DOI: 10.1111/cgf.70152

EUROVIS 2025
M. Angellini, C. Garth, and A. Kerren
(Guest Editors)

COMPUTER GRAPHICS *forum*
Volume 44 (2025), Number 3
STAR – State of The Art Report

Fluidly Revealing Information: A Survey of Un/foldable Data Visualizations

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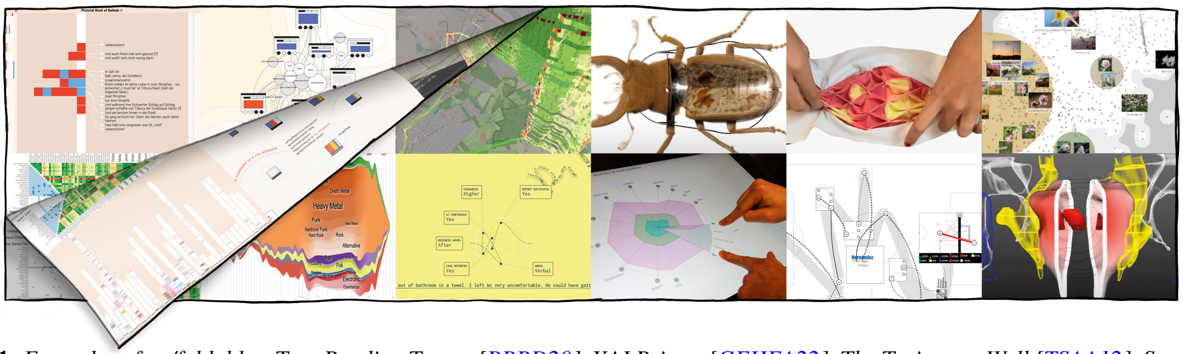


Figure 1: *Examples of un/foldables. Top: Reading Traces [BBBD20], XAI Primer [GEHEA22], The Trajectory Wall [TSAA12], Smart surrogate widgets [SB18], VISMOCK [BPS24], Fluid Views [DCW12]. Bottom: Responsive Matrix Cells [HBS*21], Multistream [CSWP18], Tied in Knots [EBC*20], Fluid Interactions for Star Plots [LKE*15], Soccer Stories [PVF13], PelVis [SLK*17].* (See *Figure Attribution*)

Abstract

Revealing relevant information on demand is an essential requirement for visual data exploration. In this state-of-the-art report, we review and classify techniques that are inspired by the physical metaphor of un/folding to reveal relevant information or, conversely, to reduce irrelevant information in data visualizations. Similar to focus+context approaches, un/foldable visualizations transform the visual data representation, often between different granularities, in an integrated manner while preserving the overall context. This typically involves switching between different visibility states of data elements or adjusting the graphical abstraction linked by gradual display transitions. We analyze a literature corpus of 101 visualization techniques specifically with respect to their use of the un/folding metaphor. In particular, we consider the type of data, the focus scope and the effect scope, the number of un/folding states, the transformation type, and the controllability and interaction directness of un/folding. The collection of un/foldables is available as an online catalog that includes classic focus+context, semantic zooming, and multi-scale visualizations as well as contemporary un/foldable visualizations. From our literature analysis, we further extract families of un/folding techniques, summarize empirical findings to date, and identify promising research directions for un/foldable data visualization.

CCS Concepts

• ***Human-centered computing*** → ***Visualization techniques; Interaction techniques;***

1. Introduction

Physical analogies have always inspired visualization research. In this state-of-the-art report, we focus on the physical metaphor of un/folding and its use in visualization, particularly influenced by Mollerup's industrial design-based album of space-saving objects, so-called *collapsibles* [Mol01].

Physical un/folding has many practical applications in engineering and design [Mol01,MCZ*21] as it enables efficient use of space under changing conditions. Similarly, display space is a precious resource in visualization when large and complex data need to be explored from different perspectives and with different levels of abstraction. So, applying the metaphor of un/folding seems to be a natural design choice for visualization [BBD20].

In this report, the term un/folding refers to the use of interactive visualization mechanisms that enable fluid information revelation on demand through gradual abstraction changes. We are particularly interested in fluid interactions, due to their potential to create enjoyable and engaging experiences [EMJ*11]. Many classic and contemporary visualization approaches involve forms of interactive visual un/folding. They go by the name of focus+context [CKB09], abstract & elaborate [YKSJ07], collapsing/expanding [SP13], or semantic zooming [BH94]. The goal of this work is to gain a better understanding of the many ways in which these and other approaches apply the un/folding analogy in the context of data visualization.

To this end, we collected a corpus of 101 un/foldable visualizations, according to four characteristics. We consider approaches that (1) involve revealing or reducing information on demand, (2) integrate seamlessly into a base visualization, (3) preserve the overall visualization context, and (4) follow the idea of fluid interaction [EMJ*11]. We derive a classification scheme to characterize collected approaches with respect to seven aspects of un/folding:

– *Data facets:* What types of data are un/folded?
– *Focus scope:* How much is actually un/folded?
– *Effect scope:* To what extent is the visualization affected?
– *Unfolding scale:* How many un/folding states exist?
– *Transformation type:* What type of transformation is used?
– *Transition control:* How can the un/folding be controlled?
– *Interaction directness:* How direct is the interaction?

Based on the categorized corpus, we created an online catalog of un/foldable visualizations at uclab.fh-potsdam.de/unfoldables. Drawing on Mollerup's collapsibles [Mol01], we further group un/folding techniques into families that share common transformation mechanisms, including fanning, hinging, sliding, stretching and more. Insights from empirical user studies and research opportunities are discussed to indicate where un/foldables have already proven useful and where future work is necessary to expand our knowledge about their design and utility.

Related work. Our survey is related to previous research on interactive visual data exploration, in particular to techniques for exploring focus regions of interest while preserving context [CKB09, KHG03]. Although approaches like focus+context and semantic zooming can exemplify un/folding, the concept extends beyond them. Inspired by the fluidity of physical folding, un/folding visualizations are particularly characterized by the continuous and contextual nature of abstraction changes. Moreover, there are existing surveys that address specific aspects related to un/folding visualizations, for example, highlighting or emphasis [LH10, HPK*16], strategies for embedding information [JE12], hierarchical aggregation [EF10], the general use of abstraction in information visualization [VI18], interactive lenses [TGK*17], interaction in conceptual modeling tools [BD23], or multi-scale visualizations [CJS*22].

Certainly, our work reviews approaches of which some have already appeared in previous overview articles. Yet, we analyze the literature specifically with respect to the metaphor of un/folding, which has not been done so far. Moreover, our survey brings together classical techniques, especially from the focus+context realm, and more recent approaches, including touch and cloth-based interfaces as well as virtual reality under the common umbrella term of un/foldable visualization. As such, we provide a unique and updated look on the state of the art in fluid visual data exploration by means of un/folding.

Outline. Our survey starts in Sect. 2 with an introduction to un/foldable visualization, covering its inspiration, relevance, and definition based on the four characteristics already mentioned. Sect. 3 will outline our methodology for collecting and selecting relevant literature. In Sect. 4, we will derive the classification scheme and give an overview of un/foldable visualizations along the different categories. Sect. 5 focuses on families of techniques inspired by physical metaphors. A summary of empirical studies related to un/foldable visualizations is provided in Sect. 6. In Sect. 7, we will identify open research gaps and opportunities for future work. We will conclude our survey with a discussion in Sect. 8.

2. Un/foldables

Many of the techniques reviewed in this paper are inspired by the metaphor of folding and unfolding, and our research on these techniques is informed by a growing research interest in interactivity in visualization [Tom15, DP20]. This section describes our motivation behind un/folding as a unique interaction concept for visualization and provides a definition for un/foldables, their core features, and their relevance.

2.1. Un/folding as inspiration

Given its beneficial effect on space efficiency, un/folding is a recurring theme across nature, engineering, and design as indicated in Fig. 2. For example, six feet of DNA are folded compactly to fit inside the nucleus of a human cell. The human brain's structure relies on intricate folds to maximize the functionality within a confined space [HV17]. Plants exemplify un/folding by adjusting their leaves and blossoms based on sunlight availability or as a protective response against other environmental factors. Animals, too, utilize complex biomechanics to enlarge or shrink their physical form for functional or defensive purposes. Birds, bats, and insects unfold their wings for flight [HV17]. Pufferfish inflate to deter predators, butterflies unfold their wings during eclosion, and peacocks fan out colorful feathers to attract mates [Mol01].

Engineering and industrial design are frequently inspired by folding mechanisms for adaptability and space efficiency [Mol01, MCZ*21]. Examples include hand fans, which expand to generate airflow and collapse for transport. Similarly, umbrellas provide rain protection and can reveal a hidden design when expanded. Musical instruments like accordions use folding not only for compact storage, but also to regulate airflow and produce sound. Other applications, such as scrolls, tents, parachutes, books, pocket knives, lifting ramps, and advanced technologies like space equipment or medical micro-robots leverage folding mechanisms to optimize functionality and form [Mol01, MCZ*21, HV17]. With regards to industrial design, Per Mollerup [Mol01] created a dedicated album of mechanisms focused on size reduction, calling them *collapsibles*. He provides examples for the categories *Stress*, *Folding*, *Creasing*, *Bellows*, *Assembling*, *Hinging*, *Rolling*, *Sliding*, *Nesting*, *Inflation*,

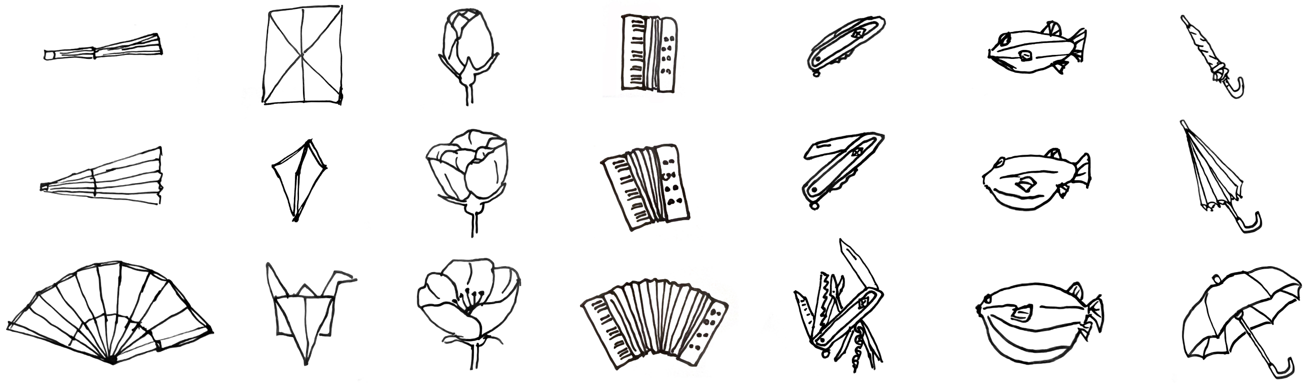


Figure 2: *Sketches derived from examples of un/folding in nature and engineering [Mol01, HV17], showing from left to right three states of a hand fan, an origami, a flower blossom, an accordion, a Swiss army knife, a pufferfish, and an umbrella.* 🅭🅯

Fanning, and *Concertina*. While some of the examples use folding as a mechanism for spatial compression, others transform their appearance or function upon unfolding.

Philosophers have also drawn inspiration from folding. Building on Leibniz's monadology, Deleuze [Del93] describes folding as a dynamic interplay of implication, explication, and complication, revealing the hidden complexity and interconnectedness of systems. The fold offers a unifying principle, blending continuous and discrete dimensions, making it particularly resonant in digital times [dF16]. The metaphor of folding transcends static representations, suggesting that information is not merely displayed but actively engaged, with each interaction revealing layers of meaning while preserving the cohesion of the whole.

Applied to visualization, the fold emphasizes the continuity between visible and invisible elements [BBD20]. It can be invoked as a principle for designing visual interfaces that enable gradual transitions, meaningful exploration, and insightful connections, aligning with the aspirations of fluid interaction. As a metaphor, folding is a prevalent theme in visualization research. Terms such as folding [TFJ12], unfolding [BDT23, vW08], fanning out [LLW08], accordion drawings [SHM05], origami [HCJ09], piling [LZC*21, BHRD*15], roll-up [YWR02], stacking [TSAA12], stretching [LGB07], and balloons [TS08] are commonly used to describe interactive data exploration mechanisms.

The notion of un/folding thus offers a compelling lens through which to examine gradual revelation of detail in data visualizations. By leveraging its transformation capabilities regarding appearance, function, and space efficiency, we posit that un/folding can serve as a powerful framework for studying and designing fluid interactions for visual data exploration.

2.2. Definition

In the context of the survey, we define the following:

> *"Un/foldables are interactive visualization mechanisms that reveal or reduce information through fluid transformations such as compression, expansion, or deformation in a focus region while maintaining the overall context."*

Defined in this way, un/foldables are further described by the following characteristics:

C1) Information Adaption: Un/foldables interactively reveal and reduce information in data visualizations, often through changes in abstraction, detail, or encoding. This includes adding data elements, increasing level of detail, changing granularities, expanding aggregations, and shifting focus onto other data facets.

C2) Seamless Integration: Un/foldables are embedded directly within the base visualization, minimizing spatial and semantic separation. Unlike tooltips and multiple coordinated views, un/foldables integrate information within the existing graphical and geometric structure of the visualization through embedding [JE12], localized aggregation [EF10], or localized abstraction [VI18].

