$ = 12) refers to systems that are dedicated to visualizing statistical information on a specific topic. Example works include: a selection of global statistics [15], summertime rainfall in Europe (Living Map [21]), costs of healthcare for different age groups in the UK [49], regional statistics for Italy [68], affordable rent for low-wage workers in NYC [43], baseball statistics [59], keywords used in news articles [101], Bitcoin blockchain data [93], and renewable energy forecasts [16]. Additionally, we observed some specialized topics with a more artistic expression such as visualizing sound waves (Dust Serenade [21]), different world-views using geopolitical data [35], and visualizing flutists muscle tension during choir concerts [76].
- **Configurable platform** ($f$ = 11). Lastly, we observed a group of systems that were not dedicated to one particular dataset, but were presented as a configurable platform system.

The current systems were using exemplar data for the purpose of research and development, and were designed to support a variety of possible datasets. Example works include actuated research prototypes such as Recompose [7], PolySurface [24], ShapeCanvas [25], inFORM [28], Datamorphose [52], Zooids [60], FizViz [90], EMERGE [97], and CoDa [102]; and analog prototypes such as Tactile Data Representations [26], and Tangible Tokens [42].

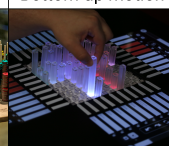
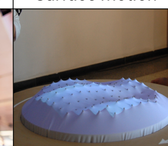
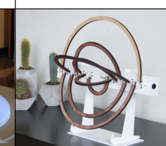
*5.1.4 Data Type Summary.* To conclude, the sample list shows a variety of data topics, varying in scale and relation to the user. Regarding the changing data attributes, more than half of the samples ($f$ = 35) involve the change of solely quantitative data, followed by the change of both quantitative and categorical data for 13 samples. Regarding the availability of data, we observed that the majority of dynamic data streams involved topics more related to the user, whereas static data files involved more public and environmental topics. Relating this back to the physecology concept, reflecting on the data availability helps us understand to what extent the data is more or less directly related to the physicalization. Static data is inherently integrated in the physicalization, whereas dynamic data can be more flexible, for example the coupling can be closer or further away, either within or outside the physecology. In the case of personal or community data, it is likely that the creation of the datastream occurs within the physecology as it concerns data closely related to the user in the immediate environment of the physicalization. In contrast, in the case of more public, environmental, or online data, these datastreams are less bound to a location or specific user group, hence likely occur outside the physical scope of the physecology. Figure 2 shows the relations between the three data type concepts. In the next section we discuss how the data is reflected in physicalization changes.

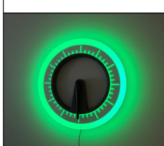
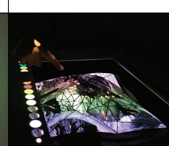
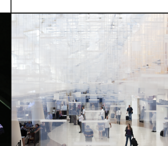
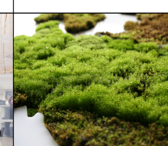
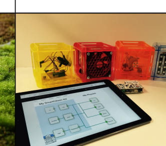
### 5.2 Information Communication – How is the information represented?

*Information communication* refers to the method that is used in the physicalization to represent *changes* in *states* of the data. While the working definition for physicalization suggests that the information is purely communicated through (change in) physical or material form, *this is rare in practice*. To give an example, in case of Econundrum [84], movement along a linear path *and* changes in colored LED light are used to 'update' the data. The method of information communication in this case is a combination of positioning in space – which resonates with change in physical form – but additionally the control of optical properties is used (change in visual form). Hence, the working definition can only partly accommodate for the changes observed (as also illustrated by the case studies). Additionally, we observed that more than half of the samples ($f$ = 33) use physical movement (change in shape and geometry) to communicate information changes, but only 5 samples applied change in material properties.

We acknowledge there have been different prior ways in which the mapping of raw data to visual or physical forms have been suggested. Bertin [5] provides the first systematic overview of visual encodings: *visual variables* such as position, size, shape, color, and motion that can be used to communicate different characteristics in a visualization. However, physicalizations go beyond purely visual charactisterics, which was later accommodated for in the extended infovis pipeline model [45]. This model proposes *rendering* to describe the final step from visual encoding to an actual physical form and bring it *"into existence in the physical world"* [45]. This rendering process is later further unpacked by Djavaherpour et al. [18], identifying how design and fabrication tools are used to realize exemplar systems. However, interactive physicalizations communicate changes in data states through change in visual and/or physical characteristics, which goes beyond the rendering phase.

Dragicevic et al. [22] introduced a classification of different actuation technologies that are relevant for *dynamic* data physicalizations: *positioning in space*, *control over shape and geometry*,

| Positioning in space | | | | |
|---|---|---|---|---|
| Rearrangement | Linear motion | | | Circular motion |
| | Bottom-up motion | Top-down motion | Surface motion | |
|  |  |  |  |  |
| Cairn [33] | EMERGE [95] | Econundrum [82] | Relief [61] | LOOP [83] |

| Control optical properties | | Control material properties | | Other modalities |
|---|---|---|---|---|
| (Color) light | Projection & display | Opacity | Natural growth | Vibration |
|  |  |  |  |  |
| FizViz [88] | PolySurface [23] | eCLOUD [32] | Living Map [20] | Physikit [38] |

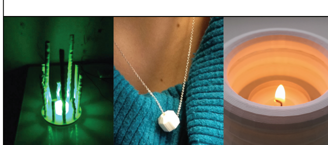
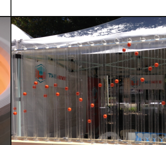
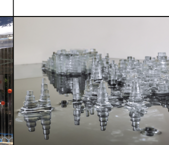
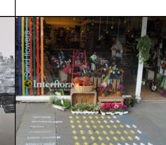
| Specialized applications | | | | |
|---|---|---|---|---|
| 3D printing | | Air | Liquid | Chalk spray |
|  | |  |  |  |
| Activity Sculptures [93] | | Pneumatic Charts [20] | Wage Islands [42] | Mill Road [56] |

Table 3. An overview of the different types of information communication, each with an exemplar system.

*control over material properties*, and *specialized applications*. However, the classes of 'positioning in space' and 'control over shape and geometry' are not mutually exclusive. Dependent on the abstraction level, many physicalizations fit both categories, by treating them either as a collection of individual data points (positioning in space) or as a whole (shape and geometry). For example, a pin-based shape display system such as inFORM [28] could be classified as the positioning of individual data points in space as well as control over shape and geometry of the installation as a whole.

