USER INTERFACES AND DIFFERENCE VISUALIZATIONS FOR ALTERNATIVES

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ABSTRACT

Designers often create multiple iterations to evaluate alternatives. Today's computer-based tools do not support such easy exploration of a design space, despite the fact that such support has been advocated. The contributions of this dissertation are centered on this.

I begin by investigating the effectiveness of various forms of difference visualizations and support for merging changes within a system targeted at diagrams with node and edge attributes. I evaluated the benefits of the introduced difference visualization techniques in two user studies. I found that the basic side-by-side juxtaposition visualization was not effective and also not well received. For comparing diagrams with matching node positions, participants preferred the side-by-side option with a difference layer. For diagrams with non-matching positions animation was beneficial, but the combination with a difference layer was preferred. Thus, the difference layer technique was useful and a good complement to animation.

I continue by investigating if explicit support for design alternatives better supports exploration and creativity in a *generative design* system. Generative design—a design method in which the output is generated by a set of rules or an algorithm—builds on computer-aided design systems that provide tools to vary designs beyond direct manipulation of specific design elements. To investigate the new techniques to better support exploration, I built a new system that supports parallel exploration of alternative designs and generation of new structural combinations. I investigate the usefulness of my prototype in two user studies and interviews. The results and feedback suggest and confirm that supporting design alternatives explicitly enables designers to work more creatively.

Generative models are often represented as DAGs (directed acyclic graphs) in a dataflow programming environment. Existing approaches to compare such DAGs do not generalize to multiple alternatives. Informed by and building on the first part of my dissertation, I introduce a novel user interface that enables visual differencing and editing alternative graphs—specifically *more than two* alternatives simultaneously, something that has not been presented before. I also explore multi-monitor support to demonstrate that the difference visualization technique scales well to up to 18 alternatives. The novel *jamming space* feature makes organizing alternatives on a 2×3 monitor system easier. To investigate the usability of the new difference visualization method I conducted an exploratory interview with three expert designers. The received comments confirmed that it meets their design goals.

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DISSEMINATION OF THIS DISSERTATION

The following chapters of this dissertation have been previously published as peer-reviewed papers:

Chapter 3:	Zaman, L., Kalra, A., and Stuerzlinger, W. 2011. The effect of animation, dual view, difference layers, and relative re-layout in hierarchical diagram differencing. *In Proceedings of Graphics Interface 2011 (GI '11).* Canadian Human-Computer Communications Society, School of Computer Science, University of Waterloo, Waterloo, Ontario, Canada, 183-190.
Chapter 4:	Zaman, L., Stuerzlinger W., Woodbury R., Neugebauer C., Elkhaldi M., Shireen N., Terry M., 2015. GEM-NI: A system for creating and managing alternatives in generative design, *In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems – CHI '15*, pages 1201–1210, ACM, New York, NY, USA.

The following chapter is currently in preparation:

Chapter 5:	Zaman, L., Stuerzlinger W., Neugebauer C., (in preparation), MACE: A New Interface for Comparing and Editing of Multiple Alternatives.

Additionally, the following extended abstract is based on this work:

Zaman, L., Kalra, A., and Stuerzlinger, W. 2011. DARLS: differencing and merging diagrams using dual view, animation, re-layout, layers and a storyboard. *CHI '11 Extended Abstracts on Human Factors in Computing Systems* (CHI EA '11). ACM, New York, NY, USA, 1657-1662.

Two more journal articles that are currently in preparation:

Zaman, L., Stuerzlinger W., Woodbury R., Neugebauer C., Elkhaldi M., Shireen N., Terry M., Peters B., (in preparation), Evaluation of GEM-NI: A system for creating and managing alternatives in generative design.

Woodbury R., Elkhaldi M., Erhan H., Guenther J., Kolaric S., Sanchez R., Shaw C., Shireen N., Stuerzlinger W., Zaman L., (in preparation), Interacting with Alternatives: Survey and Synthesis.

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Chapter 1
Introduction

Looking at multiple documents or objects for making a comparison is a common human activity, used in many areas, typically to decide among different alternatives. Humans relied on visual comparison, what they are able to observe directly, prior to the invention of computers. Thus, it was only a matter of time before computers would be used for this purpose. The first computer-based tools were targeted at text differencing. As technology advanced, comparison of graphical data, such as graphical hierarchies and vector graphics, became possible. One application area where comparing and managing multiple graphical instances is particularly important is design, as this discipline involves creating various alternative solutions to a given problem and then evaluating them against the design goals [100]. In my context I refer to *difference visualization* as a visual display of two or more artefacts (or their subsets) using techniques to support and facilitate the comparison of these artefacts to each other. Here I present new methods for difference visualization, but also look at their usage in design. Moreover, I also present a new system that makes it easier for users to generate and manage multiple alternatives in generative design.

The first robust differencing tool was the Unix *diff* tool [58]. Modern tools for text differencing are much more user-friendly, incorporate visual interfaces and side-by-side views, and enable history tracking and merging. One example of such interfaces is the use of highlighting. Another, more recent feature, is the use of animation [25]. Also, there are many publicly available tools, such as GNU *Emacs*[1], *Kompare*[2], *WinMerge*[3], Araxis *Merge*[4], and Scooter Software *Beyond Compare*[5]. Some of these are not only capable of comparing plain

[1] http://www.gnu.org/software/emacs/

[2] http://www.caffeinated.me.uk/kompare/

[3] http://winmerge.org/

[4] http://www.araxis.com/

[5] http://scootersoftware.com/

text, but can also deal with XML documents, file directory structures, and even binary files. Since then, approaches for difference visualizations of graphical hierarchies and other forms of graphics have also been developed, see the previous work section (Chapter 2). One important application area for difference visualizations is all kinds of processes where multiple alternatives are routinely considered, such as many forms of decision-making and design.

The development of a design is conceptually a process where many threads of possibilities are developed in parallel. These concepts are then abandoned or re-combined until a satisfactory scheme emerges out of the exercise. Often, this exploration is directed by the outcomes of previous explorations [75]—a key characteristic of emergence [65] and of the personal history of the designer [93]. Thus, the search for *alternatives* and the exploration of the design space have very important roles in the design process. Indeed, experts typically generate sets of alternative solutions when solving ill-defined problems [100]. This has been shown to result in higher quality outcomes [30]. For example, it is common practice for web designers [78], architects [1,75] and software engineers [103] to generate alternatives of potential designs as they solve problems.

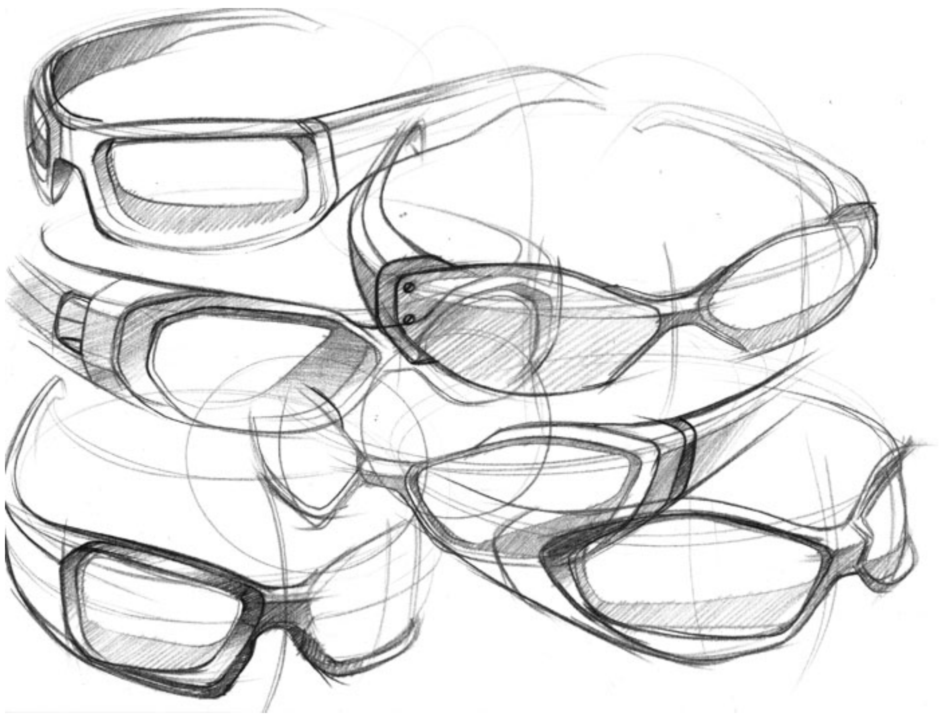


Figure 1-1. An example of a sketch provided by http://www.idsketching.com.

Traditionally, sketching [2] is used in many disciplines to explore alternatives during the design process (e.g., Figure 1-1). Buxton [21] (p. 111) describes eleven qualities that define sketches. They should:

- be quick to make,
- be cheap to make,
- be disposable,
- be plentiful,
- be distinguishable from other types of renderings,
- be open and free rather than tight and precise,
- be minimal,
- provide appropriate degree of refinement,
- suggest and explore rather than confirm,
- be ambiguous,
- be provided when needed.

Figure 1-2 shows conjectural sketches created using an existing CAD tool. Sketches help designers externalize knowledge, better understand the problem, and explore the space of potential solutions [2]. Sketching also facilitates what is now known as *visual reasoning* [84]. The existence of high level cognitive structures such as schemas and prototypes that help designers think visually has been experimentally verified [84].

Computer-based conceptual design systems often do not support these qualities adequately, which has been shown experimentally, e.g., in the domain of Computer-Aided Design (CAD) [61]. The main obstacles for such support have been identified by Krish [65] as follows:

- The invasiveness of frameworks impedes the thinking effort making it difficult to automate conceptual design.
- CAD in its current form is unsuitable for representing and considering vague concepts and forms.
- CAD does not provide the creative stimulation that designers derive from the process such as hand sketching. Essentially the tools ignore that designs are developed based on reactions to previously generated concepts.
- Design is an iterative process of searching the design problem space as well as the solution space. Designs and solutions co-evolve, during the design process. This is not supported.
- Many possibilities are considered and most of them are discarded at the early stages of design. In this context, designers need to represent a wide range of concepts efficiently. They are, therefore, reluctant to invest the additional effort required to represent such concepts in CAD.

Despite these challenges, such conceptual design systems have nonetheless been widely advocated for. For example, Shneiderman [99] summarized design principles for creativity support tools: support for exploratory search, enabling collaboration, rich history-keeping and support of “design with low thresholds, high ceilings, and wide walls”. Shneiderman further emphasized the importance of exploring design solutions (what-if tools) and “reviewing and replaying session histories” as activities for creativity that should be adequately supported by computational tools. Besides emergence, Krish [65] also identifies support for chaotic and unstructured work processes as a requirement that needs to be met for CAD to support conceptual design. Besides, studies have shown that parallel prototyping produces better design [30,31]. Despite many methods proposed by researchers for the use of CAD in early stage conceptual design [57,110], CAD is still mostly used in the final stages of design, though this is changing [113]. Due to this fact, an entire dimension of how designers actually work is largely missing from such tools, thus narrowing their scope of effective usage. It is possible to address one important aspect of conceptual design, namely, the parallel exploration of alternatives, in current CAD systems. However, this is not well supported in current tools. Typically, designers get around this limitation by various idioms of use, such as saving multiple files one for each different variations or exploring multiple ideas within the same document through conditional execution. Yet, designers already plan for and create alternatives with current tools, as this dissertation will demonstrate (Chapter 4). In fact, *CAMBRIA* [64] is at the moment the only system that provides full explicit support for alternatives. Parallel exploration of alternatives is somewhat related to sketches with pencil and paper. However, the alternative documents explored in the systems such as *CAMBRIA* do not qualify as true sketches as characterized above as they lack some key qualities, namely they are neither open, nor minimal, nor ambiguous. Similarly, the alternatives that are explored in this work are not true sketches, either.

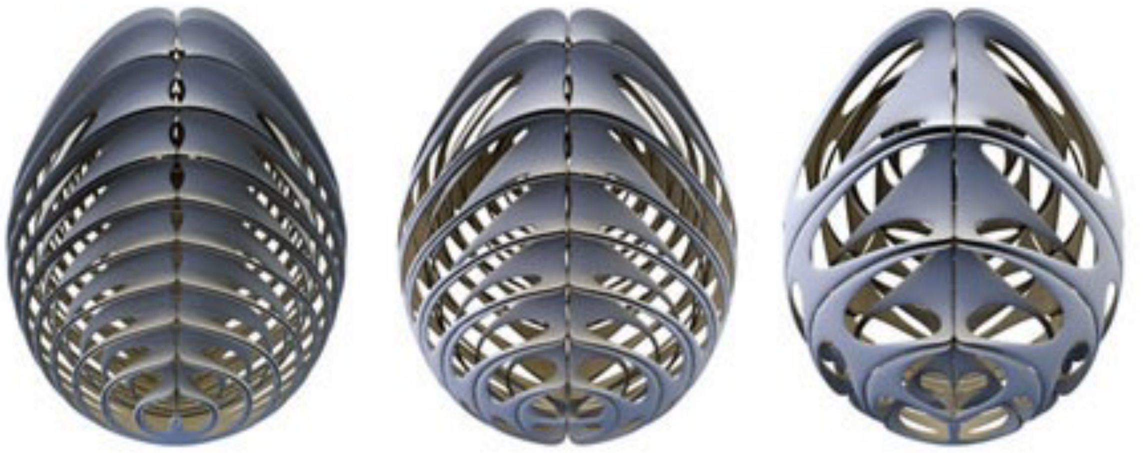


Figure 1-2. Conjectural sketches created using an existing CAD tool, http://rocker-lange.com.