C3) Context Preservation: Un/foldables preserve the context of the base visualization by keeping original elements intact or maintaining their overall appearance and arrangement. Context preservation ensures orientation within the visual framework even as more information is revealed. Local un/foldables introduce changes in a focus region and preserve the spatial and visual context, while global techniques, such as semantic zoom, retain virtual accessibility to off-screen elements. This criterion aligns closely with context-preserving techniques described by Cockburn et al. [CKB09].

C4) Fluid Interaction: Un/foldables emphasize coherence and continuity through smoothly connected interaction experiences [EMJ*11] facilitating the cognitive bridging of view changes [Woo84]. This typically requires (ideally meaningful) animated transitions, but may also be achieved through strategic positioning of new elements. Immediate visual feedback can prevent frustration and avoid confusion caused by temporal separation [EMJ*11, Nor13].

With respect to visualization tasks, un/foldable visualizations align with Shneiderman's lower-level task *details-on-demand* [Shn96]. At a higher level, they correspond to Yi et al.'s *abstract & elaborate* [YKSJ07] and Sedig and Parsons' *collapse/expand*, *compose/decompose*, and *drill* [SP13]. Additionally, information revelation can partially align with tasks such as

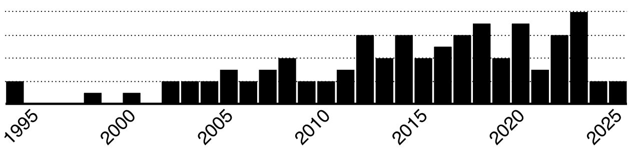


Figure 3: *Temporal distribution of our un/foldable examples.*

encode [YKSJ07], by dynamically adjusting the encoding strategy to reveal new insights, or *compare* [BM13], through targeted un/folding.

2.3. Relevance

"Great designers produce pleasurable experiences." [Nor13, p.10], states Don Norman in the usability design classic *The Design of Everyday Things*. He emphasizes the importance of factors such as immediate and informative feedback, affordances, aesthetics, enjoyment, and fun in contrast to confusing or frustrating interactions [Nor13].

With un/foldables and their alignment with concepts of *fluid interaction* [EMJ*11], we aim to follow this ambition of pleasurable experiences. Fluid interaction promotes seamless and enjoyable experiences through animated transitions, direct manipulation, and the integration of interface components directly into the visualization. Furthermore, it avoids disruptive mode changes and emphasizes continuity during display state changes.

This quality is captured by the concept of *visual momentum*, which describes the ability of a system to minimize the mental effort required to integrate new views, enabling users to quickly comprehend information after a transition [Woo84]. Similarly, *flexible visual analytics* suggests smooth animated transitions to facilitate comprehension of view changes during data exploration [TAA*21]. Even though empirical evidence supporting the comprehension benefits of animated transitions is still limited, user studies have indicated their positive impact on user experience and engagement [FPS*21].

Data visualizations often require navigating complex datasets across multiple scales while maintaining contextual integrity. Due to cognitive, technological, and screen-real-estate related factors, interaction paradigms, such as focus+context, overview+detail, and zooming address this need to interact with data visualizations across multiple abstractions or granularity levels, while preserving the context [CKB09]. By un/folding information on demand, un/foldables can take a central role in managing the complexity of data visualizations [WARB*24] and enrich this objective with their engaging qualities. This is particularly relevant, as un/foldables compete with other, often simpler-to-implement approaches for navigating complexity, such as simple overlays, overeiw+detail, abrupt view changes, or coordinated views.

Motivated by ambitions to design joyful experiences, we see a need for a review of fluid interaction techniques such as un/foldable visualizations as a strategy to reveal detail and navigate abstraction and complexity.

Figure 4: *Interactive un/foldable browser with animated thumbnails showcasing the interactivity. The full set of classified techniques can be explored at uclab.fh-potsdam.de/unfoldables.* *(See Figure Attribution.)*

3. Methodology

To arrive at a classified corpus of un/foldable visualizations, we employed a multi-stage approach. The process began with reviewing and selecting candidate techniques, and progressed to building and applying a classification system, and concluded with grouping the examples into distinct families of un/foldables.

3.1. Selection process

Un/folding is rarely the main technical contribution of a visualization research paper (e.g., in technique papers) and is typically only a secondary aspect (e.g., in design studies), making it challenging to pinpoint through direct search. In addition, un/foldables are not tied to a single specific search term, but instead span across multiple visualization approaches. Our aim was not to compile an exhaustive catalog, but to provide a representative overview of un/foldable techniques ranging from foundational to innovative approaches.

First, we collected examples through an open exploration and search process, resulting in a first list of examples compliant with the un/foldable characteristics C1-C4. For these examples, we considered related work and extracted common author keywords: *folding, focus+context, aggregation, fluid interaction, collapsible, scalable, multi-scale, cross-scale, detail level, abstraction level, zoom,* and *transition.*

In a second phase, these keywords were systematically used to query major visualization venues and repositories. For this, we first used these keywords and variations of them (e.g., fold, folding, unfolding; focus+context, focus and context, etc.) to query relevant publications via VisPubs [Lan24], which collects visualization papers from the visualization conferences IEEE VIS, ACM CHI, and EuroVis. To expand the scope beyond these conferences, we conducted further searches using IEEE Xplore and the ACM Digital Library, focusing on the search terms (and their variations) yielding the most relevant publications: *focus+context, semantic zoom, collaps*, scalable, fluid interaction, fold*, unfold**. This allowed us to also find un/folding examples from other relevant venues, such as the conferences IEEE Pacific Vis, ACM DIS, or ACM AVI, and publications from other publishers such as Springer or Elsevier.

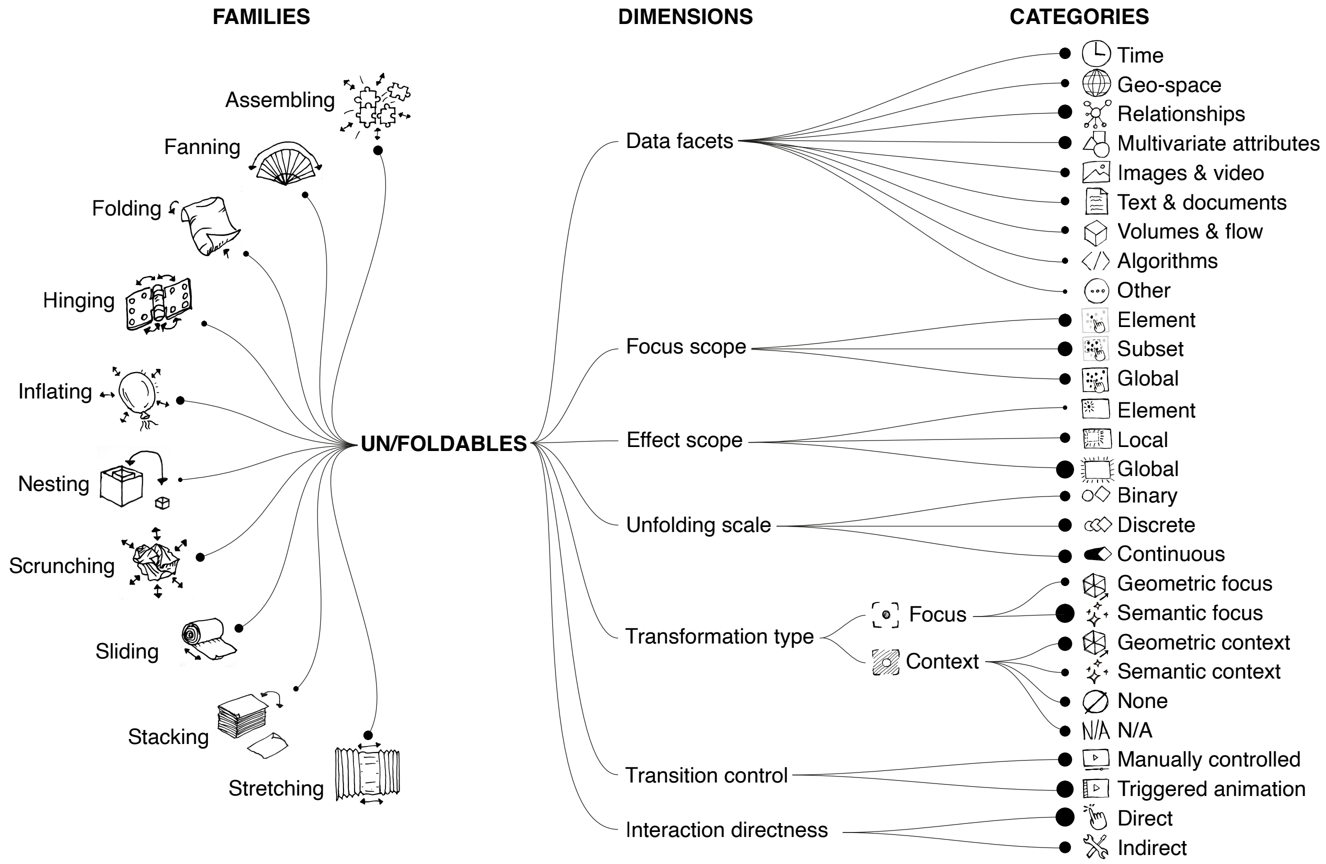


Figure 5: *Overview of the classification system, with families of un/foldables on the left, our general classification dimensions in the center, and their associated categories on the right. The size of the circles roughly indicates the distributions within our corpus.*

Each entry was screened, focusing on abstracts, figures, technique descriptions, demo videos, and prototypes, resulting in a list of about 260 examples. Furthermore, few design practice examples from outside of academia were included. In the next step, based on available demo videos or prototypes, we created video snippets that capture the un/folding interactions. These short clips facilitated internal discussions and effectively conveyed the un/folding interaction, leading to their inclusion across the entire corpus.

Finally, the selection was narrowed based on diversity, availability of documentation, and uniqueness. Techniques that were either too closely related or lacked sufficient visual or descriptive material were excluded, leading to a refined corpus of 101 visualization techniques. The resulting set provides a representative overview of un/foldable visualizations spanning 30 years (see Fig. 3 and Fig. 4).

3.2. Classification process

Once the corpus was finalized, the selected techniques were grouped and categorized by the first author, based on higher-level characteristics (e.g., zoom based, space-filling hierarchical approaches, table-based visualizations) to establish a baseline for discussing differences and similarities. With an overall ambition of analyzing transformations, interactions, and transitions, each author then individually suggested a potential classification scheme. These schemes were then discussed, compared, and iteratively merged into a shared scheme, which was tested and refined through independent classification by the authors using an initial set of heterogeneous examples. This step was followed by a comparison of results and classification experiences, and further debate in case of inconsistencies, until we arrived at a classification scheme that proved to be generalizable enough to accommodate the full range of techniques. In this process, also previous classification systems from other surveys were considered, especially with regards to the common classifications of data facets [Shn96, TGK*17, BTM*24] and interaction directness [Twe97].

Each technique was then independently classified by at least two authors using the classification scheme. Ambiguous cases were discussed among all authors to ensure consistent categorization. This iterative approach enhanced the validity and reliability of the classification process.

Next, techniques were grouped into families, inspired by physical mechanisms of un/folding in nature and industrial design [Mol01, HV17, MCZ*21]. For this, we first used the collaboration platform Miro [Mir24], which offers the possibility to create boards where elements can be freely collaboratively arranged and labeled. We laid out all the example GIFs or still images and then iteratively clustered the techniques into families. We began with approximately 20 unnamed preliminary groups. Subsequently, we iteratively refined and remixed the groups until reaching a level of granularity that felt meaningful across techniques with regards to transformation types and their transitions.

In a final step, we built on the categories of physical mechanisms introduced in Mollerup's album of space-saving objects [Mol01], retaining many categories and adapting others to ensure naming consistency and reflect the mechanisms identified in our survey. We then mapped the groups to these refined technique families, providing a metaphorical description of each group's essence in relation to un/folding.

This structured methodology not only resulted in a comprehensive and representative classification of un/foldable visualizations but also laid a foundation for the detailed analysis presented in the next section, exploring their design characteristics, use cases, and implications for visualization research and practice.

4. Classification

To better understand the broader design space of un/foldables, we classified the collected techniques along seven dimensions, as depicted in Fig. 5. The goal of the classification is to reveal broader patterns and guide future developments. Each dimension addresses a distinct aspect of the un/folding interaction, ranging from its connection to the data being visualized to the characteristics of the transformation within the visualization, and the interaction mechanisms used.

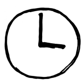
Data facets is the first dimension and it considers the types of data being visualized. This includes diverse data types from temporal, spatial, multivariate, and relational to visual media, textual datasets, volumetric data, and algorithms, each presenting unique challenges and opportunities for un/foldables.

At the heart of the classification are four dimensions that characterize the un/folding process in relation to the data visualization. **Focus scope** defines how much of the visualization is revealed or hidden during the un/folding process, whether it operates on a single element, a subset, or the entire visualization. **Effect scope** identifies the extent to which the un/folding transformation impacts the visualization (also beyond the focus), differentiating between changes affecting individual elements, a local region, or entire visualization. **Unfolding scale** examines the number of meaningful un/folding states, encompassing binary, discrete, and continuous scales. **Transformation type** explores the nature of the changes applied to the focus and context regions, which can either be geometric adjustments of form and position or semantic adjustments modifying the visual encoding of the data more profoundly.

The last two dimensions relate to user interaction. **Transition control** describes how the transformation between folded and unfolded states is initiated and managed, distinguishing between triggered transitions and full manual control. **Interaction directness** captures the proximity of the interaction and the un/foldable, including direct manipulation and more indirect use of interface elements. By analyzing the design choices within each dimension, we hope to characterize the diverse spectrum of un/foldable visualization approaches. A sample of 30 classified un/foldable visualizations is presented in Table 2.