As there are diverse ways in which prior work describes the communication of data through visual or physical form (such as visual variables, rendering or actuation technologies), we propose *information communication* as an inclusive term, focusing on characterizing how *changes* in data are realized. We take the classification of Dragicevic et al. [22] as starting point, and based on our observations of the sample list, we propose an extended overview of actuations (or manual changes) for the communication of data. We include (i) a further dissection of how positioning in space manifests in the samples, and (ii) provide a vocabulary for the other types of change we observed beyond physical and material form. We distinguish the following methods of information communication by a physicalization (see Table 3):

*5.2.1 Positioning in Space.* Spatial positioning describes the positional control of independent objects in 2D or 3D space. More than half of our samples ($f$ = 33) involved some form of motion to communicate changes in the data, of which 28 involved actuated positioning of objects and 5 involved the manual positioning by the user. For physicalizations that operate in the 2D space, such as a tabletop or other flat surface, we observed mainly the *rearrangement* of objects. This refers to the addition or extraction of objects to create changes in data, either by means of manual (such as Cairn [34], and Tangible Tokens [42]) or actuated rearrangement (for example Zooids [61]).

For examples in 3D space, the most observed type of positioning in space was by means of a *linear motion* ($f$ = 20), either from *bottom-up* (for example inFORM [28] and EMERGE [97]), *top-down* (such as Poly [17] and Clouds [83]), or horizontally in 3D space (for example Pulse [69] and CairnFORM [16]). Additionally, we observed a particular archetype that involved the change of multiple data points at once, through a 3D pin layout, creating the appearance of a *surface motion*, which resonates with the notion of 'control over shape and geometry' by Dragicevic et al. [22]. Although these systems are constrained to a grid, they allow for the realization of interactive surfaces with high precision and control. Example surface-based visualizations with connected or merged data points are Relief [62], PolySurface [24], and Point Cloud [63].

As well as linear motion, we also observed *non-linear* and *circular motions*. Examples of physicalizations using a *non-linear motion* are DataMorphose [52] and #Good vs. #Evil [23], respectively using spanned and moving sails, and cars following a race track in their visualizations. Examples of physicalizations that make use of a *circular motion* are FizViz [90], and LOOP [85].

Relating this type of information communication back towards the changing data attributes, we observed that of 33 samples, 31 used positioning in space for quantitative data change, and 2 samples to change ordinal data. These observations resonate with visualization literature that established previously that positioning in space is the most powerful visual variable to communicate information [5, 72].

*5.2.2 Control over Optical Properties.* Less than half of the samples ($f$ = 25) encoded data through the change of optical properties. In other words, this involved controlling *visual* properties such as (colored) light ($f$ = 9), projection ($f$ = 9), and display visualizations ($f$ = 7). To clarify, we distinguish projection as a projected image on the surface of an artifact, whereas (colored) light comes from a light source within the artifact. Hence, they differ in terms of technical realization, but also what you can use it for conceptually. Lastly, this application of control over optical properties is not to be mistaken with *fixed optical properties*, such as material color (for example Wable [56] or Cairn [34]), nor with the *change of material properties*, for example the change of texture or opacity (as discussed below).

For the examples that incorporate light changes in their visualization, we observed that 7 samples use color hue to communicate categorical data (such as ShapeCanvas [25] and Econundrum [84]), and 2 samples use color saturation to show quantitative data (for example CairnFORM [16] and Tidy Street [6]). PARM [79] and PolySurface [24] are examples of projection; and CoDa [102] and the Dataphys Project [15] examples of display use. To clarify, the examples incorporating displays ($f$ = 7) are still considered physicalizations, as the displace is either (i) accompanied with another form of information communication (for example positioning in space [52]), or (ii) involves another physical element (such as static bar charts that light up [15]).

Relating this application of information communication back towards the data attributes changed, we observed that of all 25 samples, for 13 samples the control of optical properties was used to change categorical data, for 10 samples to change quantitative data, and for 2 to change ordinal data. This resonates with prior work in visualization, that describes how color hue and saturation are effective means to respectively visualize categorical and quantitative data [5].

*5.2.3 Control over Material Properties.* For 5 samples we observed that the change of material properties was used to encode data. This method is not to be mistaken with fixed material properties, such as texture (for example PARM [79]), that remain unchanged, but refers to the material properties that are actively used to communicate changes in the data. Example physicalizations that showed control over material properties, through opacity change, were eCLOUD [33], and x.pose [13]. Other examples that could be considered as control over material properties are the samples involving the manipulation of natural growth such as Garden of Eden [21], Living Map [21], and Dataponics [12], that control the carbon dioxide levels and/or soil hydration to visualize topics such as air pollution, rainfall and activity data.

Relating this method of information communication back towards the data attributes changed, we observed that all 5 samples were used to change quantitative data. Additionally, the control over material properties of a physicalization is the method that, together with positioning in space, resonates most with the working definition of physicalization, as it concerns changes to it's inherent material properties. However, as our sample list illustrates, currently there is not much related work that truly accomplishes this.

*5.2.4 Specialized Applications and Control over Other Modalities.* The 16 remaining physicalizations do not fit any of the change types as mentioned above, and represent edge cases, as they encode data in varied, specialized and/or novel ways. Examples are the use of fabrication methods, other modalities, or visualizations with an ephemeral character [19]. Physicalizations include 3D printing (for example SweatAtoms [54], Activity Sculptures [95], and Edipulse [53]), the use of vibration (for example Physikit [39]), air flow (for example Dust Serenade [21] and Pneumatic Charts [21]), liquids [66, 76, 92], water vapor [11, 51], or even piles of soil [93].

Contrasting this type of information communication with the data attributes changed, we observed that 12 samples changed quantitative data, 2 ordinal, and 1 categorical data. Specialized applications in particular show how considering the wider physecology can be beneficial in understanding information communication of physicalizations. The use of fabrication techniques illustrates how a physicalization is dependent on physical and/or digital elements that are not inherent to the physicalization, but necessary to create the visualization.

*5.2.5 Information Communication Summary.* So far we discussed the different methods in isolation, however, they are not mutually exclusive, and can co-exist in physecologies. A total of 17 samples include systems using multimodal information communication, combining two or more methods. Example physicalizations are Physikit [39] (circular motion, vibration, and air flow), eCLOUD [33] (opacity and display), and PolySurface [24] (surface motion and projection).

Another observation we made whilst cross-referencing data attributes and information communication, was the general use of positioning in space to change quantitative data ($f$ = 31), control of optical properties to change categorical data ($f$ = 13) or quantitative data ($f$ = 10), and ordinal data changes were performed through a variety of ways. More specifically, of all 60 samples, 10 have the specific combination of positioning in space to change quantitative data, while control of optical properties changes categorical data. Lastly, we observed the trend that categorical information, which was not part of the changing data, was regularly represented by inherent material properties, such as color ($f$ = 14). These observations confirm prior findings from visualization literature [5, 72]: the effectiveness of using positioning in space to represent (changes in) quantitative data and color or brightness for categorical data. Figure 2 provides an overview of the different types of information communication as discussed in this section.