In my work, I target CAD tools in the category of *generative design* as such tools include features that make the exploration of a design space easier. Generative design is a design method in which the output is generated by a set of rules or an algorithm. According to Krish [65] the generative process involves the following:

- a design schema, i.e., a model,
- a means of creating variations,
- a means of selecting desirable outcomes.

Generative design enables designers to create design variations based on a model. This model can vary just in parameters, be expressed as a network of computational nodes and/or constraints, or even full algorithms as in e.g., the earliest versions of *NodeBox*[6] or the *Processing* programming language[7]. Because the system generates the solution from a model, the design process based on generative models is often referred to as generative design. By structuring design concepts as models, it is possible to explore a much larger

[6] http://www.emrg.be/software/nodebox-1.html

[7] http://processing.org

number of viable design options compared to what is manually possible. Generative modeling is a rapid method for exploring many design possibilities and is used in various design fields such as art, architecture, and product design. Adoption is widespread in avant-garde practice and design schools and there are established textbooks and professional development courses.

Generative design qualitatively changes the design process. The inherent capabilities of such systems also create new opportunities for design support tools. With generative design, it is possible to easily create a very large set of viable design options that satisfy a given set of constraints, as defined in the model. These options, the number of which is much larger compared to what is manually possible, represent points in a high-dimensional design space that must then be explored, narrowed, and filtered. The central role of the designer involves continuously modifying the generative model based on the resultant outcomes. Through this the designer navigates the solutions space in search of viable design solutions. A very simple approach is to just have the user repeatedly select attractive solutions to zero in on desirable options [73]. Better approaches give more control to the user. One of the key challenges in generative design is to facilitate the use of alternatives.

In generative modeling, exploration of forms takes place within design spaces [113]. There, alternatives are defined as "structurally different solutions to a design", while variations are "design solutions with identical model structure, but having different values assigned to parameters". To compensate for the lack of adequate software features to support an easier, more efficient exploration of the design space, current designers rely on strategies, referred to as idioms of use [113]. Some common idioms for creating, comparing and managing design alternatives are opening file versions in different windows, copying within the same file, or using layers [107]. However, current computational design tools still do not support managing, viewing, exploring or comparing alternative solutions in an adequate manner. Moreover, these adaptations of the traditional workflow sometimes create more problems than they solve, e.g., when the file naming and window management overhead becomes large. In my work here, I argue for the explicit use of alternatives, instead.

Generative models require a computer-aided design system that provides tools to vary designs beyond direct manipulation of specific design elements. Such systems can be understood as lying along a spectrum from direct manipulation to fully automatic design. Thus I consider variational modeling, where changing parameters is a tool on top of manual model construction, to be a minimal generative system leaving most control with the designer. Genetic algorithms form an opposite and delegate exploration to the computer, while permitting user selection only at intermediary generations [117]. Here, I focus on the direct manipulation end of the spectrum, enabling designers to interactively control design decisions and provide "power tools" to make, modify, track, evaluate and visualize their work and to explore a larger number of design options.

Due to the ease with which parameters can be varied, variational modeling, where solutions are represented as models, is a particularly compelling technology to assist in exploring a design space. A variational model represents the structure and hierarchy of a solution, the result of which is determined by relationships, constraints, and choices of parameter values at a given time. While building such models requires more effort, variational modeling systems make variations easier and are now used in various domains. A prominent example is architectural design, as in the construction of the International Terminal Waterloo in London, England [113], pp. 43-45.

Current systems represent generative models as DAGs as in, e.g., *CATIA*[8]*, Inventor*[9]*, ProENGINEER*[10], and *SpaceClaim*[11], or as networks of operations in a dataflow programming environment, as in, e.g., *Grasshopper 3D*[12] (Figure 1-3), *Max/MSP*[13],

[8] http://www.3ds.com/products-services/catia/

[9] http://www.autodesk.com/products/inventor/

[10] http://www.ptc.com/product/creo/proengineer

[11] http://www.spaceclaim.com/

[12] http://www.grasshopper3d.com

[13] http://cycling74.com/products/max/

Houdini[14], *GenerativeComponents*[15], *Dynamo*[16] and *NodeBox 3*[17]. Such network-based dataflow-programming systems are what my work focuses on.

How alternatives should be supported in generative design, how they affect creativity, how designers navigate through a large space of design options produced by generative design systems, and how they evaluate alternatives has not been investigated in detail. Moreover, to my knowledge there are currently no tools that allow users to explicitly compare these design options. No tools currently exist to compare dataflow networks, either. The work described here addresses these questions.

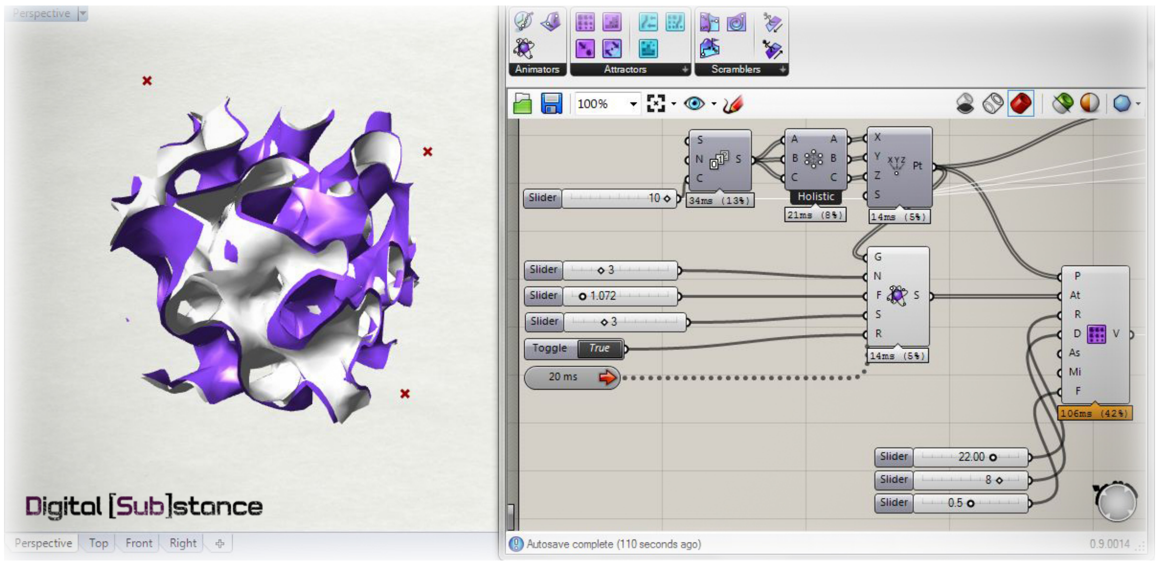


Figure 1-3. An example of a design created in *Grasshopper 3D* provided by http://digitalsubstance.wordpress.com.

1.1 Objectives

As discussed above design is an iterative process of searching the design problem space as well as the solution space where solutions co-evolve during the design process. In other

[14] http://www.sidefx.com

[15] http://www.bentley.com/

[16] http://dynamobim.com

[17] http://www.nodebox.net

words, it is also a parallel process where concepts are abandoned or re-combined until a satisfactory scheme emerges out of the exercise, where, often, this exploration is directed by the outcomes of the previous ones. All this indicates that design space exploration is an important part of the design process. The primary objective of this dissertation is thus to facilitate this part of the design process. I accomplish this by investigating if the introduction of various forms of exploration with design alternatives into generative design, results in better support of creativity. As discussed above, support for such functionality is missing in today's tools. One of the key challenges is to facilitate the fluidity of the design process where many threads of possibilities are developed in parallel. Another challenge is to keep a balance of features, user interactions, and workflows to enable designers to focus on exploring alternatives, as opposed to just managing them. To address this, I introduce these techniques in *GEM-NI* – a graph-based generative-design tool that I built. The system supports parallel exploration of alternative designs and is representative of a typical generative design system with a dataflow-programming environment. The new interaction techniques are parallel editing, recalling history, branching, merging, comparing, and Cartesian products of and for alternatives. Further, I introduce a modal graphical user interface and a design gallery, which both allow designers to control and manage their design exploration. Many of these introduced techniques are novel in the context of generative design and also in general. By introducing explicit support for parallel exploration of alternatives, *GEM-NI* comes one step closer towards to supporting conceptual design. Because of this, unsurprisingly, *GEM-NI* complies with all six key requirements that need to be met for CAD to support conceptual design as identified by Krish [65], namely:

- makes minimal demands on and minimal disruption to designer's work processes.
- is flexible in allowing the designers to navigate the design space in the way they see fit.
- is able to support chaotic and unstructured work processes.
- is structured as an assistive tool, giving the designer the choice to either use it or not use it.
- supports and enables emergence in order to stimulate the creativity of the designer.

- enables an efficient transition of design content to the detailed design phase.

GEM-NI also addresses identified problems with user interfaces that directly hinder creative needs in design exploration tasks [106]. Further, I investigate the usefulness of my approach in two user studies.

Managing, keeping track of and comparing multiple generative design solutions to each other becomes increasingly difficult as the number of them grows. Thus enhancing these processes is an important problem in generative design. I accomplish this by introducing *MACE*, – a new user interface for interactive comparisons of multiple alternatives in the context of generative design systems that use generative networks. The solution revolves around on the expectation that there is more similarity among the alternatives than there are differences. I confirm the validity of this assumption by performing a similarity analysis on the alternatives obtained from the participants of the second user study with *GEM-NI*.

The growing number of design alternatives makes it also difficult to fit them onto a single monitor, if all alternatives are still to be view- and editable. As a solution to this issue, I extend *GEM-NI* and *MACE* to support multiple monitors to help the designer keep the overview of all alternatives.

Part of my solutions for enhancing managing and comparing of design comparisons emerged through my earlier experiments with generic diagram differencing techniques. In those experiments my primary goal was to address the lack of previous quantitative research on diagram difference visualizations and on visualizations that support merging of diagram versions. For this, I built and evaluated a new system for differencing and merging diagrams that make use of Dual View, Animation, Re-Layout, Layers and a Storyboard, abbreviated as *DARLS*. The system is targeted at diagrams with node and edge attributes. Such diagrams are used frequently in architecture, information and concept visualization, software engineering, e.g., for UML diagrams, and in generative design as networks for dataflow programming. One can use the system to track the evolution of a course dependency diagram over the years, a particular course in a prerequisite visualization, or to visualize the evolution of any diagram in general. It also can be used to merge versions of a diagram and to perform selective undo.

1.2 Contributions

In the scope of this dissertation, I implemented two systems *DARLS*, *GEM-NI*, and added the *MACE* interface as an extension of *GEM-NI*. Further, I conducted user studies and expert interviews to investigate the effectiveness of the introduced solutions. *DARLS* enables users to:

- create new versions of graph, editing existing versions, and committing back into the repository,
- access versions directly in the scrolling storyboard,
- perform differencing of diagrams using dual views, animation, layering and toggling, with synchronized zooming and panning,
- perform relative graph re-layout using two heuristic approaches: optimal and incremental,
- perform version merging using selection through a context-sensitive right-click menu.

I ran two user studies to investigate the benefits of the introduced difference visualization techniques and found that the basic dual-view visualization was not well received. The dual-view option with a difference layer was most preferred for comparing diagrams with matching node positions. For diagrams with non-matching positions, I found evidence that animation is beneficial, but that the combination with a difference layer was liked best. In summary, I can say that the difference layer technique is useful and a good complement to animation for showing changes. This supports diagram merging in *DARLS*.

GEM-NI is a graph-based 2D design tool that supports the exploration of design alternatives in various ways. *GEM-NI* is built as a branch of *NodeBox 3*, a vector graphics generative design tool that uses graphs to express the computation behind the design. *NodeBox* has been used for visualization and generative art. Examples include visualizations of real-time data, evolutionary art installations that react to users, documents in a single visual style but with variations across pages, and customized wallpapers based on e-mail spam [101]. *GEM-NI* adds several novel features:

- interactive, selective post-hoc merging in alternatives;
- an enhanced interactive design gallery that explores ranges of parameters and structural changes to the model.

In the context of generative design, *GEM-NI* presents the following new features:

- methods to control parallel/linked editing: checkmarks and sandboxes;
- a non-destructive method for resurrecting past states from history with undo lineage, via enhanced "skating" [107];
- methods to quickly generate alternatives via branching;
- local and global undo;
- tools to manage alternatives and visually compare them;

GEM-NI's design gallery interface, described later, employs elements of genetic algorithms, but enhances them through Cartesian products of generative networks. The exploration facilities of *GEM-NI*, also described later, enable designers, to explore a much larger number of design options than what is possible through manual interaction. To investigate my design choices, I evaluated my system with moderately and highly skilled users. Informed by the lessons learned from *DARLS*, *GEM-NI* also uses stable layouts to facilitate visual comparison of alternatives.

Existing approaches to compare graphs do not generalize to multiple alternatives, because practically all of them compare only two graphs at a time. Animation can be used to compare the linear evolution of a graph. But this also does not apply to alternatives because alternatives do not necessarily evolve linearly with time. To address this issue, I introduce a technique that allows the visual comparison of *more than two* alternatives without using animation. This new difference visualization technique is fully interactive. As a result, *MACE* enhances *GEM-NI's* approach with the following new contributions:

- a new difference visualization that simultaneously compares more than one DAG against a given reference;

- subtractive encoding to hide common elements for better difference readability, encoding as well as scalability;
- node-focused difference visualization for selected node(s) and a “diff exclusion” view to give the user the control over visual clutter;
- a “reveal-to-edit” feature for difference visualizations;
- group node difference visualization to enable scalability to larger networks;

I also include the following minor enhancements: emphasizing differences in parameters using transparency for difference visualization of non-numerical data types; post-hoc merging of the state of a parameter across a set of alternatives; and multi-monitor support to show how my techniques scale to up to 20 alternatives. Multi-monitor support also includes a new technique called jamming spaces for designation of monitors to certain states to make organization of a large workspace easier.