4.1. Data facets

The literature makes clear that different data require different visualizations [Mun14, TS20]. Accordingly, un/folding techniques are typically designed with specific data types in mind. Inspired by Shneiderman's task by data type taxonomy [Shn96] and previous surveys on interactive data visualization [TGK*17, BTM*24], we consider the following practically relevant data facets for categorizing un/folding techniques: time, geo-space, relationships, multivariate attributes, images & video, text & text-based documents, volumes & flow, and algorithms. Techniques that could not be assigned to either of these data facets are subsumed under other data facets. Also note that some techniques are agnostic to data facets, in which case we have assigned a technique to the data facets for which it has been demonstrated with concrete examples.



Time is an essential data facet that is relevant in many application domains. A typical challenge is to deal with large time series that span a long time interval or exhibit a very fine-grained temporal resolution. Here, un/folding can be used to focus the visual analysis on selected time periods. To do so, the time axis can be unfolded to give more display space to relevant time periods and folded to reduce the space used for less relevant periods. This is analogous to classical focus+context techniques, such as the *Signal Lens* [Kin10] and *Multistream* [CSWP18], which is depicted in Fig. 8b.

Un/folding can also be used to adjust the level of detail with which time-dependent data values are visualized when there are many time series in the data. For stock price data represented as horizon graphs, *Touch the Time* [RROF18] includes touch-based un/folding techniques that gradually grant more display resources to selected stocks as the user performs drag gestures along the vertical display axis. This allows users to read the unfolded data with greater accuracy. Similarly, un/folding can switch between representing time points or time series as several individual or aggregated marks, as in *#FluxFlow* [ZCW*14] or *Touch Wave* [BLC12].

A particularly interesting example of un/folding time is *Time Curves* [BSH*16]. Here, the time points are initially displayed along a horizontal 1D line representing the temporal order of the data values. The un/folding transforms the 1D line into a 2D curve whose control points are determined by the multivariate similarity of the time points, as shown in Fig. 6a. In other words, a representation emphasizing temporal order is semantically unfolded to a representation that highlights similarity among the time points.

Geo-space refers to data associated with the geographical space of the Earth. A fundamental design decision when visualizing geo-spatial data is whether to show the spatial frame of reference as a 2D map or a 3D globe, and if a map is used, how to project the original spherical coordinates to Cartesian coordinates of the display. The *Cesium* platform [Ces] supports un/folding a globe to perspective or orthographic maps. Similarly, the *Trajectory Wall* [TSAA12] un/folds a map with color-coded

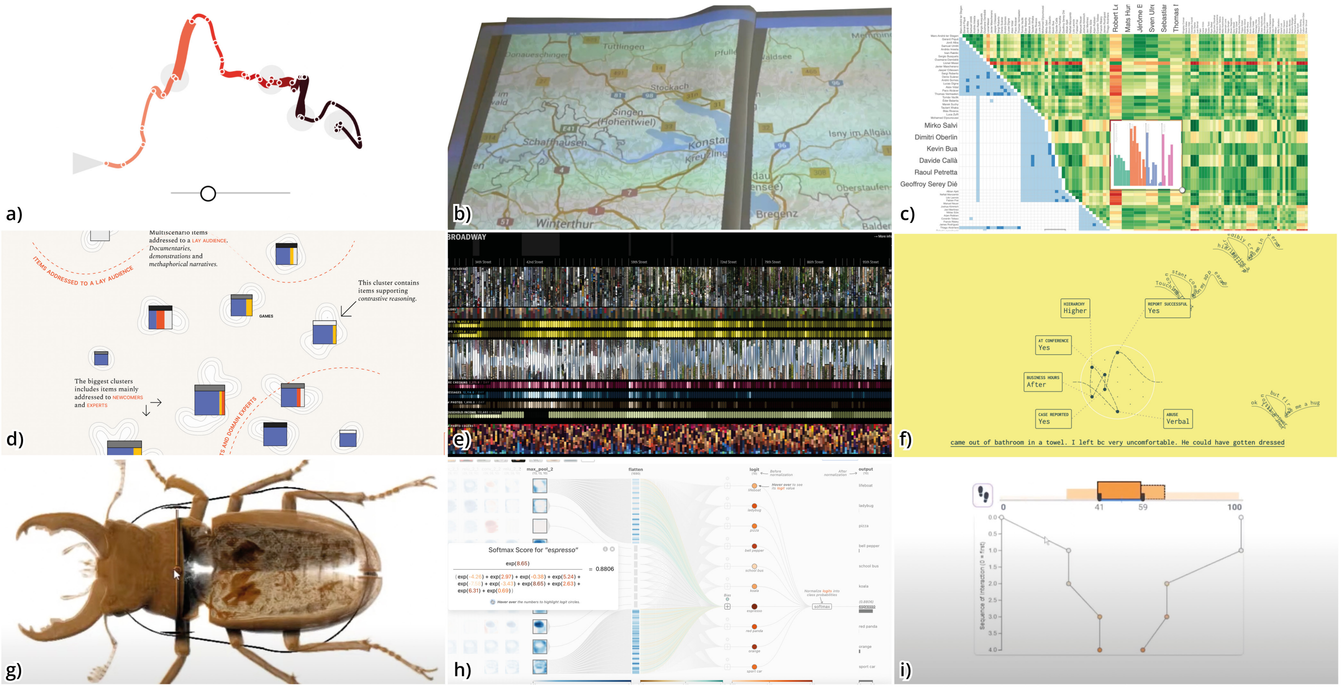
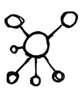


Figure 6: *Examples of un/folding for different data facets. a) Time: Time Curves [BSH*16]; b) Geo-space: InformationSense [BDR17]; c) Relationships: Responsive Matrix Cells [HBS*21]; d) Multivariate Attributes: XAI Primer [GEHEA22]; e) Images & Video: On Broadway [GSBM14]; f) Text & Text-Based Documents: Tied in Knots [EBC*20]; g) Volumes & Flow: Smart surrogate widgets [SB18]; h) Algorithms: CNN Explainer [WTS*21]; i) Other data: Provenance Widgets [NOEAE25]. (See Figure Attribution)*

2D movement trajectories to a 3D map with stacked 3D trajectory bands, which is illustrated in Fig. 8c. The un/folding metaphor has also been used to illustrate *Myriahedral projections* [vW08], for which the spherical hull of the Earth is cut open in different ways and flattened to a map.

As for time, not all regions of geo-space may be equally important to the task at hand, which naturally matches the idea of folding irrelevant regions. *Melange* [EHRF08] and *SpaceFold* [BHR14] use axis-aligned folds to reduce the display space occupied by irrelevant map regions, effectively giving more space to relevant regions and bringing them closer together for easier comparison. More free-form folds of geo-space are possible with cloth-based interfaces as in *InformationSense* [BDR17] (see Fig. 6b).

In cases where both geo-space and time are present in a dataset, un/folding can transform 2D visualizations of spatio-temporal data into 3D visualizations as in the *PolyCube* [WSL*20] in Fig. 7c. This can be useful for switching between views that emphasize geo-space or time, and for balancing the display resources used to encode these data facets.



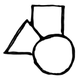
Relationships in networks and hierarchical data are typically visualized as node-link diagrams, adjacency matrices, and treemaps. Expanding node-link diagrams and exploring hierarchical data are especially common and well-established visualization approaches, which is probably why this facet contains the most examples of any data facet.

For relationships, un/folding can be used to expand sub-levels in hierarchies/aggregations, focus on specific elements, areas, or their associated attributes, transform representations, or compare data entities. For node-link diagrams, it is common practice to show a reduced version of the data and expand further nodes [TAS09, KMK*23] or to disaggregate nodes via selection of sub-networks [SLT*14, JER16]. For these un/folding operations, animated transitions can reveal the sub-networks or nodes making them visually emerge from an expanded node.

Space-filling approaches like interactive treemaps [BHA*23] or radial variants [SZ00] enable the navigation into hierarchical data structures (see Fig. 12a). These techniques typically start with an overview of the upper hierarchy, enabling the iterative navigation through levels by expanding selected sub-hierarchies to fill the space while leaving traces of higher levels.

Other approaches work with geometric expansion of a focus area and simultaneous compression of other areas, often in a fisheye manner [SHM05, TS08, MGT*03]. Less common is un/folding of encoded attributes or other details related to selected nodes or edges in networks. For example, in *AVOCADO* [SLSG16], sub-networks of a hierarchical provenance graph can be expanded by clicking on a node, and semantic zooming gradually unfolds more contextual details directly inside the network nodes depending on the zoom level (see Fig. 10c). Similarly, *Responsive Matrix Cells* for adjacency matrices [HBS*21] (see Fig. 6c), or *Word Bridge* [KKEE11] and *Unfolding Edges* [BDT23] (see Fig. 9a) for node-link layouts allow the unfolding of additional multivariate information of edges.

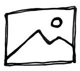
Relationship un/folding can also be realized by transforming subgraphs into alternative representations. Notably, *NodeTrix* [HFM07] allows on-demand transformation of subsets of a node-link diagram into adjacency matrices (see Fig. 7b) and *Responsive Matrix Cells* [HBS*21] (see Fig. 6c) transform submatrices into bar charts, parallel coordinate plots, or node-link representations. Similarly, *Elastic Hierarchies* [ZMC05] transform parts of a hierarchical node-link diagram into treemaps.



Multivariate attributes refer to datasets with multiple data dimensions for each data point. Accommodating multivariate data in visualizations presents a challenge due to the increased density and complexity of connections between attributes. Un/folding techniques can help manage this complexity by collapsing specific dimensions or revealing additional details for specific elements on demand. This dynamic interaction can support exploratory analysis, pattern recognition, and comparative tasks without overwhelming users with excessive information. Common multivariate un/foldables are stretching-based zoomable Parallel Coordinates [RRF20, YGX*09] or StarPlots [LKE*15] (see Fig. 10b), or cell-based visualizations, in which the tabular structure is utilized for the selective revelation of additional details in selected rows [RC94, KS02].

Notable examples of un/foldable techniques for multivariate data also include approaches that dynamically reveal detail information while preserving overall context in the visual structure of another data type. For example, the previously mentioned technique *AVOCADO* [SLSG16] applies semantic zooming to hierarchical provenance graphs to address the complexity of multi-step biomedical analysis workflows (see Fig. 10c). This approach combines hierarchical and motif-based aggregation with a degree-of-interest function to expand only the graph regions most relevant to the task. *Glyphboard* [KKG*20] is a zoomable interface that combines dimensionality reduction for overviews with gradual unfolding of glyph-based visualizations to highlight key dimensions.

Multivariate visualization techniques can be combined with visual representations of other data types, such as timelines, maps, or node-link diagrams. For example, the *XAI Primer* [GEHEA22] uses un/folding as part of a multi-layered visualization structured into clusters, items, and networks (see Fig. 6d). These layers allow the progressive unfolding of details via semantic zooming. Only at the lowest level, the network connections are revealed, while higher level views use glyphs to visually aggregate multiple dimensions.



Images & video data are unique among the data facets as they inherently possess their own visual representations. Unlike abstract data, images and videos require visualization techniques that preserve and integrate their visual content, such as color, texture, and for videos motion and time-dependent information. Image and video data are often enriched with other types of data, creating challenges for un/folding techniques that must simultaneously balance the visual media and associated metadata. For instance, *On Broadway* [GSBM14] exemplifies a comprehensive integration of visual and multivariate data (see Fig. 6e). This interactive urban visualization about the Broadway in Manhattan, combines images, social media data, and other metrics into vertically stacked slices that can be progressively expanded via zoom or selection, unfolding the visual media and associated metadata with a stretching motion.

For images, un/folding can facilitate hierarchical exploration, where individual components or features of an image can be selectively revealed to analyze finer details or regions of interest [BHA*23, PPBT12, HTCT14]. For videos, un/folding techniques can support temporal exploration by expanding particular time segments or compressing others, to focus on key moments while maintaining a sense of the overall narrative [BGSF10, RON*23,JER16]. These techniques are particularly useful for tasks requiring detailed inspection, such as identifying patterns, comparing segments, or exploring metadata [LLS*18, WTS*21, FUB*24]. In large datasets of visual media, un/folding can also reduce visual clutter, enabling transitions between overviews and detail views [EHRF08, LZC*21, HSJ14]. For instance, in cultural heritage collections, un/folding can integrate associated metadata with visual media, enhancing storytelling and contextual analysis [Cas24, dGNK*23].

Fluid Views [DCW12] bridges overview and detail by combining dynamic queries and semantic zooming. This system allows users to explore image datasets by transitioning smoothly between high-level maps based on similarity and detailed representations, integrating visual media and metadata for exploratory search. Another example is *DendroMap* [BHA*23], which adapts treemaps to organize and explore large-scale image datasets hierarchically (see Fig. 12a). Users can dynamically unfold image clusters to examine their diversity or delve into regions of interest, facilitating the discovery of patterns and outliers across multiple abstraction levels.

Text & text-based documents encompass un/foldables ranging from virtual documents and high-level text visualizations to textual content enriched with additional details on demand. Text visualization is often related to distant-reading practices [Mor13, JFCS15]. In this context, on-demand un/folding of additional details can provide ways to fluidly modify the level of abstraction, helping to bridge views across different scales [AF06]. Statistical overviews of textual content can be un/folded to facilitate discourse analysis [ZCCB12], exploring relationships in text corpora [KKEE11], analyzing information spreading in social media [ZCW*14], exploring annotations in an author's library [BBBD20], or lead-lag analysis [LCW*15].