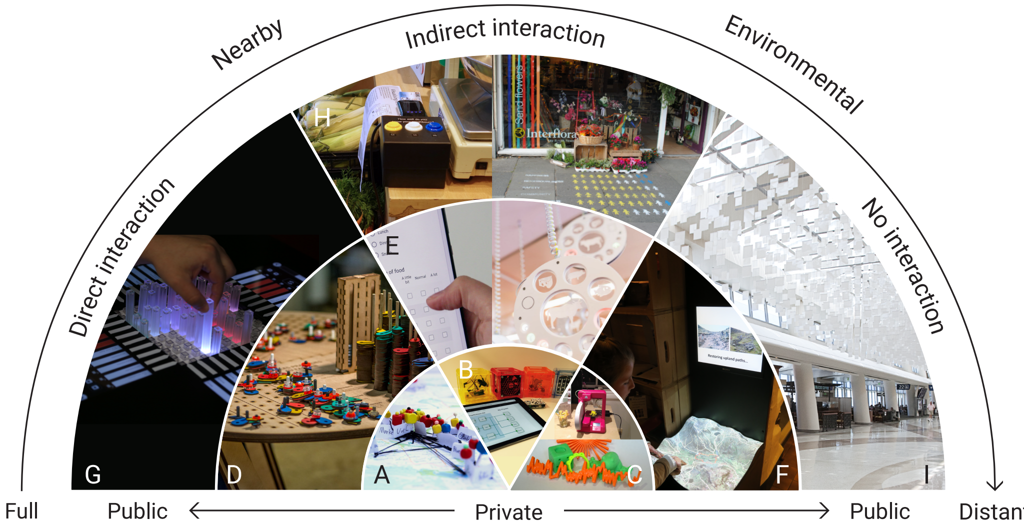



Fig. 3. An overview of nine exemplar physecologies, illustrating how they position on different design dimensions. Directness of interaction is shown in the three slices from left to right (direct to no interaction), spatial coupling is shown in the arc from full (left) to distant (right), and the privacy of audience is represented from middle (private) to ends (public). The physecologies included are: (A) Personal Constructive Physicalization [100], (B) Physikit [39], (C) SweatAtoms [54], (D) Cairn [16], (E) Econundrum [84], (F) PARM [79], (G) EMERGE [97], (H) Mill Road [57], and (I) eCLOUD [33].

### 5.3 Interaction Mechanisms – How is the information changed and/or can it be interacted with?

Whereas the physicality and tangibility of physicalizations inherently affords interaction [45, 47], the majority of interactions in existing systems part of our corpus do not occur on the physicalization itself. Instead, interaction is mediated by another source that is not inherent or intrinsic to the physicalization (for example a sensor, touch interface, or digital switch), but a necessary component within the physecology that allows for interactivity. This observation was true for more than half of both published ($f$ = 16) and non-academic samples ($f$ = 16). The *interaction mechanisms* as discussed below focus on the interactions that occur between the physecology and the *user*, which includes the people that 'own' and/or engage with the system.

Looking at the actual types of interactions that took place, we observed the following actions for 41 samples of our list: *direct interactions* such as manual rearrangement ($f$ = 4); *indirect* but *explicit* interactions such as gestures ($f$ = 2), the use of controlled objects ($f$ = 4), buttons ($f$ = 6), touch interfaces ($f$ = 4), tangible user interfaces ($f$ = 2) , digital interfaces ($f$ = 2), or phone or web applications ($f$ = 4); *indirect* but *implicit* interactions through sensor data ($f$ = 8); and *both* explicit (in)direct interaction ($f$ = 5) by touching the physicalization (direct) together with an indirect method as mentioned before. In this section we further discuss the *directness* and *implications* of the interactions we observed.

*5.3.1 Interaction Directness.* Considering the *directness* of interaction, we distinguish three different types, based on the classification from Rasmussen et al. [82] on the interaction with shape-changing interfaces (see Figure 3). We observed that more than half of the samples ($f$ = 32) involved *indirect* *interaction*, almost a third involved *no interaction* ($f$ = 19), only 4 samples involved *direct interaction*, and 5 samples a combination of *both direct* and *indirect interaction*.

- **No interaction.** In this case, physicalization changes are solely used as output and disregard user input, or creators do not disclose information on user input (for example open-ended configurable platforms). These physicalizations can still be observed and perceived by their audience, however there is no direct relation between their actions and the visualization. Examples are public installations such as Yellow Dust [11], and Microsoft Research Physical Charts [64]; and design or research prototypes such as ON BRINK [93], DataMorphose [52], and Living Map [21].
- **Direct interaction.** Direct interaction occurs when physicalization changes are used as both input and output. Physicalizations that involve direct interaction are systems that, for example, allow for the manual rearrangement [26, 34, 42, 100], or touching of the physicalization elements [28, 61, 97]. This interaction type is likely to occur for physecologies that use rearrangement or bottom-up motion to communicate information (Table 3).
- **Indirect interaction.** Physicalization changes are used as output, but are based on remote user input. When looking at indirect interaction, based on [82] we made the division between *implicit* and *explicit* indirect interaction. Implicit indirect interaction refers to situations in which the user may not realize that their actions are used as input for the physicalization. Example physicalizations that involve indirect implicit interaction are systems that use sensor data as input, such as x.pose [13], LOOP [85], and Clouds [83]. Explicit indirect interaction describes situations in which the user consciously performs actions as input for the physicalization. Examples that involve explicit indirect interaction are systems that use gestures [62]; tangible [36, 99], touch [15, 24, 39, 59], or digital interfaces [29, 101]; phone or web applications [51, 69, 84, 90]; slider, dial and/or press buttons [43, 44, 56, 57, 68, 73]; or designed [30, 48] or existing objects [49] for interaction.

Lastly, we observed 5 samples that combined explicit direct and indirect interaction, using direct touching of the physicalization in combination with gestures [7], controlled objects [28], buttons [102], or touch interfaces [61, 97].

*5.3.2 Interaction Implications.* Apart from the directness of the interaction, we also analyzed the *implications* of these interactions, which describes the way in which the action changes the data visualization conceptually, such as changing the scale or adding a data point. For this we used the work from Jansen et al. [45, 47], which discusses types of physical interactions with data physicalizations, and describes the difference between *exploring*, *manipulating*, or *reconfiguring* data (which are elaborated upon below). We observed the following frequencies in our sample list: exploration ($f$ = 14), manipulation ($f$ = 14), configuration ($f$ = 8), and combinations of two out of three ($f$ = 5).