With these techniques *MACE* supports the non-linear evolution of alternatives in generative design by facilitating the comparison, management and editing of more than two alternatives. For the *MACE* interface, I re-implemented a variant of *DARLS*’s difference layer visualization within *GEM-NI* to enable the user to visually compare alternatives. Given that the networks used in generative design use directed edges to represent the data flow, my work in *DARLS* formed a good basis for *MACE*.

1.3 Outline

The outline of this dissertation is as follows. Chapter 2 provides an overview of literature related to difference and history visualization for graphs, generative design, graphical operation history, design space exploration, interacting with alternatives and multi-monitor user interfaces. These are concepts directly related to the topics in this dissertation. Chapter 3 introduces *DARLS*. It then describes the objectives of the user studies, which I conducted to evaluate diagram-differencing techniques. The chapter concludes with the findings. Chapter 4 introduces *GEM-NI*. It discusses how to evaluate open-ended creative tasks and reports the findings of two user studies and of an interview. Chapter 5 introduces the *MACE* interface. It describes the rationale for the design choices made behind the interface backed by previous research and results of an informal exploratory interview with the expert users. The chapter also describes the multi-monitor interface, designed to address the scalability of the difference visualization in *MACE*. It also introduces the concept of *jamming spaces* to facilitate the organization of alternatives on multi-monitor systems. Chapter 6 engages in overall discussion. Chapter 7 concludes by highlighting the major contributions of this work. It proposes areas for future work. Appendix A shows the version pairs of a course prerequisites diagram that were used in the user studies with the *DARLS* system described in Chapter 3. Appendix B presents some of the interesting designs that were created by the participants of the second user study described in Chapter 4.

Chapter 2
Related Work

Here I discuss previous work relevant to this dissertation. To clarify the contributions better, I mention at the end of each subsection the differences of my work relative to the discussed previous work.

2.1 Difference and History Visualization for Graphs

Dynamic graph drawing deals with the problem of visualizing a graph that evolves over time. Therefore, dynamic graph drawing is directly related to the work in *DARLS*. *MACE* employs graph difference techniques to illustrate changes between alternatives in the dataflow networks and, therefore, it's related to dynamic graph drawing as well. The concepts in dynamic graph drawing such as *mental map* and *animation* are relevant to my work in *DARLS*, *time slice* and *difference map* are also relevant to my work in both *DARLS* and *MACE*. Also, my work builds on side-by-side views for visual comparison (*DARLS* and *MACE*), storyboards for non-linear access (*DARLS*), as well as text and UML diagrams versioning (*DARLS*).

2.1.1 Mental Map

Graph layouts aim to preserve the user's mental map, which refers to the structural cognitive information a user creates internally when observing the layout of a graph [27]. A mental map then facilitates navigation in the graph or comparison of it and other graphs. Purchase et al. [86] examined the effect of mental map preservation on dynamic graph readability for directed acyclic graphs drawn in a hierarchical manner. The authors found that the mental map was important for questions that required nodes of the graph to be identified by name, but less important for questions that focus on edges or do not require nodes to be differentiated. Maier and Minas [71] demonstrated that it is meaningful to define incremental layout algorithms for visual languages with both graph-like and non-graph-like features, such as class diagrams. For other work on mental maps see, e.g., [87,91].

The findings of Purchase et al. and Maier and Minas motivated my use of relative graph re-layout in *DARLS,* as I target the same kind of diagrams. For the same reasons I also used incremental layout methods, instead of automatic (global) re-layouting, for differencing diagrams.

2.1.2 Difference Map

A difference map is a graph that encodes all of the differences between the node and edge sets between two graphs [7]. It presents the union of all nodes and edges in the two graphs for two different time slices [7,8]. Difference maps [8] were found to produce significantly fewer errors when determining the number of edges inserted or removed from a graph evolving over time. They were also significantly preferred on all tasks. Graham and Kennedy [41] summarize work on multi-tree visualization in their survey. They distinguish five methods of comparing nodes in two trees: edge drawing, coloring, animation, matrix representation, and agglomeration.

The following work was published after *DARLS* but nonetheless is worth mentioning. Gleicher et al. [39] proposed a general taxonomy of visual designs for comparison that groups designs into three basic categories, which can be combined. They provide a survey of work in information visualization related to comparison. They conclude that all visual designs are assembled from the building blocks of *juxtaposition*, *superposition* and *explicit encodings*. Recently, Alper et al. [4] evaluated two techniques for weighted graphs comparison. Their results indicate that matrix representations are more effective than node-link diagrams. Bach et al. [11] also explored matrix representations with their *Matrix Cube* visual representation and navigation model targeted at dynamic networks with *undirected* edges. They also describe *Cubix*—an interactive system for the exploration of Matrix Cubes. It visualizes dynamic networks by decomposing the cubes into meaningful 2D views. They received positive feedback from the two domain experts who used *Cubix* to explore and report on their own network data.

The difference visualization technique in *MACE* can be seen as a new variant of a difference map, which excludes nodes and edges common to the compared graphs. *MACE* employs, among other techniques, edge drawing and coloring for difference visualization. *DARLS* uses coloring and animation, which were identified to be critical by Graham and Kennedy [41]. Edge drawing and coloring are used in *MACE.* Although Graham and Kennedy present these techniques only for multi-tree visualization, the approaches are also directly applicable for the visualization of changes in DAGs (directed acyclic graphs), which define the data-flow networks in *GEM-NI*.

In my research with *DARLS*, I explore the effect of using juxtaposition with stable layouts and superposition. A hybrid approach of juxtaposition and explicit encodings is used in the design of the *MACE* interface. From explicit encodings identified by Gleicher et al. [39] I use highlighting of the corresponding nodes. Gleicher et al. [39] also identified *additive encoding*, where the members of the intersection are added to one of the graphs. In contrast, I use *subtractive encoding*, where the members of the intersection are removed from one of the graphs. This is a reasonable choice, as I expect that there will be fewer differences among data-flow network of alternatives compared to the number of similarities. As a result, this improves the readability of my difference encoding by keeping visual clutter low. Since *DARLS* involves only unweighted graphs and *MACE* further uses only directed edges, Alper et al.'s techniques are not an appropriate design choice for my context. Bach et al.'s [11] Matrix Cube approach is also not appropriate as it cannot handle directed edges.

2.1.3 Static Techniques for Comparison

Layering is commonly used in diagram differencing and merging, e.g., [26]. The layering technique superimposes multiple graphs, but can only handle a very small number simultaneously. Thus it is most useful to show pair-wise differences. A generalized approach to depict evolution of a dynamic graph in more than two versions is by using time slices. In dynamic graph drawing, time slices display dynamically evolving data via a matrix of images that visualizes the differences between objects. Each image is a time slice [9].

Side-by-side views have been used for visual comparison of objects long before computers were invented. One popular modern adaptation is a side-by-side view for comparing text documents. There are many publicly available tools, such as GNU *Emacs*, *Kompare*, *WinMerge*, Araxis *Merge*, and Scooter Software *Beyond Compare*. Some of these are not only capable of comparing plain text, but can also deal with XML documents, file directory structures, and even binary files.

Side-by-side views are a special case of *time slice* visualization, which show only two versions. *DualNet* [77] visualizes sub-networks of node-link diagrams in side-by-side views. The work cited below, however, focuses only on trees, rather than graphs. As a result, most of these methods are not directly applicable to my context. *TreeJuxtaposer* [76] targets the comparison of large trees with side-by-side views. *TreeVersity* [47–50] is an interactive information visualization tool for comparing trees by showing changes in topology and node values. The system uses carefully designed color palettes to show positive/negative, absolute, and relative value changes; and glyphs that pre-attentively show these changes. *TreeVersity* also highlights created and removed nodes. *TreeVersity2* [50,51] is an interactive data visualization tool that allows the exploration of changes in trees over time addressing the direction of a change, if it is an actual or relative change, starting and ending values, created and removed nodes, and inner nodes' values, while keeping the hierarchy context. *TreeVersity2* allows the exploration of change over time in trees using a novel interactive data visualizations for exploring changes in the tree between two time points (e.g., two years) coordinated with time based visualizations to explore the time context. Guerra-Gomez et al. [50] identified and classified the following five types of tree comparisons:

- **Type 0:** topological differences between two trees where the nodes only contain a label,

- **Type 1:** positive and negative changes in leaf node values with aggregated values in the interior nodes (i.e., trees that can be visualized with a treemap) and no changes in topology,
- **Type 2:** positive and negative changes in leaves and interior node values with no changes in topology,
- **Type 3:** positive and negative changes in leaf node values with aggregated values in the interior nodes and with changes in topology,
- **Type 4:** positive and negative changes in leaves and interior node values, with changes in topology.

With the exception of type 0 none of these directly apply to the DAGs in *GEM-NI*. For type 0, instead of topological differences I identify structural differences between two or more DAGs in *MACE*. Guerra-Gomez et al. identify nodes as being 1) uniquely labeled in the tree, 2) contain one or more numeric variables, with values changing over time and 3) contain one or more categorical attributes that might have more than one value. This does not correspond to my work: Firstly, nodes in *GEM-NI* do not have categorical attributes in the same sense. Group nodes can be considered as categorical attributes, but in DAGs their use is optional. Moreover, I propose a special difference visualization technique for multi-group-node difference visualization (see 5.1.3.5). Secondly, in addition to numeric values, the nodes in the DAGs I target contain set, string, Boolean, point, color or custom defined type values. As a result the techniques for numeric variables are not applicable for my context. Finally, while branches can be compared in trees, as they are distinct, in DAGs they are not distinct and thus solutions designed for trees will also not work.

Another approach in the category of static visualization techniques is agglomeration. Graham and Kennedy [40] presented a DAG visualisation designed to allow interaction with a set of multiple classification trees to find overlaps and differences between groups of trees and individual trees. It merges the trees into a unified structure whilst preserving a global parent-child orientation of the nodes. This method of overlaying classifications allows nodes to be seen in the context of multiple trees, without the shrinking space problems of the small multiple design. In one of the examples they were able to compare six classifications. *Zoomology* [56] compares two classification datasets where two trees are merged into a single overview. Isenberg and Carpendale [59] presented a new system that facilitates hierarchical data comparison in co-located collaborative environment using structural comparison through overlay. Their system dealt with up to six trees. *CandidTree* [68] that merges two trees into one and visualizes two types of structural uncertainty: location and sub-tree structure uncertainty. Yet, agglomeration is not applicable to (generative design) networks, as neither individual nodes nor sub-networks can be combined meaningfully into a hierarchy in DAGs.

My new layering technique in *DARLS* is related to the concept of a difference map in dynamic graph drawing where two versions of a graph are compared to each other. In *DARLS*, layering is used in the side-by-side views. A layering technique depicting missing nodes is employed in *MACE*. In *DARLS,* the side-by-side views can be thought of as a base case of time slices, whereas in *MACE* multiple time slices are normally compared. However, in *MACE* I do not think of the diagrams as time slices but rather as of alternatives without time related semantics. Similar to previous work in this area, I use side-by-side views in *MACE*, but generalize previous work to the simultaneous comparison of *more than one* alternative against a given reference.

2.1.4 Animation & Small Multiples

Today, many visual systems utilize animation to help the user understand transitions. It has been shown that animation facilitates text document comparison [25], and enables users to better identify changes between versions. Examples include changes in node-link diagrams and structural relationships [95], perception of statistical data visualizations [55], and dynamically evolving data in graphs. A number of papers support the idea that animation can be beneficial for the purposes of visualization, e.g., [14,111]. The utility of animation has been questioned by Tversky et al. [109], yet it was acknowledged that animation may be an effective way of presenting transitions. Robertson et al. [89] compared animation, trace line, and small multiples visualization on multi-dimensional data. Animation was found least effective, whereas small multiples and trace lines were faster than animation, and small multiples were more accurate. Griffen et al. [43] suggest that animation can be helpful in discovering space-time clusters.

Animation has also been used for communicating dynamically evolving data in graphs, which is directly related to my work. I'm aware of three user studies that explored the effects of difference maps, small multiples, slide shows, and mental map preservation. Farrugia et al. [36] compared animation and small multiples on two dynamic graph series. Small multiples were faster for most tasks. Archambault et al. [9] performed a user study where they investigated the effect of animation, small multiples, and mental map preservation for reading graphs that evolve over time. The study found that overall small multiples gave better performance than animation, but animation had fewer errors for some tasks. No effect for preserving the mental map was found, but this study used graphs with unlabeled nodes. The same authors also conducted a study to evaluate the effectiveness of difference maps in comparison

to presenting the evolution of a dynamic graph over time in three interfaces (animation, slide show, and small multiples) [8]. Evidence was found that difference maps produced fewer errors when determining the number of edges inserted or removed from a graph as it evolves over time. Also, difference maps were preferred on all tasks.