Text can also be un/folded between different representations. As described earlier, *WordTree* [WV08] gradually transforms sub-nodes between text and hierarchical representations. *Tied in Knots* [EBHC22] uses un/folding to support the exploration of reports about sexual harassment (see Fig. 6f). Sentences from the reports are visually folded into knots, which are placed on a zoomable canvas. Selecting a knot fluidly unfolds it into a readable form and reveals details about its associated data attributes.

Instead of displaying a visual abstraction of text data, text-based documents can also be enriched with related entities and images [dGNK*23, Cas24]. For example, in the *ReFa*

Reader [dGNK*23], highlighted keywords in an essay are visually linked to dynamically scrolling entities, and selecting a keyword or entity reveals a sub-network that can be gradually expanded, shifting the activity from essay reading to associative exploration of a cultural collection.

Physically-inspired folding has also been explored for documents, for instance by mimicking physical document handling with multi-touch gestures to arrange and fold documents [CLC11]. The virtual documents can be handled like sheets of paper, allowing users to fold away less relevant parts to align focused sections side by side for contextual comparison.

Volumes & flow data play a central role in a variety of scientific, medical, and engineering domains where volumetric scans, fluid dynamics simulations, or large-scale spatial models need to be analyzed. A defining characteristic of these data is their space-filling nature: they span entire 3D regions, making occlusion management a primary challenge. Techniques for un/folding therefore tend to focus on displacing specific parts of the dataset to reveal salient internal structures without losing crucial contextual information.

For instance, *Deformations for Browsing Volumetric Data* [MTB03] and *Smart Surrogate Widgets* [SB18] (see Fig. 6g) employ sets of widgets to cut into and open up, spread apart, or peel away parts of the volume. In some approaches, these operations are applied in a view-dependent manner, to provide the user with an unoccluded view without the need for additional camera manipulation [BG06, BV09]. In many cases, the un/folding operation preserves relevant focus structures while employing alternative visual mappings (e.g., special transfer functions) to highlight key features for a given task [SLK*17] (see Fig. 9c).

Furthermore, instead of manipulating a direct representation of the underlying volume itself, some techniques also operate on derived structures, such as streamlines [TEC*16] or glyphs [TLS17], to provide unobstructed views of the raw data values. In this way, un/folding assists in comparative analysis and verification.

Finally, multiscale frameworks like *DimSUM* [MDLI*18] (see Fig. 13a) and *Multiscale Unfolding* [HKM*22] reveal structural hierarchies (e.g., from microscopic DNA details to volumetric organ systems) through seamless transitions between global overviews and localized exploration.

Algorithms involve data related to computational logic, code structures, or machine-learning processes, and therefore frequently assume layered and/or hierarchical representations [HWX23, KMK*23, LLS*18]. Un/folding techniques enable users to expand or collapse the intricate steps within an algorithm to better understand its operation and performance. This can entail revealing deeper layers of a function call graph, unfolding nested workflows in software architectures, or focusing on particular subroutines when searching for bottlenecks or bugs.

A central use case in this domain is the exploration of deep neural networks. For machine-learning pipelines, un/folding allows selective inspection of training stages, model components, or hyperparameters, thereby helping analysts manage the complexity of AI workflows [WTS*21]. By un/folding layers, activation maps, or neuron clusters, one can trace how input data transform through successive stages of computation, facilitating a deeper understanding of model decision-making. As an example, *CNNVis* [LSL*17] provides a CNN explanation visualization that increases the granularity of neuron clusters on demand, as shown in Fig. 6h. Convolutional layers can also be expanded into sub-layers or individual feature maps, effectively bridging a high-level overview and a fine-grained examination of hidden activations. In this way, un/folding not only supports debugging and optimization tasks but also promotes transparent communication of algorithmic processes, revealing how specific components act together to form the final output. Ultimately, this layered approach ensures that the analyst can flexibly switch between macro-level system structures and micro-level details, shedding light on otherwise opaque algorithmic behavior.

Other data facets exist, such as uncertainty or provenance, that are worth mentioning in addition to those discussed so far. However, our literature review identified relatively few examples explicitly targeting these facets, which is why they are only briefly summarized here.

While some examples show provenance or uncertainty-related data, they do not use un/folding to specifically show these facets. For example, *PMC-VIS* [KMK*23] visualizes probabilistic models, but its un/folding mechanism is concerned with the hierarchical exploration of the models, not the involved model uncertainty. The *AVOCADO* tool [SLSG16] (see Fig. 10c) supports exploring provenance graphs for biomedical-research workflows, but its un/folding mechanism addresses the data exploration of multiple aggregation levels in general, not specifically of the provenance facet. A notable example of un/folding tailored specifically for provenance data is *ProvenanceWidgets* [NOEAE25] (see Fig. 6i), which are UI control elements designed to display analysis provenance. These widgets can slide out to reveal detailed interaction histories, conveying the sequence of actions or decisions taken during a data analysis.

Finally, there are un/folding techniques that are agnostic to data facets. They provide mechanisms that can be applied flexibly across various data types, supporting the exploration of diverse datasets regardless of specific domain requirements. For example, naturally inspired folding interactions [TFJ12] (see Fig. 12b) can peel off visualization views regardless of what the views actually show.

4.2. Focus scope

Un/folding requires specifying which regions of interest are to be unfolded. We distinguish three categories for the scope of the un/folding focus: **element**, **subset**, or **global**. As un/folding is a reversible operation—e.g., a node can be unfolded to reveal multiple child nodes or multiple nodes can be folded into an aggregated meta-node—our classification of the focus scope is based on the initial state of a visualization and whether unfolding or folding is the primary operation. In cases where the initial state is not clearly defined, we determine the focus scope based on the unfolding direction. For some un/folding techniques, the exact focus scope can be difficult to determine as it may involve an intermediate middle ground [HPK*16], which we do not consider in our classification.

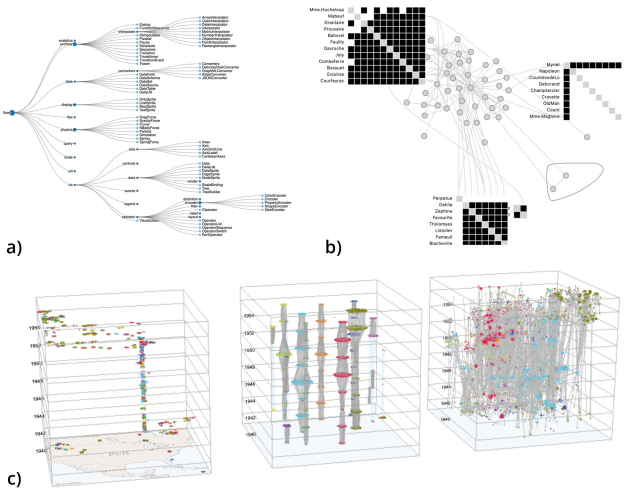
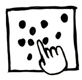


Figure 7: *Focus scope. a) In a collapsible tidy tree [Bos24], individual elements can be un/folded to expand or collapse sub-hierarchies. b) With* NodeTrix *a subset of the network can be transformed into a matrix [HFM07]. c) The* Polycube *transforms globally to provide new perspectives on the data [WSL*20]. (See Figure Attribution)*

Element focus scope means that a single, specified element of interest is un/folded. This type of focus is therefore only possible for data with discrete elements. Typically, element un/folding is induced through direct or query-based interaction. A common case for an element focus is the expansion of a node in a node-link diagram [dSPT*19] or scatterplot [Ros06] into a more detailed [LLS*18] or disaggregated state [SLT*14]. Other examples are the collapse or expansion of lower sub-hierarchies in tree representations [Bos24] (see Fig. 7a), the transformation of an individual cell in an adjacency matrix [BCCR04], the selection of an individual image [RON*23], or text element [dGNK*23]. We consider the unfolding of a hierarchy node or cluster of elements to be in the element focus category, even if the visualization shows a preview of its contained elements [BHA*23, SLSG16, LMR19], because the node or cluster is the selected unit that is unfolded, not the elements it contains.

A **subset focus scope** corresponds to the un/folding of several data items, intervals, or regions. It is typical for quantitative and continuous data such as time series or volumetric data. The subset focus scope category also includes techniques that are capable of un/folding multiple discrete foci at once. In contrast to the typical click interaction for an element-based un/folding, a subset focus is oftentimes induced through region-based or query-based interactions, such as lasso selection [HFM07, RM13], brushing and dragging [CSWP18], or interface widgets [TS08]. With the multi-focus context technique *Balloon Focus* [TS08], for example, regions of interest in a treemap are enlarged through query-based/faceted selection and a zoom slider, while reducing the size and opacity of less relevant elements. *NodeTrix* [HFM07] folds lasso-selected parts of a node-link diagram into miniature matrices as shown in Fig. 7b. In cell-based visualizations, such as *Table Lens* [RC94, JTS08], *LiveRAC* [MMKN08], or *Responsive Matrix Cells* [HBS*21], cells, rows, and columns (individual or multiple) can be un/folded to display more detailed, summarized, or differently encoded information. Volume manipulation techniques, such as *Smart Surrogate Widgets* [SB18] (see Fig. 6g) or *View-dependent peel-away visualization* [BV09], typically operate on subsets and fold away the occluding parts of the 3D visualization to reveal details of the focused sub-volume.



Global focus scope means that the un/folding operates on the entire visualization. A common example of a global focus scope is semantic zoom, which globally un/folds details of the visualized data depending on the current zoom level, while it also pushes some elements out of the viewport. In *Glyphboard* [KKG*20], the dots of a scatterplot are unfolded into flower-like glyphs as users zoom in, allowing them to see more details of the multivariate data items. Global un/folding of elements on zoom has been used to reveal contained sub-elements with new visual encoding and information in *XAI Primer* [GEHEA22], increased data granularity in *Shifted Maps* [OHN*18], or more detailed summaries in *Video Tapestries* [BGSF10]. In volume data, global semantic zoom can adjust the overall level of abstraction, for example, from a representation of a cell nucleus to the composition of DNA [HMK*20].

In addition to semantic zoom interfaces, we also identified global focus scope for techniques where global uniform un/folding transformations are taking place. For example, *PolyCube* [WSL*20] un/folds 2D representations of maps, timelines, and networks to 3D cube representations with additional information encoded into the added third dimension as shown in Fig. 7c. In *Deimos* [LSC*23], 2D charts are globally transformed into a 3D chart in an XR environment. Similarly, *Time Curves* [BSH*16] globally unfold a 1D line representation into a 2D curve (see Fig. 6a). Volumes are also oftentimes globally un/folded [HTCT14, MTB03], and techniques replicating natural folding tend to operate with a global scope, as well [BHR14, vW08].

While many techniques work with a specific focus scope, some approaches, such as *TreeNetViz* [GZ11], *LDG Viewer* [Fre22], or *Fluid Views* [DCW12], support different scopes from un/folding single and multiples element to global un/folding.

4.3. Effect scope

Effect scope refers to the extent to which the un/folding operation impacts the visualization. While the previously discussed *focus scope* refers to what or how much gets unfolded, the *effect scope* characterizes the resulting visual changes, including both the focus transformations and possible compressions or simplifications of the context. Trivially, a global focus scope implies a global effect scope because a global un/folding changes the entire visualization.

The distinction between focus scope and effect scope is more interesting when the focus scope is not global, in which case the effect scope can still be **global**, only **local**, or even only on the un/folded **element**. The effect scope can have a considerable impact on the performance and scalability of a visualization. For example, global transformations or simultaneous local transformations of many data

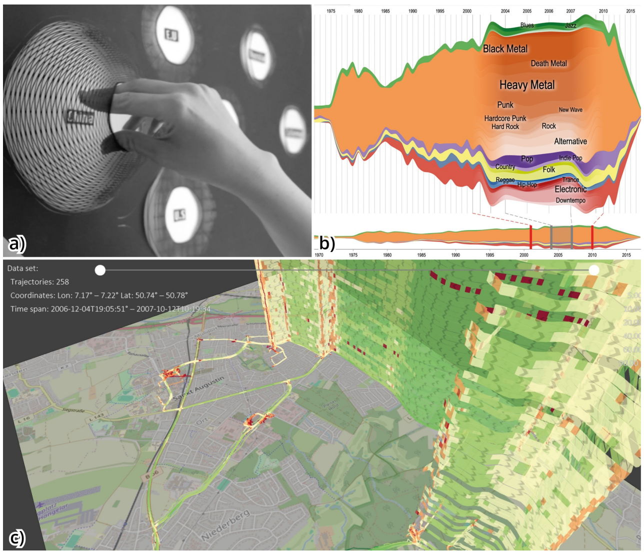
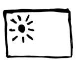
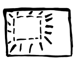


Figure 8: *Effect scope. a)* © *In* KiriPhys*, only the unfolded element itself is affected through stretching [DPC23]. b)* 🅭🅯 *In* Multistream*, a local region of the visualization is transformed through unfolding [CSWP18]. c)* 🅭🅯 *The* Trajectory Wall *is modified globally during the un/folding transformation [TSAA12]. (See Figure Attribution)*

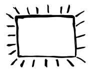
points require not only more computational power, but also substantial cognitive effort.