- **Exploration.** We define *exploration* (similar to Jansen's 'exploration' [47]) as the act in which the input is used to assist in the task, for example navigating through the data or filtering data. Example physicalizations are Wable [56] in which you can explore personal online activity over time through a slider button, and Relief [62] in which you can move and scale a 3D landscape through hand gestures.
- **Manipulation.** We define *manipulation* (similar to Jansen's 'manipulation' [47]) as the act in which the output is used to assist in the task, for example to correct, update or collect data. Example physicalizations are Cairn [34] in which data collection of creative practices in a fabrication lab happens through manually stacking and positioning tokens of different shape

and color, and Activity Sculptures [95] in which sensor data of the user's physical activity influences the shape of 3D printed objects.

- **Configuration.** Lastly, we define *configuration* (similar to Jansen's 'reconfiguration' [47]) as the act in which the input and/or output is used to reconfigure the task, for example to switch between components of the task or change the selected dataset. Example physicalizations are Physikit [21] in which a tablet is used to connect the PhysiCubes to different data streams, Zooids [61] in which the physicalization objects and/or tablet are used to change the axes of the visualization, and Pulse [69] in which the device is rotated as a whole to switch between three information feeds of the user's choice.

*5.3.3 Interaction Mechanisms Summary.* In summary, the most frequently occurring directness of interaction was indirect interaction for more than half of the samples ($f$ = 32), followed by no interaction for almost a third of the samples ($f$ = 19). Indirect interaction happens in an explicit or implicit way. However, there are cases in which this might be ambiguous or dynamic. To illustrate this, we take the physecology of Mill Road [57] as an example. The input for the visualization happens through small voting devices inside shops along a street, and the output occurs a day later in front of each of the respective shops through a stencilled visualization. Hence, there might be an explicit indirect interaction in case users are aware of their voting showing in the stencilled visualization. However, it can also occur that users are unaware of their prior input being of influence on the visualization at the current day. Hence, there are cases in which the directness may differ between users and/or change over time.

Cross-referencing the data topic with interaction mechanisms, we observed that city and environmental data are likely to have no interaction ($f$ = 7); personal data ($f$ = 9) and specialized topics ($f$ = 8) are likely to be indirectly interacted with; and community data ($f$ = 5) and the configurable platforms ($f$ = 10) are likely to allow for both direct and indirect interaction. In general, the most observed implication of all interactions was exploration ($f$ = 19), followed by manipulation ($f$ = 16), and configuration ($f$ = 11).

Lastly, the high number of indirect interactions that we observed in our samples – for both published and non-academic work – is indicative of the need for the physecology concept, as users not interact with the physicalization itself, but with another medium in proximity to the system. Introducing the physecology allows us to fully describe and incorporate the different interaction possibilities in one overview model. Figure 2 shows and overview of the different interaction mechanism concepts and their relations.

## 5.4 Spatial Input & Output Coupling – What is the spatial mapping between the user and the physecology?

The working definition of physicalization suggests a full coupling between user input and visualization output. As all information is meant to be communicated in the materiality and form of a physicalization, changing it would mean a direct interaction with the physical objects. In contrast, we observed a wide range of spatial couplings between user and visualization, from a coupling within close proximity to a distant coupling (see Figure 3). Moreover, this is not just our observation, but was observed and discussed before in the related field of TUIs [27]. Although TUI research is a considerately different and broader field than physicalization, they both are concerned with directness of user interaction and the relations that can exist between the technology and the user. Hence, frameworks from TUI can be operationalized for physicalizations. For this dimension, we apply Fishkin's taxonomy [27] in the scope of physicalization, and categorize the spatial coupling between input and output by the following four layers: *full* ($f$ = 4), *nearby* ($f$ = 18), *environmental*

($f$ = 9), and *distant* ($f$ = 5). Additionally, we observed 5 cases of nearby to full coupling, and 19 cases of no coupling (as a result of no interaction).

*5.4.1 Full. "The output device is the input device: the state of the device is fully embodied in the device"* [27]. In this case the users can directly interact with the physicalization, manipulating the visualization ad hoc. This form of coupling comes the closest to the current definition of physicalization, as the physicality of the physicalization affords to be touched and interacted with directly, yet this rarely happens. Hence, in comparison to the other couplings possible, full coupling shows the largest overlap between the physicalization and the physecology. Example physecologies that show a full coupling are Cairn [34], Tangible Tokens [42], and Personal Physicalization Constructions [100], as they allow for the manual rearrangement of data points to update the visualization.

*5.4.2 Nearby. "The output takes place near the input object, typically, directly proximate to it."* [27]. In this case the user can perform explicit, but indirect interactions with the physecology, through a nearby medium that is not directly part of the physicalization. The focus of the input is strongly coupled with the output and the medium is co-located to the physicalization (for example displays, digital switches) within the physecology. Example physecologies that show a nearby coupling are ShapeCanvas [25], ProjecTable [99], and Podium [44]. Additionally, we observed the specific coupling of *nearby to full* for 5 samples, as these physecologies allow for the direct interaction with the physicalization, as well as with an other co-located medium (such as Zooids [61], EMERGE [97], and CoDa [102]).

*5.4.3 Environment. "The output is 'around' the user"* [27]. In this case the user only interacts indirectly with the physicalization, either implicit or explicit, through a medium that is in the surrounding of the physicalization, within the physecology. Example physecologies that show an implicit environmental coupling are LOOP [85] and Dataponics [12], in which an activity tracker senses the steps of the user and feeds it into the visualization in their home environment. Examples that show an explicit environmental coupling are Physikit [39] and Econundrum [84], in which users either use a tablet or mobile phone to makes changes to the visualization that is co-located in their home or work environment.

*5.4.4 Distant. "The output is 'over there', on another screen, or even another room"* [27]. In this case the user interacts indirectly with the physicalization. The visualization output can be distant in both spatial and temporal ways, for example in a different location and/or at a different time than the input happens. Hence, the user might be unaware of their relation to the visualization output (implicit indirect interaction). Example physecologies that show a distant coupling are Clouds [83], for which the interaction happens through sensor matts on the stairs and the visualization is in the center of the building; and Mill Road [57], for which the interaction happens inside shops and the visualization is created a day later outside the respective shops.

*5.4.5 Spatial Coupling Summary.* From our observations we conclude that a full coupling relates strongly with direct interaction; a nearby to full coupling correlates strongly with the combination of direct and indirect interaction; nearby, environmental, or distant coupling with indirect interaction; and no coupling with no interaction.

Cross-referencing the spatial coupling with interaction implications, we observed that a nearby coupling most likely serves the exploration of data ($f$ = 13), whereas for an environmental ($f$ = 7) and distance coupling ($f$ = 4) this is manipulation. Lastly, the high number of physecologies with no coupling ($f$ = 19), can be explained by them not allowing for any form of interaction, hence there is no relation between the user and the physecology.