In Chapter 3 I investigate usefulness of animation for showing differences between graphs with matching and non-matching layouts. The following works were published after *DARLS* and are worth mentioning. Bach et al. [12] presented *GraphDiaries*, a visual interface designed to improve support for identifying, tracking and understanding changes in dynamic networks. The techniques in *GraphDiaries* were evaluated against techniques commonly found in visualization systems for temporal graph navigation. A minor increase was observed in task completion time that is compensated by a significant decrease in error rate in favor of animated transitions. The latter improve the perception of changes and provide users with a rich set of exploration strategies. Bach et al. [10] also presented a review of techniques for temporally changing data by describing them as series of operations performed on a conceptual space-time cube. They introduced a taxonomy of elementary space-time cube operations, and explained how they can be combined to turn a three-dimensional space-time cube into an easily-readable two-dimensional visualization. This model can describe many forms of difference visualization for graphs. Rufiange and McGuffin [90] presented *DiffAni*, a system that allows a graph to be visualized as a sequence of three kinds of tiles: diff tiles that show difference maps over some time interval, animation tiles that show the evolution of the graph over some time interval, and small multiple tiles that show the graph state at an individual time slice. This sequence of tiles is ordered by time and covers all time slices in the data. An experimental evaluation of *DiffAni* shows that their hybrid approach has advantages over non-hybrid techniques in certain cases. Small multiples have also been used for visualization of non-graph data. One of the recent examples is the work of Van den Elzen and van Wijk [34] who introduced a new visual exploration method for multivariate data analysis using small multiples. It is based on alternation between large singles and small multiples. They produced small multiples by applying split operations on large singles and also introduced a navigation mechanism based on explicitly showing the visual history of the exploration path. They tested the effectiveness of the exploration method in a user study comparing four different interaction methods. Their work did not find a significant difference for execution time of tasks and the number of errors that were made. However, they found users needed fewer steps in answering questions about the data and also explored a significantly larger part of the state space in the same amount of time. Overall, participants preferred the small multiple interaction methods rating them the most useful and easiest to use. Participants were faster without using the visual history.

I use animation in *DARLS*. The technique is used with the full set of features for comparing diagrams with non-matching layouts. Fading only is used for matching layouts. In *DARLS,* animation can be used in conjunction with layering. Animation, however, is not appropriate for multi-graph difference visualization in *MACE*, as node positions are synchronized across alternatives. More importantly, in *GEM-NI* alternatives can be created non-linearly and the user can create multiple, potentially fully independent alternatives. Thus, they *cannot* be thought of as time slices. Animation is best used for showing gradual transitions, i.e., it is suited to show successive graphs that represent an evolving change of a single data set. This has been previously pointed out, e.g., in [40]. Due to the unique features of sets of alternative solutions, I have to deal with situations well beyond the evolution of a single graph. Thus, I needed to extend previous work. The closest relevant work compares multiple graphs at the same time. It is important to highlight that in generative design non-linear creation and editing of alternatives is the norm. In other words, generative design typically is ill described by a linear time flow. Thus time/history-based difference visualization techniques such as animation and small multiples are not directly applicable to the comparison of alternative designs. *MACE* employs new graph difference techniques to illustrate the changes between alternatives. Also, with respect to Bach et al.'s [10] taxonomy of data visualization, *DARLS*'s basic visualization uses juxtaposition, and a compound operation of time cutting, space scaling, space shifting, time flattening. However, this does not apply to the technique in *MACE,* where the compared artifacts are not temporal, due to the non-linear design process.

2.1.5 Techniques to Access Versions

A time slider can provide interactive access to different versions over time. This technique is used in the *Diffamation System* for text version differencing [25] and in *TimeTree* [22] for navigating hierarchies changing over time. Su [104,105] introduced a new interaction metaphor and visualization of the operation history for 2D illustrations, i.e., drawings changing over time. These are called storyboards. The user has access to the history via graphical depictions at the top of the document. Other approaches to storyboards have been presented as well [66].

Unlike the *Diffamation System* I use a scrollable storyboard in *DARLS* instead to enable the user to access all versions. In *DARLS,* the storyboard can be thought of as time slices (along with the side-by-side views discussed above).

2.1.6 Generic and UML Diagram Differencing and Merging

Difference visualization is also used in software engineering, typically for UML diagrams. Software engineering research on UML model versioning is extensive, e.g., [3,62,79,116]. However, this work focuses more on theoretical foundations, efficiency, robustness, and correctness. Often, the work is backed up by case studies using evolving software projects. Such work is typically not concerned with user interface issues, a gap that I am trying to address. Visual comparison of UML diagrams is rarely investigated. Nonetheless, Förtsch et al. [37] presented a survey on differencing and merging of software diagrams and listed requirements for UML diagram versioning tools. One of the main requirements identified is a user-friendly representation. They also point out that it is desirable for diagrams to be displayed side-by-side with differences marked graphically. If not enough space is available, a unified diagram may be constructed instead. Ohst et al. [82,83] introduced a unified document approach that highlights common and specific parts of two diagrams. Girschick [38] introduced a similar system using a unified approach, where eight colors were used to visualize eight different types of changes in class diagrams. As part of the work on the *Pounamu* system [74], the authors conducted a user survey and got positive feedback for response time for their difference visualization, the support for incremental changes, merging, and the overall support for diagram-based design activities.

A single unified diagram for graph comparison was studied by Dadgari et al. [26]. They evaluated multiple graph differencing and merging techniques qualitatively with a questionnaire. A translucent layer approach was preferred for the simple examples they considered. Shireen et al.'s [97] conceptual prototype of a user interface for parallel work with design alternatives included a difference visualization.

Ohst's approach, where graphs are displayed side by side with differences marked, influenced my decision to try side-by-side views for diagram versioning in *DARLS*. Most mentioned approaches for UML diagram differencing are applicable to other forms of node-link diagrams and graphs. This is why in *DARLS*, differencing of generic diagrams is also supported in addition to UML diagrams. In contrast to Dadgari et al.'s work in *DARLS*, I present a side-by-side approach for graph differencing. *DARLS* displays two versions of a diagram side-by-side with differences marked appropriately, even if a node was moved. The system offers functionality to re-layout one version of the diagram relative to the other with stable node positions between the two versions. Moreover, *DARLS* offered the ability to accept/reject individual changes to facilitate reconciliation. In Shireen et al.'s work, they only showed nodes that are common. Also, they employed a concept of dragging of nodes to reveal them for editing. Yet, dragging of objects has a different meaning in GUIs and does not scale to multiple alternatives. *MACE* extends Shireen's concept and previous work on layering by emphasizing (un)changed, added or subtracted nodes and edges using highlighting as in e.g., [38] and [82]. *MACE* also supports nested group nodes. To reveal (common) nodes that are omitted from the visualization, I present a new "reveal-to-edit" user interface technique. In summary, most previous work addresses the problem of showing pair-wise differences reasonably well. Animation and small multiples are used for visual comparisons of more than two DAGs. This is only effective for content that has evolved linearly, such as in *DARLS*. None of these approaches can handle the visual comparison of up to 20 data-flow networks that have evolved non-linearly or in parallel as in *GEM-NI*. Moreover, none of the above approaches supports editing in a difference visualization mode.

2.2 Graphical Operation History

According to Shneiderman [98], history mechanisms can play an important part in the design process, supporting iterative analysis by enabling users to review, retrieve, and revisit visualization states. Many recent systems provide history-keeping mechanisms in the form of a timeline [63]. Moreover, history tools can help users to create reports or presentations, facilitating communication. When interactive [33], graphical histories can amplify the exploration capabilities of a system. Users then can not only go back in time [44] and defer decisions [114]; they have a mechanism to try out variations [107] by creating revisions [23] and versions [32,67] of the timeline. Heer et al. [54] and Grossman et al. [44] together provide a comprehensive survey from an HCI perspective. Here I focus mainly on works that employ time sliders, graphical histories and histories of diagrams, as they are most relevant to histories that can be used in variational design.

One of the earliest examples of graphical history is *Chimera* [66], which features an editable graphical history through panels depicting the results of each user operation. *Chronicle* [44] is a sophisticated system for exploring a document's history via a zoomable and track-based video playback metaphor. *The Diffamation System* for text version differencing [25] employs a time slider that permits the user to explore differences over time. *Diffamation* [25], a system for text version differencing employs a *time slider* that permits the user to explore differences over time. Su [104,105] presented new pictorial visualizations for the operation history of 2D vector illustrations as interactive storyboards.

GEM-NI keeps a history for each alternative and maintains it during cloning or a new feature that permits (non-destructive) resurrection of past states as new alternatives through a simple GUI that enables the user to scroll through previews of past states or to select specific operations.

2.3 Design Space Exploration

Woodbury and Burrow [115] argue that design activity is well-modeled by a network structure. This network reflects the strategies and structure of the designer's exploration. They introduce the notion of *design hysteresis*, which points out that insights are discovered not just by explicitly visiting parts of a design space, but also through re-combination of visited alternatives in said *hysterical design space*. The term *hysteresis* refers to the lagged entry of an effect into a system. There, information needed to form a state exists in prior discovered states, which causes said lag. *Design Galleries* [73] explores the hysterical design space by automatically generating and organizing variations of graphics or animations produced by a parametric model. Ma [72] introduces an interactive and dynamic graph representation of a database, which represents relationships between nodes, and argued that this type of visualization enhances the user experience in exploring the data. It presents multiple views of the data such as a local, global and summary view. Jankun-Kelly and Ma [60] introduce a 2D spreadsheet data visualization for multi-dimensional database exploration. Terry et al.'s *Parallel Pies* [107] enhance the user experience in generating and comparing alternatives by displaying several alternatives of a model simultaneously. The system enables variation and alternative generation by changing the parameters. Lunzer and Hornbæk [70] propose a novel subjunctive interface where GUI elements can assume multiple states simultaneously. The three design principles on which the subjunctive interface is built on are as follows:

- enable setting several, perhaps totally different scenarios independently;
- display multiple scenarios simultaneously to facilitate comparison;
- synchronous adjustment of multiple scenarios to escalate the exploration process.

The authors realized these principles by presenting an interface with multiple sliders for each parameter with multiple handles each representing a different input value for the respective parameter resulting in multiple scenarios. Experimental results indicated higher user satisfaction, and shorter (up to 27%) task completion times. For this, they propose an interface with several multi-state sliders for each GUI element parameter.

Sheikholeslami [96] implemented the *Dialer* interface in Bentley Systems' *GenerativeComponents*. This interface is used for interacting with the hysterical space. The *Dialer* comprises concentric interactive rings where each ring represents one parameter and the divisions of the ring correspond to the explored values of that parameter. The outermost ring illustrates the items of the hysterical space. This is a compact visualization, but limited in the number of divisions that can be displayed and the number of parameters that can be visualized.

GEM-NI provides for design space exploration through an interactive design gallery to explore changes to both the parameters as well as the structure of the generative model. This interface improves previous work [96], by enabling users to select which parameters and/or parts of the generative network to use for populating the design gallery. Moreover, the design gallery of *GEM-NI* also supports ranges, in addition to sets, and network substitutions. Furthermore, I added the ability to create new alternatives from the product of generative networks. *GEM-NI* is the first system that does this allowing designers to explore the design space more quickly and widely than with other approaches. I believe this is a great addition to the design space exploration tools in *GEM-NI*.

2.4 Interacting with Alternatives

Minimal support for alternatives is found in industry tools such as Autodesk's *Showcase* and Dassault Systèmes *SolidWorks* ([113], pp. 276-277). Both focus mainly on supporting alternatives through configuration management, *alternative lineup* features and side-by-side spreadsheet-like user interfaces. *CATIA* by Dassault Systèmes shows alternatives in *Catalogs*, a static gallery of assemblies and parts. It does not support interactive exploration.

Work on subjunctive interfaces [70] introduced interaction techniques for side-by-side exploratory analysis. Their system supports viewing and editing of parallel parametric models with a multi-handle slider user interface.

Terry et al. [106] presented techniques to better support systems for parametric variations; *side views* – an on-demand command preview, the *parameter spectrum* – a replacement for the traditional slider control to display a range of possible results, and the *design horizon* – a complementary design space visualization.

In contrast to Heer et al.'s work [54], which describes branching history as a way to remember operations that have been undone, Terry et al. [107] describe undo as a tool for reflection-in-action, in other words, for exploring variations. In their *Parallel Paths*, when users duplicate a particular variation, its lineage is also duplicated. The copied history enables users to create variations after applying a command: when a result is not what was anticipated, but still worth keeping, users can duplicate the current state then non-destructively return to a previous state. They call this function *skating*. Skating also reduces ambiguity when working with multiple variations in the same workspace. The *Parallel Paths* model was implemented in *Parallel Pies*, a user interface for image manipulation that also supports side-by-side comparisons. *GEM-NI* supports a number of ways to create alternatives. In *GEM-NI*, I introduced a new method for creating alternatives from a graphical history via skating with support for lineage duplication, where previous states can be accessed and instantiated non-destructively. The method is the first of its kind in generative design and improves over previous work by providing previews.

Hartmann et al.'s [53] Juxtapose presents a parallel code editor and a runtime parameter tuning environment for exploration of interaction design alternatives. The system enables its users to write sets of programs that can be executed in parallel. When alternatives are linked, any block of code written in one alternative is shared among the rest. The idea of being able to work with multiple linked programs is very exciting, but requires strong coding skills. Bueno et al. [20] propose a technique for managing variations and explorations of a design, via the metaphor of rewriting history. They demonstrate this by enabling users to change the design's history, with common use cases of merging, generalizing and specializing.

Alternatives, together with revision control, change tracking and annotations, feature in the design of the *d.note* tool [52]. In *d.note*, users can introduce alternatives, represented by duplicating the original state and visually encapsulating both the original and alternative.

Smith et al. [102] conducted a user study on computational sketching tools. For this, they compared the effects of three interaction models for working with design alternatives in the early design stage: a tab interface, a layered canvas, and spatial maps. They found that spatial maps better support idea reflection, as they permit side-by-side comparisons.

Shireen et al. [97] presented a conceptual prototype, a "sketch", of a user interface to enable parallel generation and editing of design alternatives as an extension to existing variational CAD tools. It includes a dependency graph to enable simultaneous work on multiple design variations and difference visualization for alternatives.