Element effect scope describes techniques where only the un/folded element is affected in the visualization; no other transformations take place. This type of scope is rather uncommon in the literature because increasing detail or size in one place typically requires decreasing detail or size in other places to create space, limit complexity, and avoid occlusions or overdrawing [BDT23]. Still, *KiriPhys* [DPC23] is a data physicalization example with an element scope. A flat, elastic, circular mesh structure, representing a country's CO_2 emissions in this case, can be pulled out to encode additional data details through the depth and pattern of the pulled-out mesh (see Fig. 8a); other elements are not affected. Another example of element effect scope is *Tied in Knots* [EBC*20], which only unfolds an individual knot on demand. It does not account for overlap with other nearby knots and does not employ strategies to compress or reposition other elements. Un/foldables with element effect scope therefore often either have enough space to unfold details or make the compromise of allowing overlaps with other elements.



With a **local effect scope** several elements or a local region are affected by the unfolding transformation. In the already mentioned *NodeTrix* [HFM07], for example, the un/folding from a node-link representation to a matrix affects a set of selected nodes plus their incident edges (see Fig. 7b). Un/folding transformations may locally fold away occluding parts of a volume [TEC*16] or semantically stretch parts of an augmented-reality (AR) visualization [LGB07] (see Fig. 13b) without causing global changes. The *SignalLens* [Kin10] for time series enables detailed observation of a focus interval while preserving the context of the entire time line. Only the focus interval and the transition between the focus and the context areas are locally affected by changes. Techniques with local effect scope commonly enlarge or provide more details, oftentimes with additional dimensions, for a limited subset of the whole data [CSWP18] (see Fig. 8b), [LKE*15] (see Fig. 10b), and [RRF20].



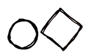
Techniques with a **global effect scope**, such as *PRISAD* [SHM05], a rendering infrastructure for accordion drawing, the related *TreeJuxtaposer* [MGT*03], or the horizon graph interface *Touch the Time* [RROF18], create space for local detail enlargement by gradually compressing the rest of the visualization. Un/folding details in node-link diagrams also often entails a global reconfiguration of the graph layout to avoid occlusions [WYC*20, MB05, SLSG16] (see Fig. 10c). Similarly, techniques where details slide out of existing visual marks, such as *BarCodeTree* [LZD*20] and *UpSet* [LGS*14], often globally adjust the layout to create the needed space. For the same reason, (space-filling) hierarchical navigation techniques, such as the *DendroMap* [BHA*23] (see Fig. 12a), Collapsible Trees [Bos24] (Fig. 7a), or the *Word Tree* [WV08], typically have a global effect scope, even when their focus scope is an individual element.

Finally, as already mentioned, a global focus scope naturally implies a global effect scope. For example, the *Trajectory Wall* [TSAA12] globally transforms a two-dimensional map into a three-dimensional stack of trajectory bands (see Fig. 8c).

4.4. Unfolding scale

The unfolding scale characterizes the number of states that can be un/folded. We have identified three types of scales: **binary** scales with two states, **discrete** scales with a fixed number of states, and **continuous** scales with an infinite number of states.

The states constitute key points in the un/folding mechanism that can be semantically meaningful for the visualization. As a physical example, consider a folding chair. It has a binary unfolding scale with the two states folded and unfolded. Intermediate states like a half-folded chair are not meaningful (or useful), and therefore do not contribute to the unfolding scale. The same is true for intermediate states in un/folding visualizations: States that exist merely for the purpose of smoothly transitioning, or 'tweening', the un/folding are not considered meaningful states of the unfolding scale.



A **binary** scale is the most basic unfolding scale with two states, folded and unfolded. Any un/folding technique must have at least these two states. In many cases it is sufficient to have only these two states. For example, *NodeTrix* [HFM07] un/folds between a node-link and a matrix representation. *Unfolding Edges* [BDT23] shown in Fig. 9a unfolds a single edge into a fan of lines adding more information about the edge. The *Table Lens* [RC94, JTS08] folds alphanumeric table cells into visually encoded table cells. *Myriahedral projections* [vW08] are un/folded between a globe and a map.

Also *Time Curves* [BSH*16] are categorized as having a binary unfolding scale, although the user can control the un/folding with a slider, which yields many intermediate states. However, these states

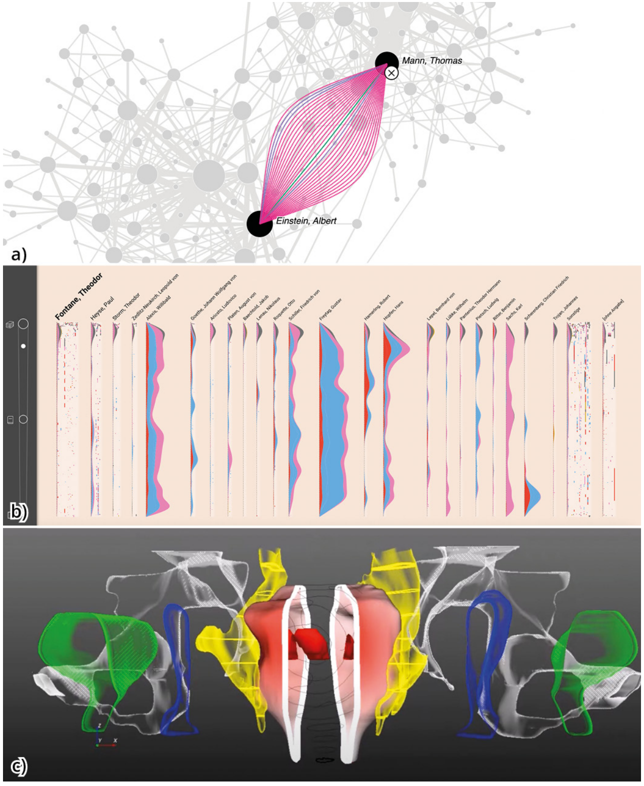


Figure 9: *Unfolding scale. a) Binary: In* Unfolding edges, *individual edges can be unfolded on demand to show context [BDT23]. b) Discrete:* Reading Traces *provides the possibility to explore a library across three discrete states [BBBD20]. c) Continuous:* PelVis *allows the continuous unfolding of pelvic structures [SLK*17]. (See Figure Attribution)*

are not semantically relevant and serve only the purpose of visually transitioning between a 1D line representing temporal order and a 2D curve representing similarity.

A **discrete** unfolding scale consists of more than two states and thus enables multiple levels of un/folding. The discrete states typically correspond to different levels of data or graphical abstraction displayed in the visualization. For example, *Reading Traces* [BBBD20] (see Fig. 9b), un/folds document corpora along the states of author, book, and page using three different visual representations, namely, bars, matrices, and stream graphs. In *SoccerStories* [PVF13] (see Fig. 10a), groups of data points can be un/folded across different faceted views, including node-link, matrix, tag cloud, hive plot, and heat map, each emphasizing a specific aspect of the data.

Discrete unfolding scales are prevalent in hierarchical data visualization. Quite a few techniques exist that allow users to un/fold hierarchical information spaces in a stepwise manner by expanding or collapsing the hierarchy nodes. In these cases, the number of distinct un/folding states depends on the number of nodes in the data hierarchy, as exemplified by *Sunburst* [SZ00], *InterRing* [YWR02], *Elastic Hierarchies* [ZMC05], and *DendroMap* [BHA*23].

Continuous unfolding scales have an infinite number of states. They are usually accessed by continuously controlling the amount of display space used for the un/folded focus data. *SignalLens* [Kin10], for example, un/folds a focused time interval into a space whose size can be dynamically adjusted. Similarly, *Responsive Matrix Cells* [HBS*21] un/fold plain color-coded matrix cells into miniature visualizations with varying levels of graphical abstraction and also dynamically adjustable size (see Fig. 6c).

Techniques that closely resemble physical folding often use a continuous folding scale, for example, peel-away visualizations for volumetric data [BV09], 3D flexible tangible lenses in AR [LGB07], folding interaction for visual comparison [TFJ12], cloth-based visualization interfaces [BDR17], or 3D folding for surgical planning [SLK*17] (see Fig. 9c).

Note that in all these works, we consider the continuous states to have semantic value. This is mostly the case because continuously incremental unfolding uses more and more pixels, and hence, continuously adds more and more information to the visualization.

4.5. Transformation type

The transformation type captures *how* un/folding operations modify the visualization. We consider both, the type of the **focus** transformation, which regards the un/folding focus, and the type of the **context** transformation, which adjusts the surrounding periphery. Note that the focus transformation characterizes the un/folding effect that can be seen for the focused portion of the visualization, not how the focused data itself is transformed. For example, the streamline deformations in [TEC*16] fold away occluding streamlines (effect in the focused region) to reveal a focused volumetric structure (focused data), which remains unchanged. In this case, a focus transformation is considered to happen even though the focused structure does not change at all. Yet, the streamlines in the focus area are displaced with the visual effect that the focused structure becomes visible.

The primary types of transformation we distinguish are **geometric** and **semantic**. For the context transformation only, there are two additional types, **none** and **n/a** (not applicable), which are applied when there is no context transformation or no context at all.

Geometric transformations involve changing in the shape, size, orientation, or position of elements, such as repositioning, rotating, or moving elements off the screen. They also include magnification, expansion, and other forms of geometric distortion, such as those associated with fish-eye techniques, which can be described by mathematical functions.

Geometric transformations are especially common for changes in the context area. Often this is simply a matter of moving elements to make room for an enlarged focus area, for example, by moving parts of a visualization away from each other [LMR19], or by repositioning the nodes in a node-link based layout [MB05]. For the same purpose, geometric transformations are frequently used to compress the context, either uniformly [YYZ*22] or gradually based on the distance to the focus [Kin10]. Geometric focus enlargement and context shrinking can also be based on semantic similarity [TS08].

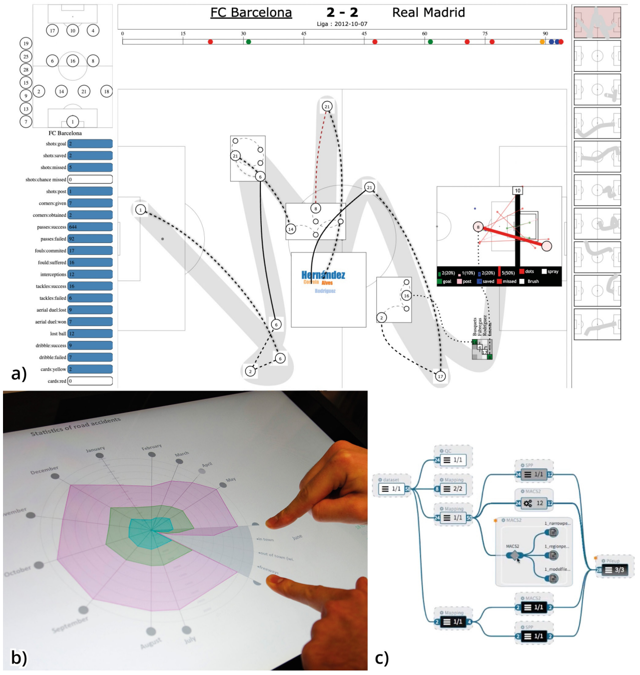


Figure 10: *Transformation type. a)* 🅭🅯 Soccer stories *[PVF13] is an example for local semantic focus transformations. b)* 🅭🅯 Fluid Interactions for Star Plots *[LKE*15] semantically fans out information, while geometrically compressing the context. c)* 🅭🅯 AVOCADO *[SLSG16] uses semantic focus and geometric context transformations, and foreshadows un/foldable content in the nodes. (See Figure Attribution)*

Distorting or folding away parts of a volume [MTB03] and physical manipulations of data physicalizations [DPC23] (see Fig. 8a) are also forms of geometric transformations. A quite unique example is *VISMOCK* [BPS24] (see Fig. 11), which uses the embroidery technique called smocking to un/fold areas of a fabric in order to reveal new information as a physicalized zoom.

Semantic transformations go beyond purely geometric operations. They involve adding or removing data elements or marks and modifying their visual attributes. Examples include abstracted aggregations or splitting of data points [GEHEA22, CSWP18] (see Fig. 6d and Fig. 8b), abstraction changes [MDLI*18] (see Fig. 13a), but also just additions of labels, colors, or other visual marks [LKE*15] (see Fig. 10b).

Semantic transformations often imply some geometric transformations as well. For example, semantic transformations may result in layout changes that are induced by data-related projection changes [HVP*19, BSH*16]. Also a semantic switch in dimensionality typically entails geometric changes, for example, when switching from a two-dimensional to a three-dimensional representation [WSL*20, TSAA12] (see Fig. 7c and Fig. 8c).

Degree-of-interest approaches as described for geometric transformations also exist for semantic transformations. For example, expanding a node in *DNN Genealogy* [WYC*20] also triggers the

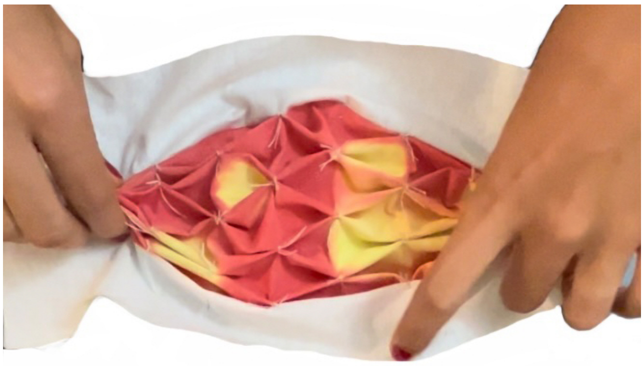


Figure 11: VISMOCK *uses the textile "smocking" technique for interactivity in data physicalizations [BPS24].* 🅭🅯 *(See Figure Attribution)*

expansion of other relevant DNNs while reducing the prominence of less relevant ones. In addition to influencing the size of a node, this also influences the display of glyph-based details and labels inside the nodes.