### 5.5 Physical Setup – How does the physecology function as a whole?

Whereas static physicalizations typically have one physical setup, for many existing interactive systems we observed that there are mechanisms outside the physicalization that are crucial to make it interactive. In the previous section we discussed the conceptual coupling between physicalization components and surrounding users. Herein, we discuss the physical setup and distribution of physecology components. This resonates with a taxonomy on cross-device interactions [10], that describes the different distributions that can exist between digital devices. Although a physecology does not merely consists of digital devices, the taxonomy provides distribution concepts that apply to physecologies.

*5.5.1 Standalone Physicalization.* Physicalizations that function as a standalone device with no dedicated additional physical or digital components, which we observed for 26 samples. In this case, the physicalization is the mere facilitator of interaction (if any), without any external elements within the physecology. Examples are analog physicalizations [26, 34, 100]; non-interactive installations or data sculptures [35, 55, 66]; and configurable platform systems [7, 28]. This group includes physicalizations that extract data from an external source – such as an online cloud or web space – as these distributions are spatially disrupted and not trivial for the single device or artifact to be interactive with the audience. Examples are Point Cloud [63], Tidal Memory [91], and Drip-by-Tweet [92].

*5.5.2 Physecology with Spatial Distribution.* This refers to a physicalization and one or more additional co-located physical or digital components, for the purpose of (i) extending the visualization, or (ii) providing additional information. This relates to the cross-device notion of *spatial distribution* [10], and was observed for 7 of our samples. Example physecologies are PARM [79] which uses a projection on top of a physical terrain model with a display extending the physicalization of a landscape; and Tidy Street [6] which uses EL wire displays [2] to show energy usage per household, extended by a chalk visualization on the street showing the collective usage.

*5.5.3 Physecology with Logical Distribution.* This includes a physicalization and one or more additional physical or digital components, either remote or co-located, to (i) allow for the exploration of or navigation through the visualization, or (ii) for the purpose of reconfiguring or manipulating the visualization. This relates to the cross-device notion of *logical distribution* [10], and was observed for 27 of our samples. Examples are Virtual Gravity [36] in which a navigation dial and touch interface allow for the *exploration* of frequency of search keywords, visualized by two actuated physical bar charts; Econundrum [84] in which a phone application allows for the *manipulation* of an interactive ceiling installation, visualizing climate impact of dietary choices by height and color; and Podium [44] in which a dial button allows for the *configuration* of social media channels, to see how a brand ranks on each of these, visualized in height.

*5.5.4 Physical Setup Summary.* In general, we observed that standalone physicalizations are likely to visualize a static dataset, since this does not require any additional sensing or interaction capabilities elsewhere to function; or in case of a dynamic dataset, allow for direct manipulation on the visualization. Likewise, a spatial distribution is likely to visualize a static dataset, merely to further inform the user. In contrast, a logical distribution is likely to visualize a dynamic dataset, merely allowing the exploration, manipulation, or configuration of it.

Cross-referencing the physical setup with spatial coupling and interaction directness, we observed that all 7 physecology samples with a spatial distribution, involved no interaction, and subsequently

[2]EL wire comes in a range of colors and consists of a thin copper wire covered in plastic material that produces light when alternating current is applied.

no spatial coupling. Similarly, of all 27 logical distribution physecologies, 24 solely involved indirect interaction. Lastly, standalone physicalizations was the only group of physecologies that involved direct interaction ($f$ = 4), among all other forms.

The concept of physecology is not to be mistaken with the concept of 'composite data physicalization', which describes physicalizations that consist of *"multiple elements whose typology can be reconfigured or can reconfigure itself"* [61]. Whereas this concept is concerned with the internal structure of a physicalization (such as the updating of location or orientation of data points), physecology additionally considers factors externally to the physicalization (for example physical and/or digital elements as part of the factual setup, but also conceptual relations such as interaction mechanisms and audience). To give an example, the system of Zooids [61] is a dynamic composite physicalization. However, the physecology of Zooids further explains the logical distribution between a touch interface (tablet) for explicit indirect interaction with the wheeled-robots, complementary to the possibility to directly interact with them.

### 5.6 Audience – Who is interacting in what way with the physecology?

The working definition of physicalization is user agnostic and does not explicitly acknowledge the user or their relation to the system. Hence, it remains unclear what the implications of a physical representation are for the type of *audience* one can expect. In our analysis, we distinguish between two types of audiences. We define the *user* as the people that own, operate and/or engage with the physecology. However, the physicality and spatiality of physecologies makes them perceivable to a wider group of people, which we define as *spectators*.

Inherently, there are different types of audiences involved in a physical depiction of data. To give an example, for a physecology in the home context, the household represents the *direct users* and anyone visiting is a *spectator*. Herein, we discuss three types of context that correlate to the extend the audience of the physecology is private or public:

*5.6.1 Private.* This was observed for 9 samples, and concerns physecologies meant for the domestic context, for example for individual use [85, 100], or for it to be shared by a household [39]. Private physecologies are likely to visualize personal data, such as Dataponics [12], LOOP [85], and Activity Sculptures [95], and users interact repeatedly with the visualization, for example multiple times a day. The occasional spectators of a private physecology are visiting friends or family.

*5.6.2 Semi-public.* This was observed for 19 samples, and concerns physecologies meant to be used by a particular community, for example an office or company space [30, 44], university building [48, 83, 84], community space [34], or events such as a conference [66, 99], award show [92], or concert [76]. Similar to private physecologies, users interact regularly with the visualization, for example on a daily or weekly basis. Hence, semi-public physecologies are likely to visualize personal or community data. Physecologies of this type can expect more regular spectators than private ones, since their context often concerns spaces that can be visited by a larger variety of people. Whereas most physecologies of this type contain both users and spectators, we observed cases in which only spectators occurred [55, 64, 66].

*5.6.3 Public.* This was observed for 10 samples, and concerns physecologies meant to be available for the general public, for example in public spaces such as museums [91], airports [33], outside squares [11], or neighbourhoods [64]. Public physecologies are likely to visualize community data [6, 57, 64], or city and environmental data [11, 33, 91]. In case the physecology contains users ($f$ = 5), they are likely to interact with it on a less regular basis than a private or semi-public physecology. To give an example, physecologies in neighbourhoods [6, 57, 64] are probably visited on a weekly or monthly basis and show data relevant to the co-located communities. In contrast, physecologies in airports [33] or museums [43, 91] are probably visited on a yearly or one-off basis.

*5.6.4 Open-ended.* Lastly, there were example physecologies that do not clarify a specific context, which was observed for 22 samples. For these examples we did not create a further division in users and spectators, since these are very context dependent. Example physecologies are design prototypes [63, 93], research prototypes meant for case studies [24, 42, 61] or lab studies [97]; prototypes as a result of workshop events [23]; or graduation projects [13, 35, 36, 52].