GEM-NI enables interaction with multiple alternatives through parallel editing, history keeping, cloning, support for non-destructive resurrection, and new methods for easy management of alternatives. Parallel editing has been previously used for managing duplicated code in Codelink [108]. To enable designers to reuse their work more easily, *GEM-NI* adds a new method for post-hoc merging of (parts of) divergent alternatives. Moreover, *GEM-NI* is the first system to realize concepts proposed by Shireen et al. and to improve and extend this work in several ways.

2.5 Multi-Monitor User Interfaces

Many studies have investigated the effectiveness of large or multiple monitors in comparison to small or single screens. Grudin [45] emphasized the need to partition our digital world. He conducted a user study with various multi-monitor configurations and observed, among other things, that participants use one monitor for their primary task and treated a second monitor as additional space.

Ball and North [13] analyzed the use of a large 3×3 tiled display in a longitudinal study. They identified a decrease in cognitive load in specific tasks due to the possibility of glancing at secondary information. Another example of decreased cognitive load is viewing large images and/or visualizations, due to the reduced need for navigation. With a large display there is no (or less) need to navigate, as the entire data set might be visible. After using the system for some time, users tended to dedicate certain regions of the screen for particular applications, such as e-mail, and then rely on spatial memory. The benefits of spatial memory were already explored in Robertson's Data Mountain [88].

Andrews et al. [5] examined how increased space affects the way displays are regarded and used for cognitively demanding sense making. Their work demonstrated how the spatial environment supports sense making, by providing both external memory and a semantic layer. With naïve users, they found a number of key behavioral differences suggesting a multi-monitor workstation to be more useful. With professional analysts, they identified clear evidence for users using the additional space both as a form of rapid access external memory and as an added semantic layer in which meaning was encoded in the spatial relationships between data, documents, display, and analyst. Andrews et al. claim that even though the task was specific, the actual activities that they observed were primarily reading, identifying important information, categorizing, and arranging; common tasks across many domains.

Bi et al. [16] conducted three controlled experiments to investigate how interior bezels on tiled-monitor large displays affect user performance and various tasks. They concluded, among other things, that tiled-monitor large displays are suitable for visual search tasks. However, if high accuracy is required, objects should not be placed across bezels. Bi et al. [18] also conducted a longitudinal diary study of a very large display (4.88m×1.83m) in comparison to single and dual monitors. The participants performed 3D modeling and graphical drawing activities in addition to a typical daily task. They found a strong preference for the large display. A subset of participants reported mentally partitioning the screen real estate into focal and peripheral regions when managing various windows. All participants tended to use more windows on the large display because it improved their workflow for complex, multi-window tasks, such as programming and graphic drawing. Guided by these results, Bi et al. [17] designed a set of interaction techniques that provide greater flexibility in managing multiple windows. Their *Spread* technique is of particular interest to the context of my work. A primary document is placed at the center and surrounded by supporting ones in a tiled layout.

Multi-tiled visualizations have been proposed in the past. The following two are some of the examples: one early and one latest. Sandstrom et al. [92] presented the *hyperwall*, a visualization cluster that uses coordinated visualizations for interactive exploration of multidimensional data and simulations. Beaudouin-Lafon et al. [15] presented a multi-surface interaction system for large datasets. It enables multiple users to easily and seamlessly create, share and manipulate digital content. Some of the uses for the system were identified to be comparison of large number of related images and juxtaposition of a variety of heterogeneous forms of data.

Based on the above-mentioned findings and with the intent of reducing window management overhead further, I designed *GEM-NI* to use a tiled user interface that presents many alternatives simultaneously in a tiled arrangement. My new user interface uses the structure of the tiled multi-monitor display and facilitates designation of particular monitors for particular functions. My space redistribution feature is a generalization of the *Spread* method of Bi et al. [17] to tiled display arrangements. And the extension of the *MACE* interface for multi-tile visualization is a form of enhanced juxtaposition for the purpose of comparing multiple alternatives.

Chapter 3
The Effect of Animation, Dual View, Difference Layers, and Relative Re-Layout in Hierarchical Diagram Differencing

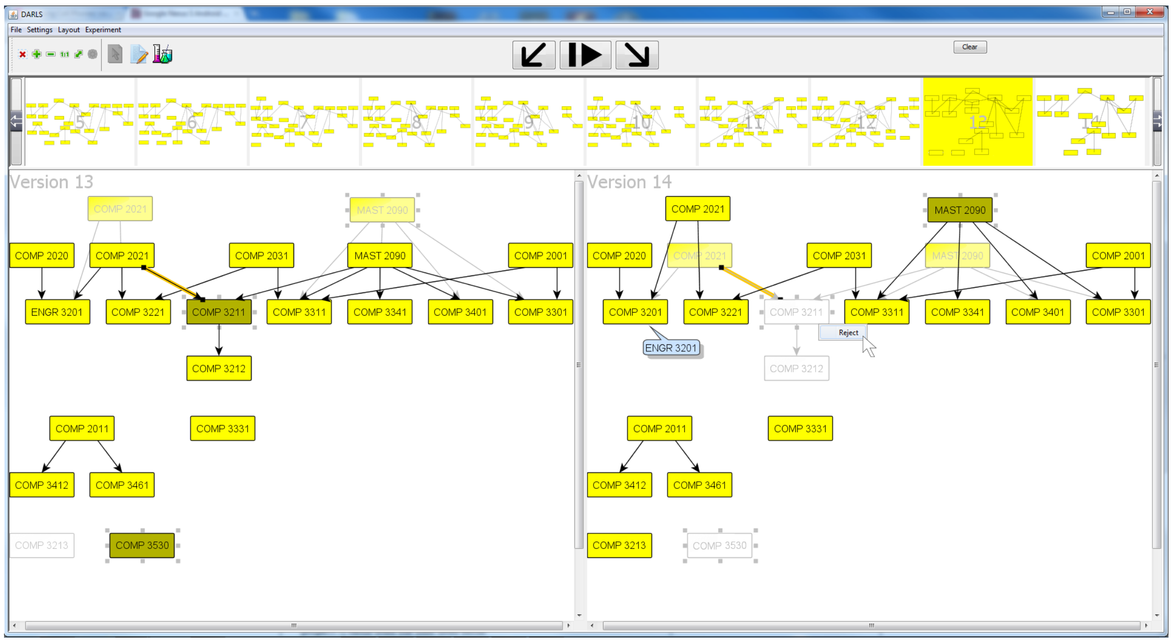


Figure 3-1. *DARLS* showing two versions of a diagram, which visualizes course pre-requisites for an undergraduate computer science program. The visualization shows a difference layer and uses the relative optimal re-layout.

3.1 Motivation

A number of algorithms and interaction techniques have been proposed for effective dynamic graph visualization. Recently, user studies were conducted to evaluate these [8,9]. However, these user studies focused on generic graphs where attribute values associated with nodes or edges are irrelevant. Only a small fraction of research addresses diagrams where nodes in the graph are identified by name, see Purchase et al. [86]. Also, dynamic graph visualization research primarily targets differencing alone, and to my knowledge, no previous quantitative research exists on visualizations that support merging of diagram versions.

To address these shortcomings, I introduce a system for differencing and merging diagrams, that makes use of Dual View, Animation, Re-Layout, Layers and a Storyboard, abbreviated as *DARLS*. The system is targeted at diagrams with node and edge attributes. Such diagrams are used frequently in architecture, design, information and concept visualization, and in software engineering, i.e., *software documents* such as UML diagrams. For example, the system can be used to track the evolution of class dependency diagram over releases, a particular course in the prerequisite visualization, or to visualize the evolution of any diagram in general. It also can be used to merge versions of a diagram and to perform selective undo.

3.2 The *DARLS* System

I developed a new system capable of versioning and visualizing differences between diagrams with a number of techniques. Nodes and edges are disambiguated with unique identifiers. The system currently supports differencing and merging of generic and UML class diagrams. It was implemented in Java using the *yFiles*[18]. To illustrate the user interface, see Figure 3-1, where I use two versions of a course prerequisite diagram from two subsequent years as an example.

3.2.1 Accessing Versions and Navigating the Views

The system features side-by-side views of two versions of a diagram. Zooming with the mouse wheel and panning with the scroll bars is synchronized between the two main views. Buttons on the panel allow toggling between the editing and selection modes. Diagram repositories are accessed through the file menu. Both side-by-side graphs can be edited and committed back into the repository. The user can directly access ten versions of the diagram in the scrolling storyboard. Any version can be compared against any other version in a

[18] http://yworks.com

repository. Selecting a version from the storyboard and clicking on the arrow button pointing to the desired view loads a version into that view.

3.2.2 The Difference Layer

Here, the differences between the two diagrams in the side-by-side views are visualized using a transparent underlay pane in the background of either view, which shows the other diagram. I call this a *difference layer*. This is similar to previous work on single-view differencing [26], but different from *Pounamu* [74], which uses also a single merged view, yet where the objects common to both compared diagrams are *not* shown. My difference layer is also different from difference maps [8], as it displays the common nodes and edges between two versions, even if a node was moved. The rationale is to also enable accept/reject of node movements. A configuration dialog accommodates different color schemes. If the visualization gets too cluttered, the types of objects displayed in the difference layers can be customized, or they can be disabled completely.

By default, all missing nodes and edges for a diagram are shown in neutral transparent grey in the difference layer. See e.g., COMP 3212 in the right view in Figure 3-1. Nodes that are common to both diagrams but shifted, resized, or morphed are visualized with reduced transparency, e.g., MAST 2090. This implicitly visualizes all differences between the diagrams, as deleted nodes show up semi-transparent in the right diagram and changed nodes are visualized with reduced transparency.

Moreover, if the user selects a node in the right view, the corresponding node in the left view is shown selected as well, with different styles depending if the node exists in the other diagram. The user can customize this, so that either the node on the foreground and the difference layer is selected, or only the node on the foreground of the left view is selected. Nodes in the difference layer in the right view also can be selected by clicking. This is used for version merging see the next section. Also, everything described applies to edges as well.

3.2.3 *Version Merging using Selection*

The ability to accept and reject graph edits was previously presented in *Pounamu* [74]. In my system, a context-sensitive right-click menu provides easier access to this functionality. See the popup next to COMP 3211 in the right view in Figure 3-1. In my system, a reject operation can undo the creation or deletion of nodes and/or edges, shifting, and morph/resize operations on nodes. For example, if the user “rejects” the change in Figure 3-1, node COMP 3211 and its adjacent edge connecting to node COMP 2021 will be re-instantiated in version 14. As other nodes are also selected, COMP 3530 will be re-instantiated and MAST 2090 will be shifted down to the same location as in version 13. Figure 3-2 shows the state of the diagrams after the reject operation.

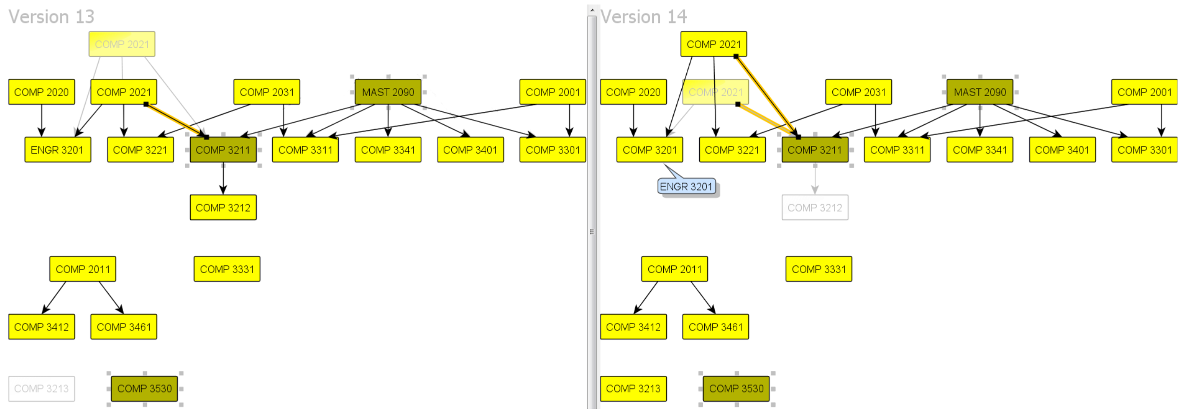


Figure 3-2. The state of the diagrams after the reject operation in Figure 1 is invoked.

3.2.4 *Animation and Other Techniques*

When the play/pause button is pressed in the top panel the differences between the diagrams in the two views are animated in three phases. First, removed objects fade out, then moved objects are shifted from the old to their new locations with morphed changes in shape and color, and finally new nodes and edges fade in. The sequence and concurrency of these events can be customized. Also, the system can highlight new nodes and edges with another distinct color (blue by default), once all animations end, to assist the user in identifying changes. Nodes that changed labels, such as COMP 3201/ENGR 3201, have a call-out added for the change. An additional option gives access to an animation where new nodes and edges blink in a distinct color (red by default), once the first animation ends. Previously, Plaisant et al. [85] proposed decomposing animation in their *SpaceTree* system into three steps: trim, translate, and grow, which is similar to my method. Heer et al. [55] demonstrated that staged animations are favored over "all at once" animations for statistical visualizations.