While many semantic transformations enhance the level of detail in the focus region through the addition or refinement of variables and marks (or the opposite for context), other semantic transformations introduce more fundamental transformations. Techniques such as *Soccer Stories* [PVF13] (see Fig. 10a) or *NodeTrix* [HFM07] (see Fig. 7b) morph node-link representations into completely different representations. A special case is *Hybrid-image visualization* [IDW*13] for large displays. Here, global transformations are not generated dynamically by the computer, but are induced through human perception, where a specifically designed static visualization is perceived differently depending on the viewing distance from a large display wall.

None applies only to context transformations and indicates that the context is not transformed. That is, the un/folding affects only the focus region, without having any effect on other parts of the visualization. Quite a few of the already described examples perform no context transformation, including *NodeTrix* [HFM07] (see Fig. 7b), *KiriPhis* [DPC23] (see Fig. 8a), or *Smart Surrogate Widgets* [SB18] (see Fig. 6g).

N/A is the second special type only for context transformations. It applies when no context is defined at all because the focus scope is global. Consequently, all techniques with a global focus scope are assigned the special n/a context transformation type. An example is the un/folding of a 3D globe into 2D map based on a *Myriahedral projection* [vW08].

4.6. Transition control

The chosen mode of transition control can influence not only the interaction experience but also the degree of fluidity afforded by an un/foldable visualization. We identified two different modes: Transitions either run as **triggered** animations or can be **controlled** manually. Hybrid approaches combine the strengths of both modes.

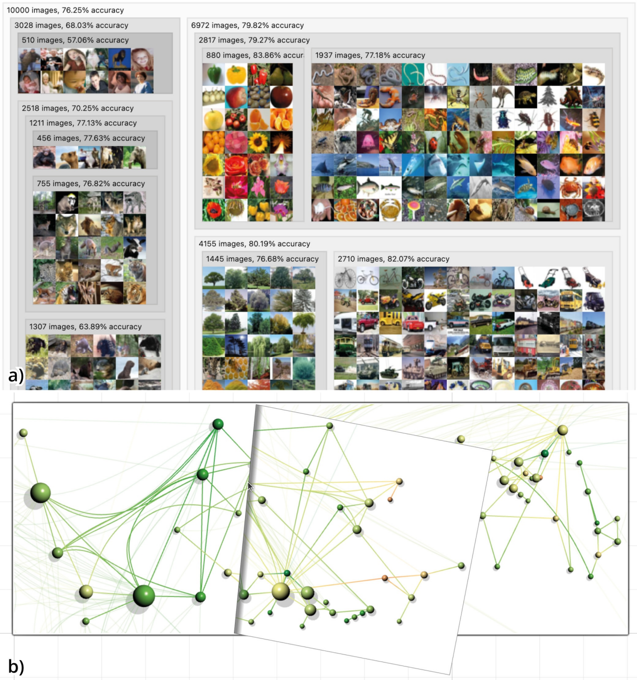
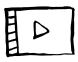
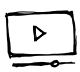


Figure 12: *Transition control. a)* 🅭🅯 *Triggered animations for zooming into a treemap of photographs [BHA*23]; b)* 🅭🅯 *Manually controlled transition for folding a node-link visualization for comparison purposes [TFJ12]. (See Figure Attribution)*



For **triggered** animations, a single user action (e.g., selection of an element or press of a button) initiates an animated un/folding transition that completes automatically without user intervention. This mode ensures smooth, consistent transformations and minimizes cognitive load by automating the progression of the intermediate steps. For example, the *WordTree* visualization [WV08] uses triggered animations to dynamically un/fold hierarchical representations of textual patterns. Similarly, *DendroMap* [BHA*23] (see Fig. 12a) employs short animations to zoom into selected cluster hierarchies, facilitating exploration while maintaining context. *FluxFlow* [ZCW*14] provides interface controls to trigger animated transitions between clustering levels. In *Compressed Bar Charts* [LMR19], clicking a bar triggers its expansion or collapse through animated morphing effects.

Triggered animations are particularly suitable for techniques with discrete or binary un/folding scales, where transitions occur between predefined states. Their primary advantage lies in creating an accessible and seamless experience that highlights key transformations without requiring additional input during the transition.



For **controlled** transitions, users adjust the un/folding state manually. Fine-grained control, often through sliders, drag-and-drop interactions, or multi-touch gestures, allows users to navigate intermediate states, which is especially relevant for continuous un/folding scales. Manually controlled transitions leverage user input to facilitate different tasks, dynamically adjust levels of abstraction, or resolve occlusions. For example, *Melange* [EHRF08] enables users to manually control local distortions on maps and matrices for comparison tasks. For *Time Curves* [BSH*16] (see Fig. 6a), a slider is used to continuously transition between a 1D line and a 2D curve, aiding the understanding of temporal pattern in relation to data similarity. Natural folding interactions [TFJ12] (see Fig. 12b) allow users to interactively fold away overlapping views to align or compare underlying data. There are also 3D visualizations that allow users to unfold occluding elements selectively through manually controlled transitions [TEC*16].

Hybrid un/foldables integrate both manual control and triggered animation, enabling users to fluidly switch between modes depending on their respective tasks and needs. With hybrid un/foldables users can freely choose to rely on automatic animations for efficiency or manually control transitions for detailed examination. For example, *AVOCADO* [SLSG16] (see Fig. 10c) employs triggered animations for element-centered drill-down tasks while offering manual control for semantic zooming to adjust the level of detail interactively. *Color Tunneling* [HTCT14] allows users to trigger transitions for global layout changes or manually control specific transformations through mouse interactions. Similarly, *Touch Wave* [BLC12] and *Multistream* [CSWP18] (see Fig. 8b) allow for triggered and controlled transformations of stream graphs, either by double tapping and pinching or via direct or indirect mouse control to either initiate or control the respective transitions. In *Reading Traces* [BBBD20] (see Fig. 9b), the exploration of annotations across abstraction levels is supported by triggered global transitions as well as manual scrolling or slider-based adjustments.

4.7. Interaction directness

Interaction directness is the last dimension in our categorization scheme. It refers to the spatial and semantic proximity of the un/folding interaction in relation to the visualization [Twe97]. In other words, the closer and more tangible the user's input is to the data being manipulated, the more *direct* the manipulation is considered. By directly engaging with the visualization, users can develop a stronger sense of control and gain immediate feedback, which can facilitate the exploration of complex data.

Direct manipulation typically involves interacting with the un/folded element or region itself, e.g., by clicking, dragging, resizing, or zooming directly on the data elements [RROF18]. For example, in a 3D volume, a user might grab a part of the volume boundary and peel it away to reveal internal structures, experiencing real-time changes in response to their actions [SB18]. Likewise, visual comparison by flipping a page on the screen [TFJ12] (see Fig. 12b) is another operation that benefits from direct manipulation. This kind of hands-on interaction can foster immersion and reduce cognitive load, since the user's mental model and the displayed representation remain closely coupled [BIRW19]. In particular, this is a natural choice for techniques based on touch interfaces [CLC11] or AR applications [LGB07] (see Fig. 13b), as well as physicalization approaches such as *VISMOCK* [BPS24] (see Fig. 11), where information is revealed/hidden by expanding/compressing a piece of fabric.

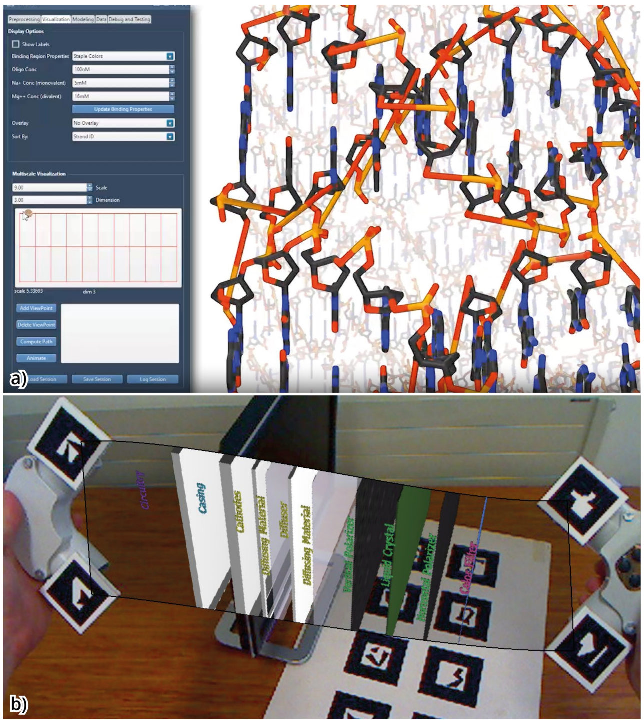


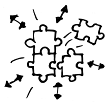
Figure 13: *Interaction directness. a)* © *Indirect: In* DimSUM*, abstraction changes are applied via external controls [MDLI*18]. b)* © *Direct: AR magic lenses support direct un/folding control via stretching [LGB07]. (See Figure Attribution)*

Indirect manipulation involves interacting with un/foldables through external interface widgets or controls such as buttons, sliders, or separate dialog boxes [HBD*18]. In this scenario, changes to the visualization occur when a user adjusts a parameter or selects an option outside of the primary view. Such indirect controls can be beneficial for more precise or repetitive tasks where fine-tuning or specialized input may be required [TS08, MDLI*18] (see Fig. 13a). However, indirect controls can introduce a disconnect between the data and the manipulation process. Some un/folding techniques offer both direct and indirect interactions so that users can flexibly switch between hands-on control and more structured or refined adjustments, depending on context and user preference [LGS*14, SLSG16, LZC*21].

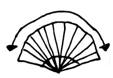
5. Families of Un/foldables

As we have seen in the previous section, un/foldables cover a wide spectrum of interaction mechanisms. The presented classification focuses on those aspects pertaining to data types and the specific visualization and interaction techniques. However, the classification does not refer to physical or mechanical equivalents of un/folding. Also classic visualization terminology (e.g., semantic zoom, focus+context) does not help much in this regard. For example, rather than classifying examples under a technique such as semantic zoom, we are interested in how elements are un/folded during the zooming process, such as whether elements disaggregate into multiple sub-elements or whether zooming enhances the detail of a single element. Therefore, this section groups un/foldable visualizations according to physical transformations, adapted from Mollerup's work on collapsibles [Mol01]. In particular, we use metaphors drawing from physical mechanisms that gradually expand, compress, or deform the shape of an object: *Assembling*, *Fanning*, *Folding*, *Hinging*, *Inflating*, *Nesting*, *Scrunching*, *Sliding*, *Stacking*, and *Stretching*.

For readability reasons, we will refer only to one direction of transformation. However, all of the principles of these technique families are reversible (e.g., inflating/deflating). In the following, we will describe the families, explain their metaphorical inspiration, and provide examples from our corpus.

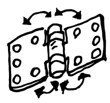


Assembling describes the combination of multiple components to form a new cohesive system, comparable to multiple puzzle pieces coming together to complete a puzzle. In this context, similar to the puzzle pieces, the individual elements that are assembled can have individual properties. Typical of assembling is that the individual components are no longer perceived individually but as part of a unified structure. Translated to interactive visualization, the principle of assembling and disassembling is present in many applications and techniques. Assembling transformations tend to visually translate to animated transitions with components entering/leaving a parent element. These parent elements also provide cues suggesting the amount or type of components via visual variables. Typical examples include collapsing or aggregating nodes in node-link diagrams [SLT*14], markers in scatterplots [Ros06], or disaggregating glyphs in semantic zoom applications [GEHEA22]. In the context of volumes, this family also manifests itself as the decomposition of a cohesive volume into individual particles [HTCT14], allowing separate analysis of its individual components.

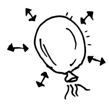


Fanning is a mechanism best exemplified by the opening of a hand fan or the spreading of a peacock's feathers. It describes a radial expansion around a fixed central anchor point (2D) or a fixed central axis (3D). Fanning involves the redistribution of elements along an arc, ensuring that the expanded elements maintain alignment with the radial structure. The extent of the expansion depends on the angular displacement along the radial lines. Fanning is typically used in radial layouts, where it expands or compresses elements or subsets of the layout in a radial manner to match the aesthetics and spatial organization of circular designs [LCW*15, GZ11]. For example, in *Fluid Interactions for Star Plots* [LKE*15] (see Fig. 10b), a star plot represents a multivariate time series with each month of the year assigned to an axis. Through touch interactions, a month-axis can be split to fan out additional axes with further dimensions, while simultaneously compressing the space occupied by neighboring axes. Another instance of fanning is *Hierarchical Sunburst Charts* [SZ00], where sub-hierarchies radially expand from a selected element using a space-filling approach.

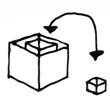
Folding not only serves as the guiding principle for the entire corpus, there is also a specific family of the same name that represents techniques that literally mimic physical folding. As seen in fabric or paper manipulation, it describes fluid transformations based on flexible bending of a planar structure or element, possibly resulting in pleats or overlaps. It is also characterized by its potential to hide parts of the planar structure within the resulting folds, or to reveal things by folding the planar structure up or revealing the backside of the folded flat surface [TFJ12]. Applied to our corpus, folding interactions typically involve controlled interactions and continuous transformation possibilities. Many members of this family use folding for comparison tasks, such as literally folding away less relevant parts through geometric distortions of geographic maps [BHR14, BDR17] (see Fig. 6 b), adjacency matrices [EHRF08], or text documents [CLC11] to directly align two regions of interest.