*5.6.5 Audience Summary.* To conclude, we observed a combination of both users and spectators across contexts of different privacy, but with differing frequencies in their encounters with the physecology. Cross-referencing context and data topics, we observed that physecologies in a private context tend so visualize more personal data, whereas semi-public and public contexts show a wider variety of data topics.

So far we have discussed the users and spectators as two types of audience, but did not yet describe the dynamic between them. As an example we take public physecologies as part of a neighbourhood [6, 57, 64]. All people part of the neighborhood community are initially spectators, as they might be unaware of the meaning of the visualization and/or their relation to it. However, after interaction occurs with the physecology, for example for Mill Road [57] when a prior spectator makes use of the voting devices available in the shops, they become an user, and contribute to the upcoming chalk visualization in the street. Likewise, spectators of a semi-public physecology such as Clouds [83], become implicit users once they interact with the sensor matts and contribute to the interactive ceiling installation. These observations resonate with findings from prior work in public displays [103], discussing the transitioning from implicit to explicit interaction zones. Hence, audience has a temporal and spatial nature, and can change over time and be dependent on location. Figure 2 shows an overview of how the different concepts within audience relate to each other.

### 5.7 Physecology – How do the design dimensions interact with one another?

Herein, we further discuss the intrinsic relations that exist between the design dimensions of a physecology, as illustrated in Figure 4, and use the case studies as examples. The *physicalization* forms the core of the *physecology*, encompassing the *data type* inside, while showing strong relations with the *physical setup* and the method of *information communication.* To give an example, EMERGE [97] communicates information through the positioning in space of physical bar charts, and can be directly interacted with by the user. Similarly, Econundrum [84] communicates information through positioning in space as well, though top-down instead of bottom-up. In contrast to EMERGE [97], the interaction is not directly with the physicalization, but indirectly through a mobile application.

All other design dimensions position themselves around the physicalization in the physecology space. The data availability (for example static or dynamic) and data attributes (for example categorical or quantitative) are interconnected with the method of communication and the physical setup necessary to interact with this data. Subsequently, the distribution of the physical setup dictates how the data is represented (information communication) and interacted with (*interaction mechanisms*), either by means of direct or indirect interaction, via a logical or spatial distribution. To give an example, Econundrum [84] visualizes dynamic data (personal food consumption) changing both quantitative and categorical properties, through positioning in space (quantitative) and the control of optical properties (categorical). The physical setup involves a logical distribution between a mobile application and the physicalization so that users can provide data ad hoc, allowing the visualization to be dynamic. In contrast, PARM [79] visualizes static data (landscape features) changing solely categorical properties through control of optical properties. The physical setup

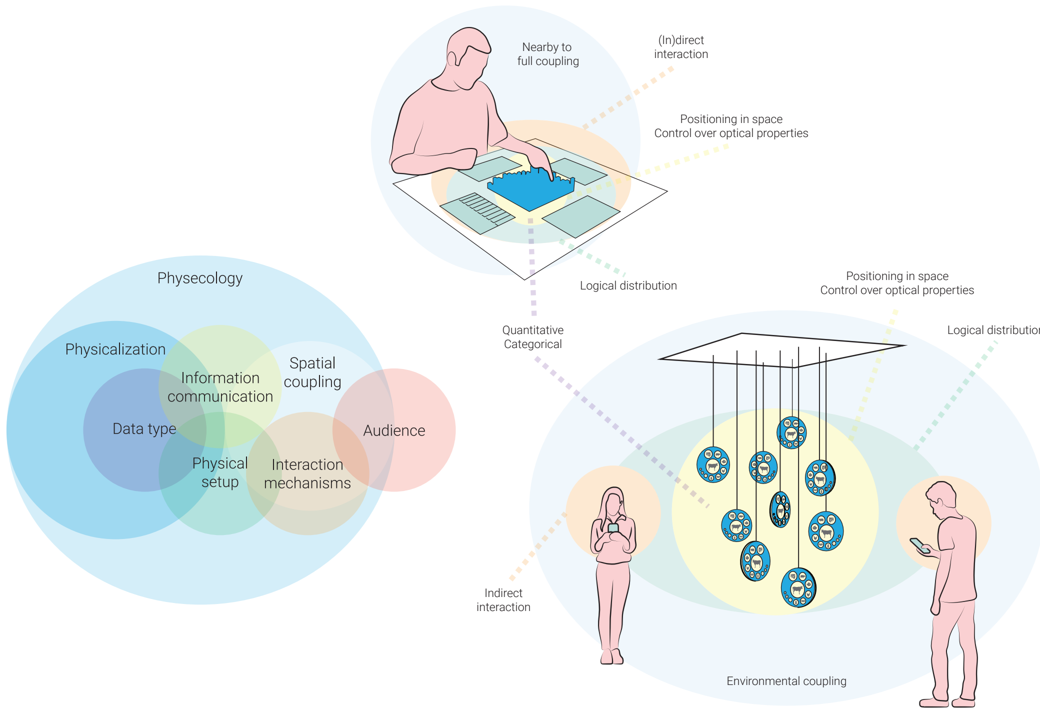



Fig. 4. A diagram showing the relation between a physicalization and the physecology it belongs to, and how the different design dimensions position themselves within these two concepts and in relation to each other. Additionally, the two illustrations show how the design dimensions manifest in exemplar systems, EMERGE [97] and Econundrum [84].

involves a spatial distribution between a digital display and the physicalization so that users can be informed about the information presented, but can not interact with it.

The *spatial coupling* is an overarching dimension describing the interactions of the *audience* with the other design dimensions within the physecology. For the example of Econundrum [84] the spatial coupling is environmental, as users perform indirect but explicit manipulations to the data visualization by submitting data entries to the system, while being co-located with the physicalization in their shared work space. Contrasting, for the example of EMERGE [97] the spatial coupling is nearby to full, which reflects in the (in)direct exploration of static data by touching the physicalization directly or the touch displays nearby (logical distribution).

In this work, we aim to illustrate how prior work on physicalization goes beyond the current definition – assigning the core value of physicalization to its inherent physical and material properties – and identified six key dimensions that together form a physecology. The *Data type* dimension shows how differences in availability of data, data attributes and topics dictate other elements within and outside exemplar physicalizations. The *Information communication* dimension demonstrates that there are more ways of visualization possible – beyond changes in physical or material form – such as the control over optical properties, other modalities and the use of specialized applications, that are currently not acknowledged in the definition. The *Interaction mechanisms* dimension discloses how more than half of existing prior work uses indirect interaction with the physicalization through another physical or digital medium. Hence, we need a physecology to be able to conceptually position the different levels of directness, intention (for example implicit or explicit), and implications of interactions in relation to the physicalization. The lens of the *Spatial coupling* dimension on prior work shows that user input can be more or less spatially related to the physicalization, which influences the coupling between input and output. The *Physical setup* dimension describes how a physecology can be beneficial in mapping out the additional physical and/or digital elements external to the physicalization, but crucial for the visualization and/or interaction with the system. The *Audience* dimension allows us to incorporate the different relations people can have with a physicalization (for example user or spectator) and how they can change over time.