3.2.5 Relative Graph Re-Layout

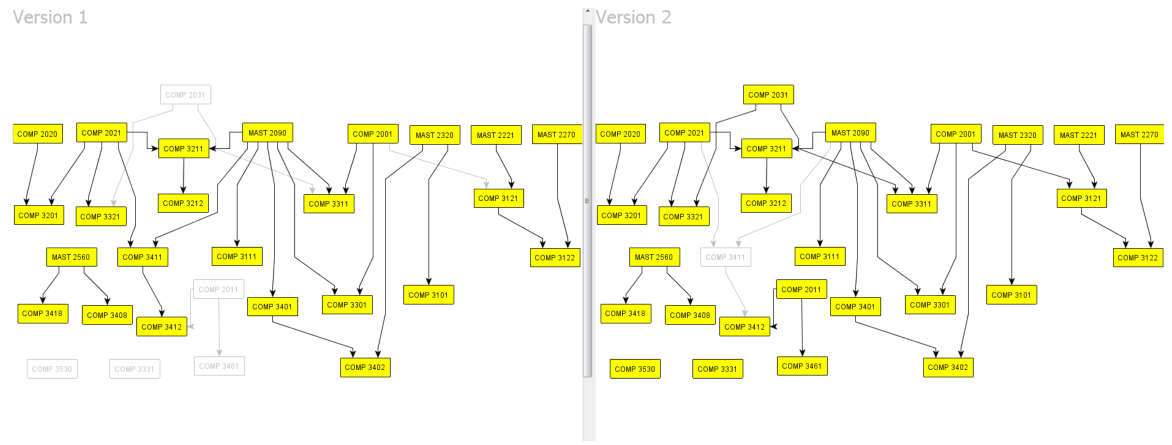
As more nodes and edges are added to later versions of a diagram it may get difficult to differentiate and merge different versions, even if the user has access to all provided features, as the layout of the graph may have changed (too) much. Therefore, I added an option to interactively re-layout a diagram relative to another to minimize visual differences between them. I implemented two relative re-layout algorithms: *incremental* (Figure 3-3a), which preserves the locations of nodes, and *optimal* (Figure 3-3b), which rearranges nodes to better use the screen space and minimize edge crossings. The optimal layout thus minimizes the need for zooming and panning. Through this, the algorithm creates a visual "rhyme" that may help the user to better understand the structure of the dependency graph. Both layout methods keep the positions of nodes and edges common to both diagrams stable and thus preserve the mental map. I based my implementation on the hierarchic and incremental hierarchic layouters in *yFiles* and adapted these to my diagram-differencing task as follows.

By default, I re-layout the left diagram relative to the right because I assume the diagram in the right is the latest version. The incremental re-layout algorithm first adds all nodes from the left graph that are missing in the right graph, to that right graph to generate a composite graph. It then partitions space into horizontal lanes and fixes the positions of the common and newly added nodes. The remaining nodes are assigned to these lanes so that the number of edges pointing upward is minimized, while keeping the edges short. Then these nodes are arranged within their lanes so that the number of edge crossings is also minimized, and finally, they are arranged to minimize edge bends. Then the layout of the composite graph is copied to the left and right graphs, but only for those nodes and edges that "belong" to the respective graph.

The optimal re-layout algorithm is similar to the one described above but with two differences: nodes are not fixed in place and node and edge placement heuristics can be specified through a menu. Figure 3-1 demonstrates two diagrams where optimal re-layout was performed. Please note that COMP 2021 and MAST 2090 were manually raised higher after the re-layout.

Currently, there is no propagation effect to keep the layout consistent across versions if merging or other editing occurs.

(a)



(b)

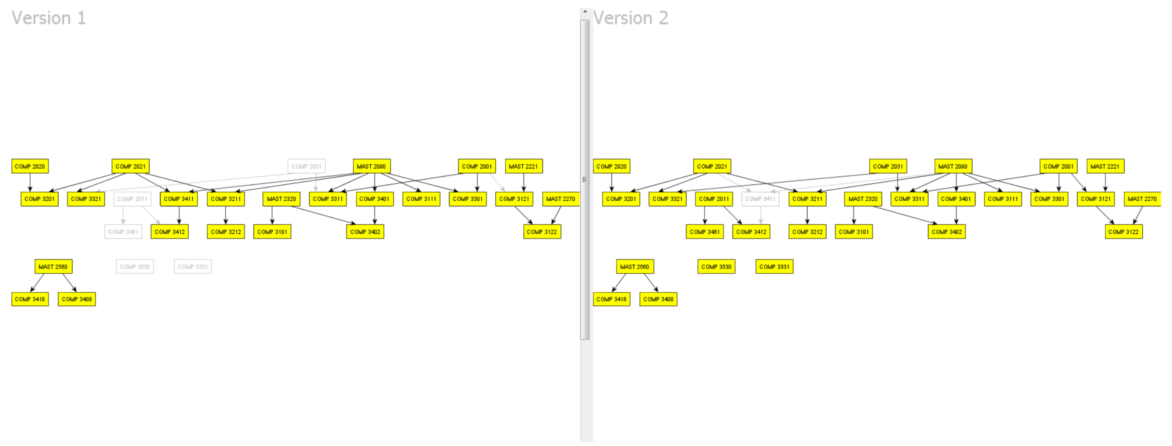


Figure 3-3. (a) Incremental layout, (b) Optimal layout.

3.2.6 Differencing UML Class Diagrams

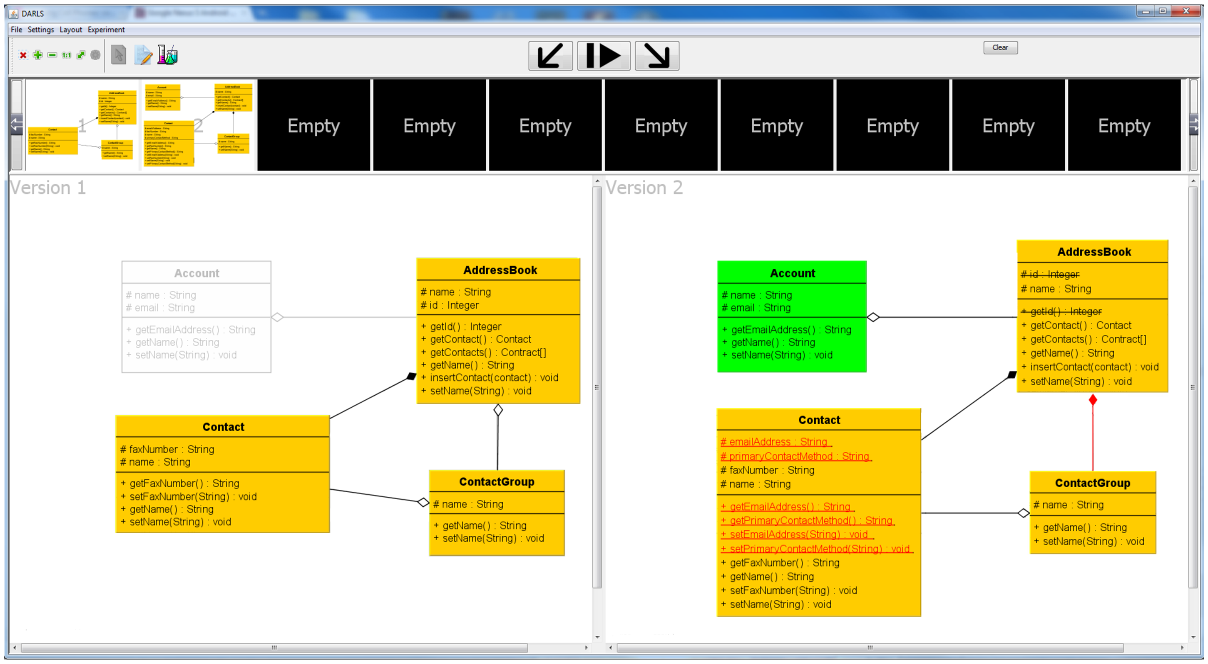


Figure 3-4. Differencing UML class diagrams.

DARLS also allows *UML class diagrams* differencing. Here I used text differencing techniques (strikethrough and underline) as well. Changes in association type, such as from aggregation to composition, are visualized by highlighting edges in a different color. Classes common to two diagrams are shown in one color, newly added ones – in another. Colors can be customized and changes can again be animated. Deleted classes are displayed in the difference layer with reduced transparency. New attributes and methods are highlighted in red and underlined. Deleted ones are crossed out. The user can customize the differences to be displayed in either view or both. Figure 3-4 demonstrates differences displayed in the right view. Currently, my system can visualize class diagrams generated from any Java application, with the help of a freely available UML diagram extractor.

3.3 User Studies

I ran two user studies on the new system. Both revolved around diagram differencing using the techniques described above. There were a number of goals for the studies. The primary goal was to investigate the fitness of difference layers for diagram merging. In contrast to previous work [26], I also wanted to *quantify* the user performance of diagram differencing techniques. I also wanted to investigate the incremental and optimal re-layout techniques. Finally, I wanted to confirm the validity of the proposed requirement by Förtsch et al. [37], which states that diagrams should be displayed side-by-side with marked differences.

A secondary consideration was that the study by Archambault et al. [9] was performed on graphs with no node or edge titles. Moreover, participants had to answer multiple-choice questions, instead of asking participants to select nodes and edges directly. This effectively removed any visual search time. The authors argued that such questions are preferable as animated nodes may move rapidly, which would disadvantage some layouts. Therefore, and as confirmed by the authors, their results cannot be generalized to tasks that involve named nodes. I wanted to address this limitation, as named nodes are important in many applications. The unenhanced dual view technique in my first user study targets this visual search time issue.

Previous studies also investigated effects globally across *multiple* versions of a graph by displaying everything simultaneously. My new difference layering technique compares only *two* versions of a diagram. With my incremental layout the locations of nodes remain stable across different versions. Hence, I investigate the effect of presenting the version pairs sequentially in this condition, to see if participants can better trace the evolution of the graph. In the first user study, I also ask participants to select nodes and edges, as I want to observe how the techniques affect the understanding of the variations in layout. Finally, unenhanced side-by-side text differencing is tedious and I wanted to investigate if this is also true for diagrams.

3.3.1 The Diagrams

In both studies I used versions of a diagram, which depicts the evolution of a subset of course prerequisites in Computer Science program at York University over the past two decades. This is a classic real-world application for diagram evolution. I excluded almost all instances without a change in prerequisites, but kept one to serve as a control. In total, I ended up with 12 versions of the diagram. From among these I selected a set of six version pairs, which cover all qualities, such as the magnitude of change in the number of nodes and edges: 1→3, 3→4, 4→5, 5→8, 8→10, 10→12. For brevity, I will refer to them as pairs 1 to 6 from here on. The second pair did not have any changes and is designed as a control. The diagrams appearing in the left view had on average 26.5 nodes ($\delta = 1.52$) and 23.66 edges ($\delta = 1.21$), and 27.33 nodes ($\delta = 1.21$) and 24.17 edges ($\delta = 1.47$) in the right. Figures of diagram pairs for both optimal and incremental layouts are included in Appendix A. Videos of the tasks are available at the *DARLS* website[19]. As I wanted to focus on the understanding of graph structure, I did not include changes in node titles in the studies.

3.3.2 Statistical Models

Analysis of variance (ANOVA) is a collection of statistical models and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. In all the analyses that appear in this chapter, I used a repeated measures ANOVA model with significance level of 0.05 (α=0.05), i.e., a chance of 1 in 20 of making a type I error, i.e., incorrectly rejecting a true null hypothesis. This is the norm for the field of Human-Computer Interaction research. The result of an ANOVA is based on the *F* statistic, named after Sir Ronald A. Fisher, and the corresponding probability value *p*. If a test of significance gives a *p* value lower than the α-level, the null hypothesis is rejected. Such results are informally referred to as “statistically significant”. The Tukey–Kramer method is a single-step post-hoc multiple comparison procedure and statistical test generally used in conjunction with an ANOVA to identify which means are significantly different from one another. It compares all possible pairs of means and identifies where the difference between two means is greater than the standard error would be expected to allow. In my analyses we used the Tukey-Kramer post-hoc test to reveal groupings, whenever the ANOVA results were significant.

[19] http://sites.google.com/site/thedarlssystem

3.3.3 Participants

Sixteen participants (five females) were recruited for both studies. The participants were between 18 and 35 years old with an average of 23.82. Four participants were left-handed but all chose to use their right hand for the experiments. Seven participants indicated that they were aware or had previous experience with text, diagram, source code differencing, or versioning tools. One participant used them regularly. None of the participants had previous experience with *DARLS*. None of the participants were color-blind or had difficulty reading small text. Participants reported an average of 6.1 hours ($\delta = 2.8$) of daily mouse use.

All participants performed both studies in counterbalanced order, but due to an implementation issue, the data for the first four participants in the second study had to be discarded.

3.3.4 Apparatus

The user study was conducted using a high-end laptop with a USB wheel mouse and a 22” external display at 1920×1080 in full-screen mode. All events, timings and responses were logged.

3.3.5 Pilot Study

In a pilot study, I asked four unpaid participants to select objects that were added in a newer version of the diagram, similar to User Study I below. The results indicated that the dual-view condition without layering was the slowest overall. Direct change highlighting was the best, but here the task degenerated to selecting all highlighted targets, without requiring any understanding of the diagram evolution. Hence, I removed this condition from User Study I. This may limit ecological validity, as one wants the system to highlight differences, but I am unaware of a good way to avoid this degeneration issue in experiments.

I also observed that when participants did not read the node labels, certain tasks became unsolvable. A good example is the unenhanced pair 4 in the optimal layout, where the added MAST 1090 node was often confused with the deleted MAST 2090 node due to both nodes appearing at the same level next to each other and having the same number of edges. As the result, some participants could not identify the change. Hence, I instructed participants to carefully pay attention to node labels in the studies.

3.3.6 User Study I

This user study investigated how different visualization techniques help in understanding the evolution of diagrams with matching layout. At any time, two versions of a diagram were shown and participants were asked to select all nodes and edges that were added to the newer version relative to the older one.

3.3.6.1 Experimental Design

I used a 4×2×6 repeated measures design (4 differencing techniques, 2 layouts, 6 version pairs). The four tested differencing techniques were single view with animation, single view with toggling between versions, dual view with difference layer, dual view without difference layer. The layouts used were incremental and optimal. In the incremental condition, I used the layout as created by the original designer of the diagrams and only re-arranged changes incrementally while keeping the original node positions. As the original layouts were created manually in an incremental fashion, the node positions for any pair matched in sequence. The optimal method re-arranged the whole layout and the settings for that method are summarized on the *DARLS* website.