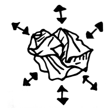
Hinging is similar to folding in that it uses geometric displacement. However, compared to folding, hinging is more restricted. Hinging can be used to open or close flat surfaces or volumes along a rigid axis, similar to opening or closing a door. Hinging can reveal new views through the elements behind the hinging mechanism or through the backside of the hinged element/subset itself, like the backside of a door revealed when opened. While some hinge transformations function by allowing movement only in one direction from the axis, others behave more symmetrically. Regarding their use in visualization, the degree of movement along the hinge can often be controlled incrementally [SLK*17] (see Fig. 9c). Due to the 3D quality of movement along an axis, examples from our corpus share exclusively the volume & flow data facet. Here it is typically used to fold away selected layers of a visualization, to unveil hidden structures [SB18, TEC*16], or to split open entire volumes [MTB03].



Inflating refers to the expansion of an elastic body, typically utilizing pressure from the inside, such as the air in a balloon. Similar to a drawing made on an inflated ballon that only resembles a small dot in a deflated state, the stretching of the elastic material by inflation can reveal and enlarge structures on the surface. In terms of visualization, inflation and deflation are used on individual or multiple elements, subsets, or the entire representation [HMK*20]. Besides geometric inflation, elements may also transform semantically. Inflating is especially useful for multifocal views, as shown in *Balloon focus* [TS08], which can inflate multiple regions of interest via a slider and query-based selection, while simultaneously deflating less relevant areas. In *AEVis* [LLS*18], individual nodes in a data path can be inflated to become an Euler diagram. Semantic zooming, as in the *Glyphboard* [KKG*20], can also be thought of as a global inflation that gradually reveals more detail while uniformly inflating all elements, including the empty space between them.

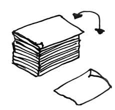


Nesting refers to the encapsulation of elements inside a parent element, potentially across multiple hierarchical levels, akin to Matryoshka dolls. Nesting is characterized by the fact that for multiple levels of nesting, the inner elements are not (fully) visible initially, requiring an unnesting process to reveal the hidden components. Un/foldables in this family include space-filling layouts using roll-up navigation, for example, to reach deeper levels of a hierarchy in a treemap [BHA*23] (see Fig. 12a) or a document browser [MDB04].

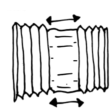


Scrunching is the compression of an element into a new shape, similar to the crushing of a piece of paper, fabric, yarn, or a sponge. Transferred to the interaction with data representations, the scrunched form, besides being more space-efficient, can reveal insights by encoding information in new arrangements with new spatial proximities between elements. Consequently, flattening a scrunched system can also provide new insights by revealing previously hidden structures. Due to its potential to completely change the overall shape of a visualization, we ascribe to scrunching not only geometric compression transformations, but also semantic transformation capabilities, making it a diverse family of mechanisms. For example, *Time Curves* [BSH*16] (see Fig. 6a) scrunch the yarn of time to create a similarity-based layout of data points. In *#FluxFlow* [ZCW*14], a temporal arrangement of nodes can be partially scrunched into an aggregated area chart still featuring some individual nodes, using a slider to control the level of aggregation. In *Reading Traces* [BBBD20] (see Fig. 9b), the annotations across a library of 100 books are globally transformed into area charts summarizing these along their authors. Similarly, the transformation of a subgraph into an adjacency matrix in *NodeTrix* is a kind of scrunching of individual elements into a new shape [HFM07] (see Fig. 7b).

Sliding summarizes a set of techniques revealing information by visually sliding out details on demand, akin to a scroll. A key characteristic of these techniques is that the focused base element, from which the slide-out occurs, remains intact in its original position, while new elements emerge from below or within through a sliding motion. Surrounding context elements are often displaced to accommodate the slide-out, without undergoing any distortions. Because new content slides out while context moves away, many techniques in this family use semantic focus and geometric context transformations. Examples of sliding are the *Provenance Widgets* [NOEAE25] (see Fig. 6i), UI controls that can slide out visualized provenance of the interaction with the widget, and *CNN Explainer* [WTS*21] (see Fig. 6h), a tool that uses sliding to show detailed simulation visualizations explaining convolutional neural networks.



Stacking is the structured organization of elements into groups layered on top of each other, with visual cues indicating the amount of stacked elements, as known from a set of stacked cards. In two-dimensional representations, stacking is mostly used for space-efficient grouping of elements [NWA10, BHRD*15, RM13, LZC*21]. In three-dimensional representations, multiple perspectives on the stacks can be used to visualize different aspects of the data [WSL*20, TSAA12] (see Fig. 7c and Fig. 8c), for example, by providing a bird's-eye or frontal view of a stack. While stacking itself uses geometric, mostly position-based transformations, a stack often uses semantic transformations to create a summarizing cover image [BHRD*15].



Stretching is inspired by elastic surfaces and compressible folded structures, similar to accordions. Stretching can transform subsets of data on a local or global scale, not necessarily defining sharp focus and context areas, but often involving intermediate transition

User study type	Number	Percentage
Quantitative	26	25.7%
Qualitative	52	51.5%
None	36	35.6%

Table 1: *Overview of user studies involving un/foldables.*

areas. Common manifestations are accordion [SHM05] or fisheye [SB92] techniques. Stretching itself is a physical mechanism that enlarges areas of choice while compressing other parts, in addition to the geometric expansion. Techniques such as *Multistream* [CSWP18] (see Fig. 8b) also employ semantic transformations by representing additional data facets or hierarchies in the stretched area. This can be seen in the *3D Flexible and Tangible Magic Lens* [LGB07] (see Fig. 13b), an AR application that uses stretching to reveal components of an observed volume. Physicalization techniques such as *KiriPhys* [DPC23] (see Fig. 8a) also use physical stretching to reveal insights through the composition and visual changes of the stretched material. Stretching often uses gradual function-based compressions that adjust to the distance to the focal area [Kin10]. Other techniques compress all context uniformly, based on the amount of space a stretched focus area requires [BBBD20, HBS*21].

6. Empirical User Studies

This section briefly summarizes the empirical user studies related to the un/folding techniques presented in this survey. In addition to user studies, evaluations of un/foldables can also include computational performance benchmarks, especially in the context of algorithm-driven techniques operating on large datasets [LZC*21, SHM05] and volume or flow rendering techniques [TEC*16, BV09]. However, we focus on user-centric evaluations.

As mentioned earlier, un/foldables are not always the main contribution of a research paper, but are often developed and described in the broader context of a design study. Therefore, quantitative user studies assessing the effectiveness of un/foldables and their perceptual advantages/disadvantages, and comparative studies with alternative techniques are not as common. Table 1 shows a statistical overview of the studies reported in our literature corpus, including non-academic examples. More than 50% of the works involve some kind of qualitative user study. For quantitative studies, the percentage is about 25%. Tools and techniques that are not evaluated through user studies often use alternative validation methods, such as detailed usage scenarios [BSH*16, KKEE11, CSWP18]. Additionally, publication types such as pictorials, short papers, or non-academic examples typically do not aim for user-based evaluation in the first place, commonly focusing more on aspects of novelty of design and interaction or application of existing knowledge.

In their survey, Cockburn et al. [CKB09] reviewed studies for focus+context techniques compared to overview+detail, and zoom. In the focus+context realm, approaches that rely on geometric distortions (such as fisheye views) were found to have drawbacks in perceptual tasks and target acquisition. Furthermore, zoom-based methods can introduce greater cognitive demands due to the temporal separation between zoom states. However, it was also observed that approaches such as pan & zoom or animated transitions can alleviate this added cognitive load.

Franconeri et al. [FPS*21] recently summarized the empirical evidence for the effectiveness of animated transitions. While cautioning that the evidence for improved comprehension remains inconclusive and advising judicious use of animation, they note that transitions are frequently cited for enhancing user engagement. This argument can be supported by several user studies within our corpus of un/foldable visualizations.

For instance, in a quantitative usability questionnaire and think-aloud study involving 16 participants, Wang et al. [WTS*21] found that the fluidity, elasticity, and transitions in their CNN explainer received positive ratings. Participants indicated that the animated transitions aided in understanding the presented algorithms, navigating the interface, and creating enjoyable, engaging experiences. In *#FluxFlow* [ZCW*14], domain experts similarly emphasized the positive impact of the interactive un/folding of the aggregation feature, describing it as *"aesthetically pleasing and that the interactions and animations were smooth"*. Likewise, in the data physicalization system *KiriPhys* [DPC23], the physical stretching interaction was reported to make the experience more memorable, engaging, and delightful compared to other techniques. For their program visualization application *CrossCode*, Hayatpur et al. [HWX23] found that controlling the fluid exploration, animations, and code aggregations into blocks aided code comprehension. However, some participants encountered challenges when navigating different levels of abstraction. For *DimSum* [MDLI*18], a domain expert stated that having continuous control of transitions between abstractions supported her overall understanding of the DNA origami process and might streamline her work.

Several applications reported that animated transitions between visualization states enhance engagement or aesthetic appeal [ZCW*14, TFJ12, BDT23] and can partially facilitate understanding of data, algorithms, or view changes [WSL*20, YGX*09, BBBD20, TEC*16, MTB03, HMK*20]. Nonetheless, some user studies described un/folding experiences as distracting, gimmicky, or confusing [BBBD20, FUB*24, LSL*17, BDT23].

Overall, the available empirical results suggest that un/folding techniques clearly hold potential for enhancing user engagement, particularly through fluid interactions and animated transitions. While some studies highlight the benefits of such techniques for understanding data and navigating interfaces, others note challenges like distraction or confusion in certain contexts.

7. Research Opportunities

In the following, we outline research opportunities and future directions for un/foldable visualizations based on the insights gathered during the preparation of this report.

Un/folding transitions. Some un/foldables are explicitly designed with the goal of supporting comprehension of data operations and encoding changes through animated transitions [YGX*09, MDLI*18, BBBD20]. As highlighted in Sect. 6, many researchers have reported promising findings from their initial user studies. Beyond the specific research thread on un/foldable visualizations, other work has also explored animated transitions to aid comprehension. For example, evidence suggests that controllable transitions can enhance perception [FPS*21]. Additional initiatives aimed at improving transitions include staggering transitions [CDF14], facilitating the comprehension of aggregate operations [KCH19], visualizing large-scale data streams [PMMG20], and transitioning between different statistical charts [HR07]. Visualization research and design often treat visual encoding, interactivity, and animations as separate components, creating a challenge to view these elements as intertwined aspects of visualization [BBD20]. Consequently, research on animated transitions offers numerous opportunities, extending beyond the exploration of novel transition designs to include their evaluation and the accumulation of empirical evidence on their effectiveness.

Foreshadowing. Managing user expectations is pivotal to conveying the capabilities of an interface and in guiding interaction decisions [Nor13]. When users' assumptions about interactivity differ from how interactive elements actually behave, frustration may arise. Consequently, un/foldables should explicitly signal their interactivity and foreshadow or preview the information they will reveal. This also relates to visualization research on information foraging and cues in focus+context techniques [PCVDW01] and suggested interactivity [BEDF16]. Many instances of un/foldable visualizations already use visible cues to foreshadow content. While some visualizations rely on simple encoding strategies, such as varying size [Ros06] or thickness [BDT23], to imply the amount of un/foldable information, more elaborate examples are hierarchical techniques, such as *DendroMap* [BHA*23], which foreshadow preview images of lower hierarchies. There are also techniques that use specifically designed abstraction methods to foreshadow visual summaries of the folded content, for example, *AVOCADO* [SLSG16], *MotionFlow* [JER16], or *Small MultiPiles* [BHRD*15]. However, further research is needed to systematically evaluate the effectiveness of different preview strategies across diverse data types and user contexts, as well as to explore how best to tailor them for improved comprehension and user experience.

Multi-focus un/folding. Many un/foldable visualizations in our corpus make use of global zoom-based abstraction changes or focus+context transformations of individual elements. Likewise, nesting techniques often limit users to examining only one subset of the data at a time. Although selective un/folding is typically possible, focusing on multiple elements simultaneously is often not supported. As a result, many un/foldables, unless specifically designed otherwise, are ill-suited for multi-comparison tasks, since users must frequently toggle focus or zoom between different elements. Future research could specifically investigate generalizable strategies for multi-focus un/foldables, as for instance seen in *Balloon Focus* [TS08]. Semantic zoom, for instance, could be handled more locally, demonstrated by local zoom-related techniques such as *Word Bridge* [KKEE11].

Responsiveness. Not only can un/folding of information on demand be useful for user-driven exploration, but we also see potential use cases for the development of responsive interfaces. Small-screen devices like smartphones, in contrast to conventional desktop displays or large high-resolution screens, require a particular focus on responsive and scalable encoding and interaction techniques [HAB*21]. Drawing inspiration from space-efficient mechanisms in nature and engineering, un/folding could inform concepts that dynamically adjust levels of abstraction to accommodate diverse display sizes across multiple device types.

Physicalization, XR & multi-modality. The adoption of physical interaction mechanisms in digital visualization also opens avenues for novel interaction concepts in data physicalizations and extended reality (XR). Especially interaction concepts for physicalizations for tasks such as zooming, focusing, or abstracting are still not explored well. Techniques such as *KiriPhys* [DPC23], *VISMOCK* [BPS24], *Deformable Cloth Displays* [BDR17], or the *3D Flexible and Tangible Magic Lens In AR* [LGB07] demonstrate the potential of stretching and folding for semantically transforming data representations. In line with these efforts, we see additional potential to adapt un/folding visualization mechanisms from the digital realm back into physical or XR interaction concepts. The principles of un/folding can also extend beyond the visual domain to encompass multi-modal interactions, for example, by unfolding sound. *Tied in Knots* [EBHC22] is an example that combines visual exploration with audio narrations. Considering the potential of such approaches for both immersion and accessibility could yield promising data exploration experiences.