To conclude, we treat a physicalization, defined as a data embodiment through material and geometric properties, as part of a larger ecology with several design dimensions: the physecology. There are many dialectical relations between these dimensions, that go beyond the concept of physicalization, and collectively create an interactive data visualization. Hence, it is important to consider the concept of physecology in future work on the physicalization of data.

## 6 DISCUSSION

The central goal of our work is to unpack how physicalizations are used in real-world scenarios. Through a meta-review of selected physicalizations, we derived six key design dimensions of a *'physecology'* which describes the necessary context around physicalizations. In this section, we reflect further on (i) the need for **physecology** as a unit of analysis and design, (ii) the relationship between the physicalization and wider physecology, and (iii) the further opportunity to develop strong conceptual interaction models to help identify the precise role of physicalizations for complex activities.

### 6.1 Physicalizations in Context

The dominant focus of research on the development of the concepts around 'physicalization' has been *device-centric*, focusing primarily on the detailed device, apparatus, or mechanisms that enable physicalization [2, 47]. This focus is mainly driven by the current *absence* of high-fidelity technical solutions that operationalize the visions behind physicalization into some form of interactive system. However, this focus also implies that other important topics, such as data mapping, user perception, or wider context of use are less well explored and understood as they rarely are included in the main unit of analysis when discussing 'physicalization' conceptually.

In contrast, our meta-analysis of physicalization literature and discussion of selected case studies demonstrate the need to consider the wider context around interaction with physicalizations. Based on our analysis, we argue that the surrounding context plays an equally – *if not more* – important role in the way people actually interact with physicalizations. Our case studies, but also the wider design space analysis highlight that, in most cases, the physicalization is only a part of a solution designed to enable people to explore certain datasets. Our findings suggest that physicalization designs and systems in fact *require* a wider ecology of sensors, input technologies and other mechanisms to function, and that the physicalization is rarely used as a standalone device. Moreover, the highly tangible and physical nature of physicalizations requires a strong grounding to the *context of use* and *variety of possible user groups*. Our empirical observations are in line with wider views on the importance and relevance of 'context' for the use, application, and appropriation of technology [1]. While there is significant previous research that demonstrates the importance of context in Human-Computer Interaction [1, 104], for physicalization this remains underexplored – both conceptually and technically.

Data physicalization is historically, conceptually, and fundamentally closely related to and derived from the field of information visualization, which explains why the explicit inclusion of context has not been actively considered. The creation of data visualizations in a 2D digital space is less integrated in physical 3D space, hence may not require as thorough a consideration of contextual factors. While this notion of context, situatedness or spatial referencing is increasingly being considered as important aspects for visualization [9, 105], there are few attempts to include context into the fabric of information visualization.

Additionally, the translation from established infovis terminology into physicalization concepts remains a fundamental challenge. We observed that the wider practices of physicalizations and their surrounding physecologies do not necessarily follow standardized infovis concepts or ideas. Hence, there is no straightforward vocabulary available to describe these concepts in physical 3D space. To give an example, *information communication* is a hybrid of conceptual models such as *visual variables* [5] – assigning visual encoding – and *rendering* [18, 45] – developing from visual encoding to physical form – and actuation technologies [22] – the implementations to accomplish changes in data states. This lack of consistent vocabulary and concepts makes it difficult to perform uniform analysis of the visualization strategies employed in physicalizations.

The effects of a lack of consideration of the wider context around physicalizations is also increasingly demonstrated in empirical research. Recent studies [46, 87, 88] demonstrate that selected physicalization designs simply do not meet their assumptions around how they visualize data to users, or how they provide singular interaction patterns. For example, studies demonstrate the different perceptions of size across physical shapes [46], the different perceptions of physical information in general across perspectives [87], and people's different interaction strategies when organizing physical information [88]. These empirical studies suggest that current strategies for physicalization are often inconsistent for elements of context such as size, orientation, or interaction. This is mainly caused by a limited understanding and conceptualization of the context surrounding the use of these physicalizations. These empirical findings and critiques are echoed by field [39, 84, 85] and design studies [24, 61, 96] that illustrate the challenges in how physicalizations mediate complex activities and support reflexive and context-sensitive interfaces to data. For example, one of the key arguments for 'physicalization' is that it enables and supports collaboration around a 3D model of data. Empirical and field studies, however, suggest that this is simply not the case because of a lack of tools and mechanisms to handle this collaborative context.

Grounded in our reflections on physicalization literature, we discuss the *'physecology'* as unit of analysis that integrates this important wider context in the form of six design dimensions. The central contribution of the concept of physecology is the *explicit acknowledgment of the importance of the wider context and audience surrounding physicalizations.* It builds directly on the widely accepted definition of 'physicalization' [47] and extends it with an interconnected set of design dimensions (see Figure 4) that are directly inspired and supported by previous work on context [1, 107], tangible user interfaces [27, 37, 89], and situated and embedded visualization [9, 105]. These design dimensions are not mutually exclusive or individual lenses on the physicalization, but are deeply intertwined and inherent characteristics of the reality of how physicalizations are actually used in real-world scenarios. The physecology as a unit of analysis proposes that physicalizations are part of a wider dynamic and evolving ecology of artifacts, tools, and spatial relations. While these six dimensions – *data type, information communication, physical setup, spatial coupling, interaction mechanisms,* and *audience* – are a starting point to unpack the properties of a physecology, we accept that other dimensions or more precise refined breakdowns of existing dimensions are possible – and arguably necessary as we move forward with building an understanding of physical data representations.

As physicalization research further matures we anticipate these dimensions to be built upon and expanded, but this work provides a starting point for conceptual clarity on context-sensitive physicalization design. The general goal with our reflections is to provide a shared vocabulary to allow for a unified discussion of physicalizations in context – the physecology. This is not only to better understand the landscape of existing physicalization research (and its gaps), but also to reveal opportunities for future work. The framework can be informative in different stages of design research practices around physicalization, for example, in initial phases of the process it can function as a set of design principles that can be operationalized in the creation of physicalization systems, interaction techniques, and specific domain applications. In later phases of the process it can be used as criteria for heuristic evaluation or qualitative sense-making of observations from in-the-wild studies.