The intent was to compare four distinct differencing techniques in a use case with matching node positions, while also investigating the effect of layout techniques. Especially in the dual view technique with no difference layer, no visual aids were available to participants, and any effect of layout should thus be most prominent in this condition.

3.3.6.2 Procedure

When the experiment started, all layouts for all version pairs were calculated and the zoom level was set so that zooming and/or panning was not necessary. In fact, it was disabled to remove a potential confound. This also guaranteed consistent size of nodes and edges across all layouts and diagrams. In the incremental layout condition, I presented pairs sequentially to allow participants to trace the evolution since this is complimentary to fixing the node positions. Otherwise, version pairs were presented randomly without replacement to combat learning effects. Technique and layout were also counterbalanced, but I blocked the order of techniques to reduce participant confusion.

In the single-view animation condition participants were asked to click on the nodes and edges that were new to the latest version of the two diagrams displayed. Participants could click on an object again to toggle selection. Moreover, a "deselect all" button was available in the top panel. Rectangle and lasso selection methods were not available to limit the effect of different experience and/or selection strategies. For the animation condition new nodes and edges were faded in and the deleted ones faded out automatically upon first display. A re-play of the animation happened whenever the users pressed the <Left Arrow> key. Pausing was not provided due to the short animation duration. Selection of nodes and edges was enabled even during the animation. During the pilot study all animations lasted about 2 seconds, and users found this duration appropriate. In all single-view conditions only the right view was used and nothing was displayed on the left side. At any given time, no more than 12 objects were animated (see the *DARLS* website for details).

In the single-view toggling condition, holding the <Left Arrow> key down switched the right view to display the previous version of the diagram. Just like in the animation condition, participants were allowed to toggle between versions as many times as needed. Participants were instructed to select new nodes and edges when the newer version was displayed. The dual-view without difference layer condition was basically the dual-view equivalent of single-view toggling. The two versions of the diagram were displayed side-by-side and participants had to select the new nodes in the right view. The dual-view with difference layer condition featured a difference layer in both views, which illustrated all differences. Since the positions of common nodes matched due to the relative re-layout, only added and deleted objects were displayed on the difference layer. Moved, i.e., shifted nodes, were excluded. When the participant clicked on any object in the right view, which was visible in the difference layer in the left view, the selection state was also shown on that left view.

Participants were asked to press the <Right Arrow> key when they thought that they were done with the task. If the current state did not match the expected result, the window blinked red and a sound was played. Participants would then have to modify their selection and submit the result again. I logged every such attempt. The submit key was disabled unless at least one change to the selection was made to prevent abuse of this feature. Based on observations from the pilot and if a participant was not able to complete the task within 2 minutes, the right side view would blink in yellow, a different sound would play and the next task would start. If a participant selected everything correctly, the right view would blink in green upon the key press and the next task would start. Whenever there was a change in the differencing technique an appropriate message box would pop up with instructions. Participants were allowed to take a break during that time. Logging only resumed once they clicked the <OK> button.

In the pilot study, I found that it is important to inform the participants before the study that there be could a situation when there is no change in the diagram, such as version pair 2, and I informed participants accordingly. I also stressed in the initial training that common nodes always had matching positions.

3.3.6.3 Results

No ordering effects were observed. For brevity, insignificant results or groupings are reported only selectively below. The main effects of differencing technique, $F_{3,45} = 104.06, p < .0001$, and version pairs, $F_{5,75} = 53.15, p < .0001$ on task completion time were significant. The layout factor was insignificant, $F_{1,15} = 0.03$, ns. There was also a significant interaction between differencing technique and version pair, $F_{15,225} = 6.93, p < .0001$ and layout technique and version pair, $F_{5,75} = 14.90, p < .0001$. The interaction between differencing technique and layout was not significant, $F_{3,45} = 1.18, p > .05$, thus any hypothesis about the potential effect of layouts was not confirmed.

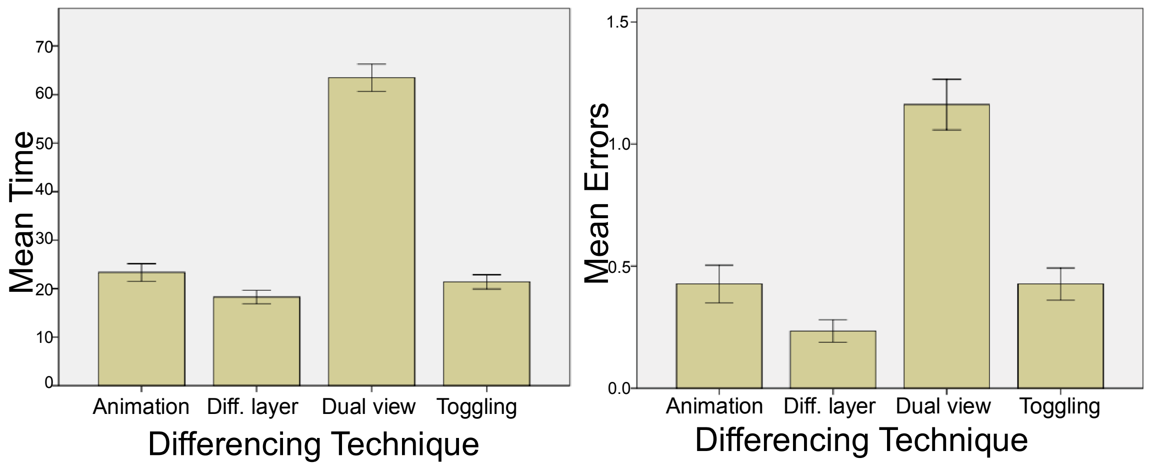


Figure 3-5. Mean time in seconds and error rate for the techniques in User Study I. Error bars: ±1 SE.

A Tukey-Kramer analysis revealed that dual view with no difference layer was significantly slower (average 65.5 s) than any of dual view with difference layer (18.3 s), toggling (21.4 s) and single view with animation (23.3 s). See Figure 3-5 (left). Another Tukey-Kramer analysis was performed to detect version pair groupings. Pair 2 (10.7 s), i.e., the unchanged one, was the fastest and different from the group of pairs 3 (21.4 s) and 5 (30.3 s), which again was different from the group with pairs 1 (50.6 s), 4 (50.7 s) and 6 (43.7 s). An analysis on the interaction between differencing technique and version pairs revealed that the dual view without differences was slowest overall, except for pair 2.

A Tukey-Kramer analysis on the interaction between layout technique and version pair revealed no difference between incremental (6.1 s) and optimal (7.2 s) layouts on pair 2, the one without differences. However, pair 6 showed a marked interaction effect. Here, incremental layout was significantly slower (40.2 s) than the optimal one (30.9 s). To investigate this in more detail, I analysed the frequency of false negatives for each of the two layouts. I found that for the incremental layout of pair 6, the top-ranked false negative nodes were COMP 3403 (64 counts), COMP 3481 (47) and COMP 3214 (45). The same nodes in the optimal layout were also ranked at the top, but with exactly 12 counts each. The top-ranked false negative edges in the incremental layout were: COMP 2031→3215 (40 counts), COMP 3213→ 3481 (32). The same edges in the optimal layout were also at the top and had counts of 21 and 28, respectively. I did not perform the same analysis on false positive nodes and edges due to insufficient sample size.

I used the number of “submit” attempts as a measure of error rate. For these, the main effect of differencing technique, $F_{3,45} = 25, p < .0001$ was significant, but layout was not, $F_{1,15} = 0.06$, ns. Tukey-Kramer revealed that dual-view with no difference layer had the most attempts (1.16) on average, which was different from the group of dual view with difference layer (0.23), toggling (0.43), and animation (0.43). See Figure 3-5 (right).

3.3.6.4 Feedback from Participants

Participants were asked to rank each of the four diagram differencing techniques on a Likert scale from 1 to 7 (7 being the best). The results are summarized in Figure 3-7 (left).

In freeform feedback I received several interesting comments. One participant pointed out that when the conditions changed, it took a few trials to get used to the new one, despite the explicit instructions on each condition change. Another stated that the greyed-out objects in the difference layer “caught his eye”, but that he found animation confusing. Yet another identified the dual-view condition without a difference layer as particularly hard, but got only gradually used to the difference layer visualization. One participant pointed out that toggling was somewhat confusing. Another participant said that the dual view with the difference layer was the easiest to use, as it was easier to see what was missing. The same participant also stated that toggling made it easier to identify missing parts and animation was sometimes confusing. Another found animation more difficult as he kept choosing the nodes that were removed instead of the new nodes.

3.3.6.5 Discussion

Dual view without difference layer was the slowest technique, which is not surprising. Similar to text differencing, showing two versions side-by-side does not make it easy to spot differences. On the other hand and as underscored by the pilot, highlighting differences makes identifying them easy, but helps little for understanding changes. Overall, the results illustrate that toggling and animation are good techniques which are well liked, but not by everybody. For example, I noticed that some participants got confused about which state permitted selection in the toggling condition. This was also reported in the feedback.

No significance was found for the layout factor. Thus, presenting pairs sequentially with incremental layout either did not help or had only an insignificant effect. The effect of differencing techniques on layout was also insignificant. The significant interaction with the version pairs indicates that rigourously preserving node positions may even be detrimental to understanding diagram evolution. One issue is that this can cause node overlap, which leads to participant complaints. However, diagram creators may need this option, so it cannot be discounted completely. To investigate the interaction of layout and version pair, I took a closer look at pair 6 diagrams and found that participants missed the same nodes and edges more often than any other pair in both layouts. However, the frequency of misses was much higher with the incremental layout. The two most frequently missed nodes had no edges attached. In the optimal layout, these two nodes were placed in a very conspicuous cluster at the bottom. For edges the same pattern was observed. I speculate that the longer average edge length in the incremental layout and/or more edge crossings and/or the absence of edge bridge connectors resulted in higher miss rates. Yet, this may also point to fundamental limitations of incremental layout techniques.

In hindsight, I should have considered shorter animations. Transition intervals of 0.25 to 1s have been found insignificant in zooming interfaces [94]. This finding may apply to my tasks, too.

3.3.7 User Study II

This user study compared two visualization techniques to identify shifted nodes in two versions of a diagram with *non-matching* layout. Participants were asked to select nodes that moved in the newer version of the diagram relative to the older version. Here, selecting edges was not investigated.

3.3.7.1 Experimental Design

I used a 3×2×6 repeated measures design (3 techniques, 2 node randomization levels, 6 version sets). The 3 tested techniques were single-view animation, dual view with difference layer, and the combination of dual view with difference layer with animation. The motivation for including the difference layer is the reject/accept technique in *DARLS*. Unlike the first user study I did not include view toggling or unenhanced dual views as initial evaluations showed that those conditions take too much time to be used in my experiment. For this study, I first laid out each diagram with the optimal hierarchical re-layout algorithm with the same node placement heuristics as in the first user study. Then I used a graph randomization algorithm, which shifts a percentage of random nodes in random directions while retaining a minimal distance constraint between nodes to prevent overlap. For simplicity, my algorithm does not employ any node placement heuristics and does not optimize for edge crossings or bends. However, I do not believe this is a major issue since my goal was to simulate scenarios when a user rearranges nodes in a diagram, which may generate substantial edge crossings. I shifted 22% or 44% of all nodes. I used the same six version sets as in the first study. I also used the same randomization seeds for all layouts to keep them consistent across participants. Counterbalancing was done similarly as in the first user study.

The intent of the design was to compare my difference layer method with animation and to see if participants would use my method if given the choice between the two. Initially, I intended to include more randomization levels but in the interest of keeping the experiment length reasonable I selected to use only two.

3.3.7.2 Procedure

Similar to the first user study, participants were allowed to select nodes while they were being animated. The <Left Arrow> key was also available for (re-)playing the animation in the single and dual-view animation conditions. The dual-view with difference layer condition was the same as in the first study. I informed participants during the training session that one possible strategy is to use the difference layer to match the selection of the nodes on the foreground in the right view with the reduced yellow color nodes on the background in the left view. Pair 2 was the one with the no structural changes and had 28 common nodes. This means that at any given time no more than 28 × 44% = 12 nodes were animated. In the combined condition, animation played automatically when new diagrams were loaded to remind participants that they could use animation. All the remaining aspects of the procedure were identical to the first user study.

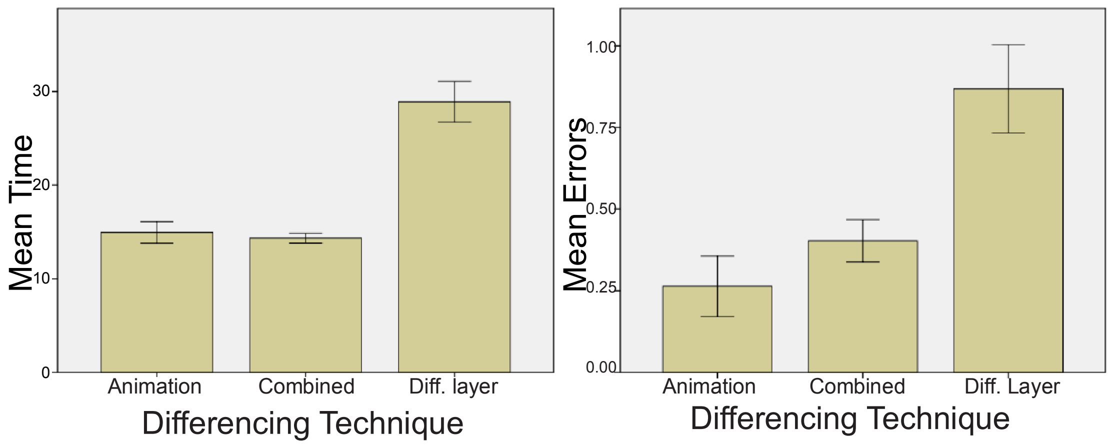


Figure 3-6. Mean time in seconds and error rate for the techniques in User Study II. Error bars: ±1 SE.