Generalization & reuse. Key characteristics for un/foldable visualizations are the use of animated transitions between view changes and the seamless integration of un/folded information into a base visualization. Achieving both can be complex to design and implement in a meaningful way. While many examples of un/foldable visualizations, such as sunburst charts, interactive tree maps, or dendograms, already have become widely used techniques, many un/foldables are handcrafted individual design solutions that are difficult to replicate. However, approaches such as *PilingJS* [LZC*21], *ProvenanceWidgets* [NOEAE25], and *ReFa Reader* [dGNK*23], are exemplary implementations that are specifically designed and distributed with the goal of facilitating reuse and adaptation. We posit that more researchers should follow these initiatives and design techniques that are generalizable enough to be used and adapted to other settings.

Un/foldables evaluation. This report offers only a brief overview of the general insights gathered so far on evaluating un/folding visualizations. However, these insights often cannot be generalized due to the task-specific nature of many applications and the often non-isolated evaluation of un/folding (e.g., in broader design studies). In the future, a more detailed analysis of evaluation results based on task and application type is needed to provide a more conclusive overview. So far, engaging qualities have been reported for several un/foldables. However, these are often based on reactions of first-time users. More comparative studies, evaluation approaches to qualify engagement, and also long-term studies could paint a clearer picture of advantages and disadvantages of un/folding visualizations.

8. Discussion

Below we discuss some limitations of this survey, reflect on the process, and conclude with an outlook.

Survey scope. The selection process (see Sect. 3) for compiling our literature corpus does not aim for completeness. Consequently, there are examples of un/foldables in the visualization literature that are not included in our corpus. Acknowledging this, we refrain from providing detailed quantitative analyses of technique type or class occurrences. Furthermore, like most classification systems, our classification includes gray areas and borderline cases.

Borderline cases. While the characteristics C1-C4 from Sect. 2.2 guided our selection of un/foldables, certain borderline cases exist that are worth mentioning briefly. Many geometric distortion-related focus+context techniques, such as *Perspective Wall* [MRC91], *DocumentLens* [RM93], or *iSphere* [DCL*17], are not part of our survey. With un/foldables, one of our intentions was to observe the use of fluid abstraction changes to reveal or reduce information. Yet, the techniques just mentioned are mostly working with geometric distortion of visualized information that is already there. While we also include some examples making use of geometric transformations for focus and context (e.g., *Balloon Focus* [TS08]), for the scope of this survey, we decided to exclude especially those working with classical fisheye distortions.

Interactive lenses also fall into the borderline category, with some techniques included in our selection and others left out. Interactive lenses often overlay information rather than embedding it, which introduces a semantic separation from the base visualization [TGK*17]. Consequently, traditional lens techniques are not considered in this survey, though more integrated lens-like approaches such as *SignalLens* [Kin10] or *TableLens* [RC94] are included. These techniques adapt aspects of the base visualization without assuming a visually or semantically separate appearance.

Interesting edge cases also include the classification of data physicalizations [DPC23, BPS24] and hybrid-image visualizations [IDW*13]. Data physicalizations often make use of physical deformations that, while purely geometric, can resemble semantic transformations by altering the physical structure of elements. However, as these manipulations are technically geometric (e.g., stretching, unfolding), we classified them as such. Hybrid-image visualizations, in contrast, rely on users changing their viewing distance rather than actual graphical transformations. Although there are absolutely no pixel changes, we treated this hybrid-image visualizations as semantic because the perceived effect goes beyond purely geometric transformations.

Use of metaphors. There is a history of visualization approaches making use of metaphors or drawing inspirations from the physical world, including *direct manipulation* [Shn83] or the *Perspective Wall* [MRC91]. Even in the early decades of interactive visualization, the potential disadvantages of such metaphorical approaches were noted, as they might limit the imagination of both designers and users regarding the behavior of existing and future interfaces [BH94]. Still, metaphors can be very helpful. From the physical un/folding and the related examples described in Sect. 2.1, to building sandcastles as knowledge generation practice [HFM18], to urban flaneurs for serendipitous exploration [DCW11], many researchers invoke metaphors to describe research methods, to provide depth and comprehensibility to their approaches, or as an inspiration for the design of visualization techniques.

That said, we do not claim that literal imitations of physical concepts like un/folding are per se advantageous for visualization. Instead, we see the unique potential in the metaphor of un/folding not as a way to mimic the physical world, but as a source of inspiration and an intuitive concept to describe interaction techniques across domains and use cases.

Documenting interactivity. In the process of developing this state-of-the-art report, we accessed many video demos and prototypes in order to understand the main principles of the existing works, their interactive capabilities, and animated transitions. Eventually, we started creating video snippets and ultimately animated GIFs of relevant parts of a demo/prototype showcasing its un/foldables. First we did this to facilitate discussion among authors and to make techniques more easily comparable. Later on we realized the value of this collection also for general understanding of interactions in visualization practices. Despite the importance of interaction and animation, researching demo and prototype material still proves to be laborious. Oftentimes, even today, many research papers do not include video material showcasing interactions and the dynamic view changes they entail. We believe that interaction techniques can only be adequately captured visually in an animated or interactive form. Therefore, our online catalog of un/foldable visualizations contains animated thumbnails. With this, we hope to inspire other researchers and designers to go beyond static images and descriptive text, and shift more focus to the dynamic aspects of interactions with visual (data) interfaces.

9. Summary

Un/foldables fluidly reveal or reduce information on demand, leveraging cohesive and engaging qualities of animated transitions [EMJ*11]. Guided by the metaphor of un/folding, we collected and classified 101 examples of un/foldable visualizations, which are also available in an online catalog. The goal of this survey was to deepen the understanding of un/folding as a unique mechanism for fluid interactive data visualization. Designing such fluid techniques with integrated abstraction changes can be challenging, as it requires the conceptualization of multiple data states and their transitions along with appropriate interaction patterns. Throughout this survey, we encountered a broad diversity of un/folding mechanisms across an extensive spectrum of visualization techniques, identifying shared characteristics that can both inspire and guide future visualization research and design. We hope this survey can help foster continued innovation in un/foldable data visualizations, prompting novel ways to fluidly reveal information.

Acknowledgements

We thank the creators of the referenced works for allowing figure reuse. Parts of this work were funded by the German Research Foundation (DFG) through grants [514630063] and [510079995]. Open access funding enabled and organized by Projekt DEAL.

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Fig. 1: Composition created by the authors, licensed under CC BY. Images are numbered left to right, top to bottom: **1)** Reading Traces [BBBD20]; **2)** XAI Primer [GEHEA22]; **3)** The Trajectory Wall [TSAA12]; **4)** Smart surrogate widgets [SB18]; **5)** VISMOCK [BPS24]; **6)** Fluid Views [DCW12]; **7)** Responsive Matrix Cells [HBS*21]; **8)** Multistream [CSWP18]; **9)** Tied in Knots [EBC*20]; **10)** Fluid Interactions for Star Plots [LKE*15]; **11)** Soccer Stories [PVF13]; **12)** PelVis [SLK*17]. All source images are published under CC BY, with permission. Reuse of this composition must include attribution to the original works.

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Fig. 4: Created by the authors. Licensed under CC BY. The screenshot contains image material from AVOCADO [SLSG16], Dendromap [BHA*23], DNBVis [HBD*18], Polycube [WSL*20], The Trajectory Wall [TSAA12], Multistream [CSWP18], Responsive Matrix Cells [HBS*21], and Fluid Views [DCW12]. All embedded images are published under CC BY, either through the original license or with permission from the authors.

Fig. 6: **a)** Time Curves [BSH*16], published with permission under CC BY; **b)** InformationSense [BDR17], published with permission. © 2017 Butscher et al.; contains map content © Google Maps. Excluded from CC BY. **c)** Responsive Matrix Cells [HBS*21], published with permission under CC BY; **d)** XAI Primer [GEHEA22], published with permission under CC BY; **e)** On Broadway [GSBM14], published with permission. © 2014 Goddemeyer et al. All rights reserved. Excluded from CC BY; **f)** Tied in Knots [EBC*20], published with permission under CC BY; **g)** Smart Surrogate Widgets [SB18], published with permission under CC BY; **h)** CNN Explainer [WTS*21]. Screenshot from a YouTube video by Jay Wang (youtu.be/HnWIHWFbuUQ), published under CC BY. **i)** Provenance Widgets [NOEAE25], published with permission under CC BY.

Fig. 7: **a)** Collapsible Tidy Tree. Screenshot by authors, adapted from [Bos24]. Source code under ISC License observablehq.com/@d3/collapsible-tree; image licensed under CC BY. **b)** NodeTrix [HFM07], screenshot taken from an implementation by Nicolas Heulot, licensed under BSD-3-Clause github.com/IRT-SystemX/nodetrix; published here with permission under CC BY. **c)** Polycube [WSL*20], published with permission under CC BY.

Fig. 8: **a)** KiriPhys [DPC23], published with permission. © 2023 Daneshzand et al. All rights reserved. Excluded from CC BY; **b)** Multistream [CSWP18], published with permission under CC BY; **c)** The Trajectory Wall [TSAA12], published with permission under CC BY.

Fig. 9: **a)** Unfolding Edges [BDT23], published with permission under CC BY; **b)** Reading Traces [BBBD20], published with permission under CC BY; **c)** PelVis [SLK*17], published with permission under CC BY.

Fig. 10: **a)** Soccer Stories [PVF13], published with permission under CC BY; **b)** Fluid Interactions for Star Plots [LKE*15], additional photo of the work by Langner et al. licensed under CC BY; **c)** AVOCADO [SLSG16], licensed under CC BY.

Fig. 11: VISMOCK [BPS24], published under CC BY with permission.

Fig. 12: **a)** Dendromap [BHA*23], based on a prototype licensed under the MIT License github.com/div-lab/dendromap, published with permission under CC BY; **b)** Folding comparison [TFJ12], published with permission under CC BY.

Fig. 13: **a)** DimSUM, reprinted from [MDLI*18] with permission from John Wiley and Sons. © 2018 Miao et al., The Eurographics Association, and John Wiley & Sons Ltd. Published in Computer Graphics Forum. All rights reserved. Excluded from CC BY. **b)** AR Magic Lenses [LGB07], published with permission. © 2007 Looser et al. All rights reserved. Excluded from CC BY.

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	Time	Geo-space	Relationships	Multivar. attr.	Images & video	Text & docs	Volumes & flow	Algorithms	Other	Element	Subset	Global	Element	Local	Global	Binary	Discrete	Continuous	Geometric	Semantic	Geometric	Semantic	None	N/A	Controlled	Triggered	Direct	Indirect
	Data Facets									Scope Focus			Scope Effect			Unfolding Scale			Transformation Focus		Transformation Context				Trans. Contrl.		Interaction	
Assembling																												
AVOCADO [SLSG16]			R	M					O	E		G			G		D			S	G				C	T	D	I
Unfolding Edges [BDT23]	T	G	R	M		D			O	E					G	B				S	G					T	D	
XAI Primer [GEHEA22]			R	M								G			G			C		S				×		T	D	
Fanning																												
Fluid Star Plots [LKE*15]	T			M						E				L				C		S	G				C	T	D	
TextPioneer [LCW*15]	T		R			D					S				G	B				S		S				T	D	
TreeNetViz [GZ11]			R							E		G			G		D			S	G			×		T	D	I
Folding																												
Folding Comparison [TFJ12]	T	G	R	M		D					S			L				C		S			N		C		D	
InformationSense [BDR17]		G										G			G			C	G					×	C		D	
Melange [EHRF08]		G	R	M	I						S			L				C	G		G				C		D	
Hinging																												
GlyphLens [TLS17]							V				S			L				C	G				N		C		D	
PelVis [SLK*17]							V				S				G			C	G				N		C			I
Surrogate Widgets [SB18]							V				S			L				C		S			N		C		D	
Inflating																												
Balloon Focus [TS08]			R	M							S				G			C	G		G				C			I
DNN Genealogy [WYC*20]			R					A			S				G	B				S		S				T	D	
Glyphboard [KKG*20]				M								G			G			C		S				×		T	D	
Nesting																												
DateLens [BCCR04]	T									E					G		D			S		S				T	D	
DendroMap [BHA*23]			R		I					E					G		D			S	G					T	D	
Expand-Ahead [MDB04]			R							E							D			S	G				C	T	D	I
Scrunching																												
#FluxFlow [ZCW*14]	T		R	M		D					S			L				C		S			N			T		I
NodeTrix [HFM07]			R								S			L		B				S			N			T	D	
Tied in Knots [EBHC22]						D				E			E			B				S			N			T	D	
Sliding																												
BarodeTree [LZD*20]			R							E					G	B				S	G					T	D	
CNN Explainer [WTS*21]				M	I			A		E					G		D			S		S				T	D	
Prov. Widgets [NOEAE25]				M					O	E				L		B				S			N			T	D	
Stacking																												
Polycube [WSL*20]	T	G	R	M								G			G	B				S				×		T		I
Small MultiPiles [BHRD*15]	T		R								S				G		D			S	G					T	D	
Trajectory Wall [TSAA12]	T	G		M								G			G	B				S				×	C		D	
Stretching																												
3D Flexible Lens [LGB07]							V				S			L				C		S			N		C		D	
KiriPhys [DPC23]				M					O	E			E			B			G				N		C		D	
Multistream [CSWP18]	T		R								S			L				C		S			N		C		D	I

Table 2: *A sample of 30 of 101 reviewed un/foldable visualizations.*