### 6.2 The Relation between Physicalization and Physecology

The introduction of the *'physecology'* has conceptual and technical implications for physicalizations. While at first observation it becomes clear that without a *physicalization* there can be no *physecology*, our analysis of literature indicates that the opposite also applies: in many cases there is no 'functional' interactive physicalization without a wider physecology. For example, in the case of EMERGE [97], the physicalization would lose substantial interactive possibilities if the touch displays around the physicalization were removed. Or for Physikit [39], the removal of the tablet-based configuration tool to configure and explore data from sensors would render the physical data cubes into useless bricks. These additional interfaces – or components of the physecology – are not 'add-ons' but a fundamental part of the full design or system required to make the physicalization work and be useful. There is, thus, a deep – potentially dialectical – relationship between both the physicalization, which is the *actual physical data or information visualization model*, and the physecology, which represents the *wider interaction context*. Both levels of unit of analysis (physicalization and physecology) are deeply intertwined and can only be understood, studied, and – we argue – designed with this relation in mind. Furthermore, the dynamic and evolving nature of this ecological view, suggests that the surroundings and audience of a physecology will change over time. While this observation holds for any type of human-computer interaction, the physicality of the physicalization demands that the notion of context becomes a fundamental aspect of the design process. As physicalization research matures, we suggest that active consideration of the *'physecology'* will be a necessary step to transform physicalizations into practical applications, real-world field deployments, and specialized domains. We suggest that our framework can help reframe the ***design*** and ***analysis*** of existing and new physicalizations. The current design dimensions can function as new lenses or perspectives that provide concepts, vocabulary, relations, and concrete examples of how to operationalize the physecology.

One central observation from our analysis is the wide variability in which physecologies are designed. Particularly the design dimensions on *audience*, *interaction*, *spatial coupling*, and *physical setup* show that there are many different strategies and interaction models possible when interacting with physicalizations. We observe that most 'interactive' physicalizations require additional input devices, sensor-mechanisms, and wider interaction context. This opens up interesting questions around the *scale* and *dynamics* of physecologies. Examples in our corpus demonstrate that physicalizations can reach audiences ranging from one individual user, to groups of ten people, all the way to thousands of passersby. Moreover, many papers in our corpus implicitly report how user groups change over time, where spectators become users, or user groups shrink or grow in size. This observation has implications as it suggests that because of the physicality and the embeddedness of physicalizations in real physical space, there will almost always be multiple user roles and audiences. Even physicalizations designed for individuals will be seen, and perhaps analyzed and used by others. This user-multiplicity is, thus, a fundamental aspect of physicalization and should be considered as a first-class problem or requirement when designing the mapping, form, and interaction of physicalizations. Our analysis also shows differences in *time*, as most physicalizations are in fact not ‘real-time’ but enable configuration or interaction with different levels of *temporality*. This means that within the physecology, users can configure or interact with data across various instances of time. In some cases (for example in Physikit [39]) the time delay between interaction with the data (where a data source is selected and configured) and the actual visualization of data (triggered by a change in the date) can be months or even years.

While it is rare in our corpus to see multiple physicalizations inside the *same* physecology, it is conceptually possible and even desirable [86]. Indeed, many physicalizations already communicate different forms or types of data using singular interfaces, so the logical next step is to move to a multiplicity of physicalizations within one physecology. These issues of dynamic scale – in space, data, time, and audience – are currently rarely considered as part of the design of physicalizations. However, as suggested by previous literature that takes an ecological view on interactive technology [10, 50], this highly dynamic characteristic of ‘ecologies’ of technology is fundamental and should be considered as a key design objective for physicalizations. Finally, there are a range of physical data installations (for example Roam-io [38] and VoxBox [32]) that technically fall outside of the strict definition of ‘physicalizations’, yet have very similar goals and overlapping attributes and characteristics that could be included into a physecology. While their analysis is beyond the scope of this paper, we suggest that further analysis in future work could analyze these physical data installations as physecologies, thus, suggesting that physecology could be an umbrella term that binds together all physical data artifacts, and installations.

### 6.3 The Need to Develop New Interaction Models

Research on ‘physicalization’ [2, 47] tends to focus on new interaction techniques and approaches that provide a *direct* and real-time interface to the physical data format [61, 94, 98]. In contrast, more than half of the physicalizations in our corpus – both published and non-academic work – only support *indirect* interaction with physicalizations through external devices (such as tablets, phones, and sensors) or more implicit means. This implies that those physicalizations would simply be non-interactive if not directly supported by additional interaction devices. However, most research in physicalization does not explicitly acknowledge the importance of these external configuration or interaction devices and very little is known about their design, operation, and general usability. This is surprising and problematic as their design is instrumental and centrally important to actually making the physicalization work. Moreover, as described in the previous section, the mere physicality, changes in scale and/or user base, and temporality of interaction with physicalizations implies that the wider interaction model across the entire physecology must be considered. User multiplicity, distance of interaction, and temporal offset of input and output are just a few examples of key elements of the physecology that needs to be supported and included in the interaction design with physical data representations.

While the design dimensions of the *‘physecology’* unpack the basic mechanisms for how physicalizations are used in the physical world and broader context, the dimensions do not explicate detailed interaction models. However, as physicalizations are a subset of tangible user interfaces (TUIs) and more general ‘Ubicomp’ devices, there are a range of interaction models that actively incorporate wider context, and even ecological views, into their fundamental operation. Example candidates for interaction models for physicalizations include spatial models (such as Proxemic Interaction [3] or the Situative Space Model [75]), or context models (such as Activity-Based Computing [4] or Context-Awareness [1]) and other ‘embodied interaction’ models [20, 89]. Furthermore, as physicalizations are increasingly used as ‘public installation’, there is a need to better connect this work to the interaction models of ‘Public Displays’ [14, 103]. One other approach to rethink interaction models within the physecology is to reframe the physicalization to an individual ‘device’ that could potentially be updated, replaced, changed, or shared within a multi-device ecology or system [10, 40], thus, leveraging 30 years of research into cross-device interaction techniques, user interfaces, and data and information models. Finally, as the fundamental goal of interactive ‘physicalizations’ is to dynamically visualize data, future work would need to consider how interaction models within the wider physecology relate to interaction models from the information visualization perspective [45, 70, 71]). While these approaches do not dictate specific ways of interaction within the physecology, leveraging these prior conceptual interaction models and approaches can unlock new ways of addressing the *user experience design* of physecology that explicitly acknowledges the entire context and situatedness of the physicalization.

## 7 CONCLUSION

In this paper we analyzed a selected corpus of publications and non-academic work in the field of physicalization, showing properties that go beyond the scope of the working definition of physicalization. From our findings we identified six key dimensions that extend the current definition, and introduced the term *physecology* as a concept to describe a physicalization inside a wider interaction context. Our work contributes (i) a detailed analysis of a corpus of exemplar physicalization work, (ii) a conceptual framework to describe the design space and relations between physicalization and physecology, and (iii) reflections on what this means for future work in physicalization research.

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