3.3.7.3 *Results*

No ordering effects were observed. The main effects of technique $F_{2,22} = 11.08, p < .0005$, randomization level, $F_{1,11} = 11.57$, $p < .001$, and version pair, $F_{5,55} = 4.15, p < .005$ on task completion time were significant. The interaction between randomization level and technique was also significant, $F_{5,55} = 4.94, p < .001$. A Tukey-Kramer analysis revealed that the difference layer alone (average 28.9 s) was slower than both animation (15 s) and animation with difference layer (14.3 s). The 22% node randomization level (14.5 s) was different from the 44% level (24.3 s), see Figure 3-6 (left). The error rate data in this experiment was not normally distributed, therefore I decided to just report the averages, see Figure 3-6 (right).

I used a Kruskal-Wallis test on the number of re-play key presses for both animated conditions, as this data was not normally distributed. This identified a significant difference,

$H_1 = 38.09, p < .0001$. Animation alone had an average of 174 button presses while the animation with difference layer had 114.

3.3.7.4 Feedback from Participants

Participants were asked to rank the techniques similar to User Study I. The results are summarized in Figure 3-7 (right).

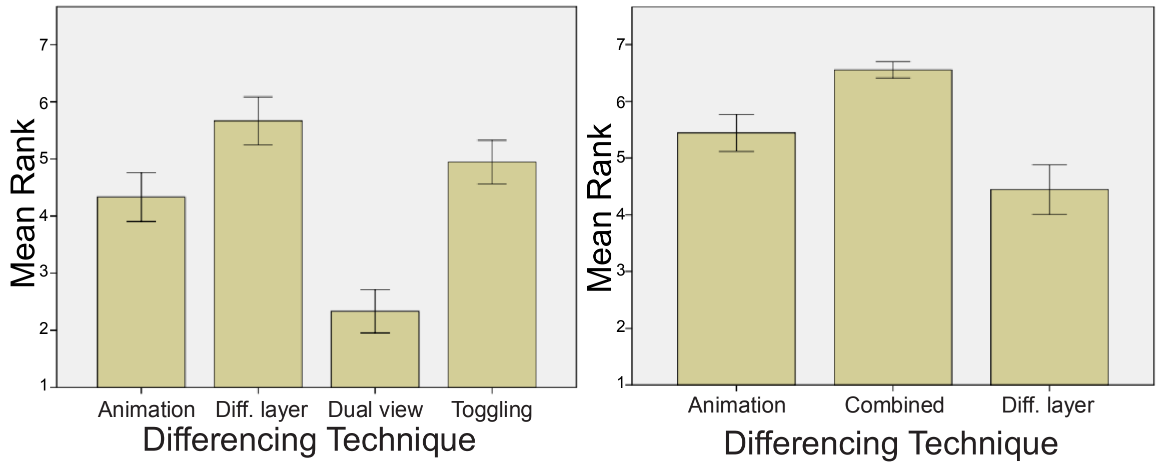


Figure 3-7. Participants' ranking of the differencing techniques in User Study I (left), User Study II (right). Error bars: ±1 SE.

Here are some of the most mention-worthy comments from the freeform feedback. One participant stated that animation helped to see the changes and moving objects could be identified even when he was not directly looking at them. Another participant found it difficult in the difference layer condition to find a node shifted slightly because the background node would be hidden under the foreground node due to overlap. Others pointed out that nodes that moved a little in the animation condition were harder to identify as well. Several participants said that for selecting the moved nodes it was easiest to use animation. They also clicked on nodes as they moved. Relative to that they pointed out that the difference layer method was harder to use, but still allowed one to check the "results" of the animation. One participant found the animation speed a bit slow. Another participant said that it would be nice to have a "shadowed" mouse cursor in the "dual-view" panel.

3.3.7.5 Discussion

Although the difference layer method itself was the slowest, it still contributed positively overall, as the combined method was both fastest overall, although not significantly so, and most preferred. Another indication for the benefits of the difference layer is the result on the re-play key presses. Also, and as revealed by the rankings, some participants found this to be the easiest technique.

During the experiment, I noted that some participants were confused about how to use the difference layer and were either trying to select objects on the background of the right view or objects that were not different. This indicates that this method might not work well if both views are fully interactive. On the other hand, I also saw that animation alone is not a perfect solution to easily identify nodes that moved just a little. To investigate this, I analysed all instances where participants failed to identify a moved node. For all 679 false negatives, the average movement distance was 83 pixels while the median was only 69 pixels. A node in the experiment was 30×80 pixels large. Since the median is smaller than the mean I can argue that participants had more trouble with nodes that moved less. This indicates that none of the techniques are perfect in isolation.

3.3.8 Overall Discussion

In my first experiment where node positions matched, the dual-view technique with difference visualization was the fastest technique overall and had the least amount of errors. It was also ranked highest in terms of user preferences. In my second study with partially non-matching node positions, animation and the combination with the difference visualization technique was best.

It is not easy to compare my work directly with Archambault et al. [8,9], as many details are different. But I do not believe that my findings contradict their work. The participants, for example, also preferred the difference layers in the first study and made fewer errors with them. However, the difference layer was not preferred in my second experiment. Archambault et al. also stated in earlier work that a small number of timeslices (such as two) are not enough to represent the evolution of a graph adequately. My findings generalize this insight to diagrams with named nodes.

Both of my layout methods were designed to preserve the mental map. The optimal layout was based on aesthetics, but the incremental layout preserved the mental map more faithfully. Hence, the incremental condition in the first study would show the effect of mental map preservation best in my context. However, and as I did not find significant effects of layout, this suggests that mental map preservation is not effective, similar to [9].

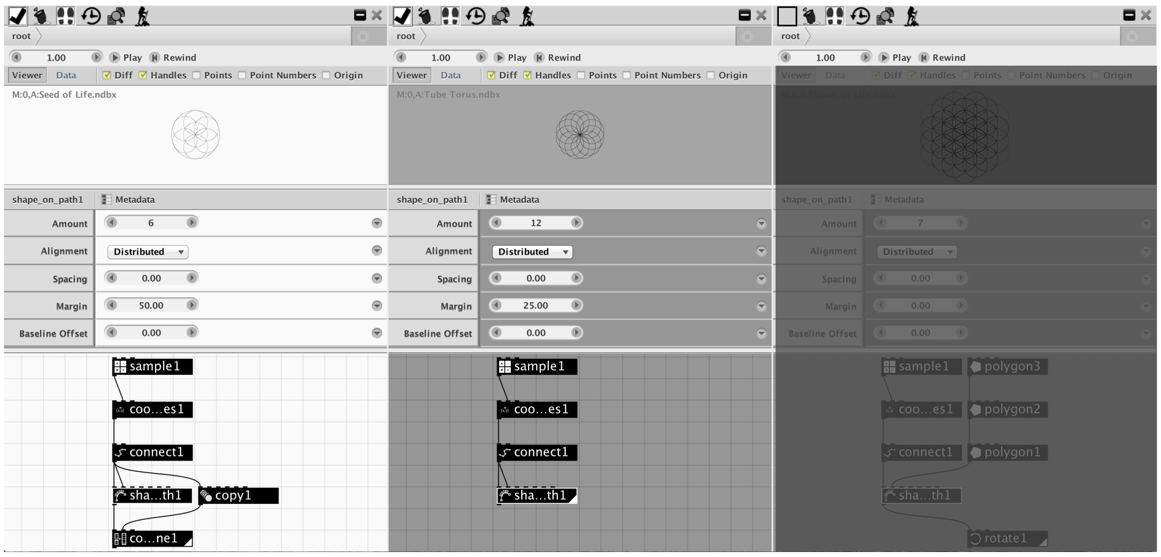
Heer and Robertson [55] found that animated transitions between statistical visualizations work well and that staged transitions are preferred. Similarly, my first study suggests that animated transitions in diagram differencing tasks are preferred.

Naturally, the results of the first user study are only directly valid for hierarchical diagrams laid out top to bottom. My results may not generalize to other types of diagrams. Many other factors can influence the results and I even observed an interaction between layout and the version pair. On the other hand, I believe the results of the second study are more generalizable, because they depend less on the layout technique.

3.4 Summary

In this chapter, I presented a new system for diagram difference visualization and merging. It uses animation, dual views, a storyboard, relative re-layout, and difference layers. I ran two user studies to investigate the benefits of the system and found that naïve dual-view visualization is not desirable. The dual-view option with a difference layer was most preferred for comparing diagrams with matching node positions. For diagrams with non-matching positions, I found evidence that animation is beneficial, but that the combination with a difference layer was liked best. In summary, I can say that my difference layer technique is useful and is a good complement to animation. This has positive implications for the diagram merging method introduced above. To better support dataflow programming for alternatives, I re-implemented this method in *GEM-NI*. The findings of the user studies here favour approaches that use a stable layout, which again informed their usage in *GEM-NI*. I also later adopted the difference layer with translucency technique for difference visualizations in the subtractive encoding in *MACE*.

Chapter 4
GEM-NI: A System For Creating and Managing Alternatives In Generative Design



M:0,A:Seed of Life.ndbx
shape_on_path1
Amount 6
Alignment Distributed
Spacing 0.00
Margin 50.00
Baseline Offset 0.00

M:0,A:Tube Torus.ndbx
shape_on_path1
Amount 12
Alignment Distributed
Spacing 0.00
Margin 25.00
Baseline Offset 0.00

shape_on_path1
Amount 7
Alignment Distributed
Spacing 0.00
Margin 0.00
Baseline Offset 0.00

Figure 4-1. *GEM-NI* enables users to work with alternative generative designs simultaneously. Specifically, *GEM-NI* provides tools to manage the set of alternatives affected by edit operations, post-hoc merging of (parts of) alternatives, and several ways to create new alternatives, such as resurrection of past states with full undo lineage duplication or selection from an enhanced design gallery implementation. The leftmost alternative is the original design and is active, the center one is passive, and the rightmost one is idle.

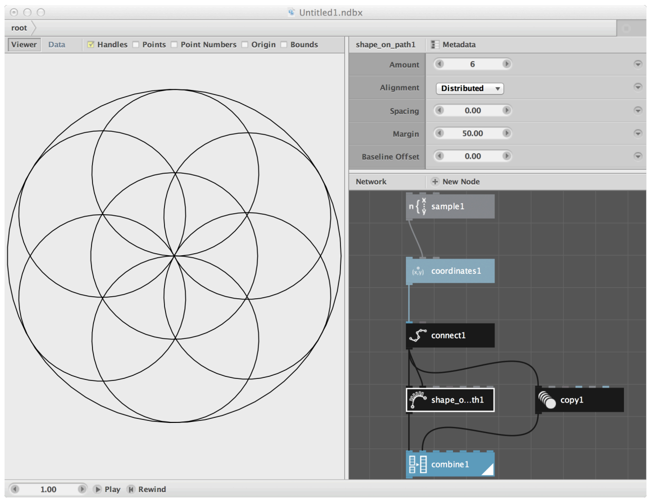
In this section, I describe the *GEM-NI* system and my findings from its evaluations.

Using the example in Figure 4-1 I demonstrate the capabilities of *GEM-NI*. Imagine that Ann, a designer, is tasked with creating a design for a book cover. To match the book content, she initially selects the "Seed of Life" pattern and recreates it in *GEM-NI*, by using three nodes (SAMPLE1, COORDNIATES1, CONNECT1) to create a circle. She then distributes copies of the circle along the same circular path (SHAPE_ON_PATH1), Figure 4-1 left. As the result does not seem complex enough, she goes back in the operation history and generates a new clone from an earlier state. After some parameter variation, she arrives at the "Tube Torus" design shown in Figure 4-1 center. Not entirely satisfied, she branches this design again to create a third, where she uses repeated polygons to arrange the circles in a more complex pattern, the “Flower of Life”. She could also have initiated this design as a branch from the history of the left-most design, which would then constitute a non-linear design process. Next, Ann creates several more alternatives using the Cartesian product (not shown in Figure 4-1) and uses individual and linked editing to tune the designs’ parameters and manages them in the workspace. Throughout this, she uses local and global undo to correct mistakes. Merging is illustrated with another worked example below.

Encouraging exploration of a design space with parallel alternatives in design tools is a subject of current research. Outside of generative design, some of the concepts used in *GEM-NI*, such as parallel editing, checking and sandboxing, were introduced in the recently presented *CAMBRIA* system [64], where the authors apply these ideas to regular 2D vector graphics design. However, I am not aware of any mainstream end-user tools that support this approach to design exploration for generative design. Thus, I ran a user study with moderately and highly skilled users to investigate the appropriateness of my approach by gathering feedback and understanding the implications of parallel editing on their design process.

4.1 GEM-NI

The name *GEM-NI, Generative Many-Nodes Interpreter*, is inspired by the many-worlds interpretation in quantum physics. It implies that all possible alternative histories and futures are real, each representing an actual “world”. I focused on 2D graphics, a domain that offers sufficient complexity for common issues and patterns in generative modeling to emerge, yet still practical for user studies. Also, *GEM-NI* supports exploratory design tasks widely used in the design literature and in HCI in Green’s cognitive dimensions of notations [42].



Amount 6
Alignment Distributed
Spacing 0.00
Margin 50.00
Baseline Offset 0.00
1.00

Figure 4-2. The original interface of *NodeBox 3*.

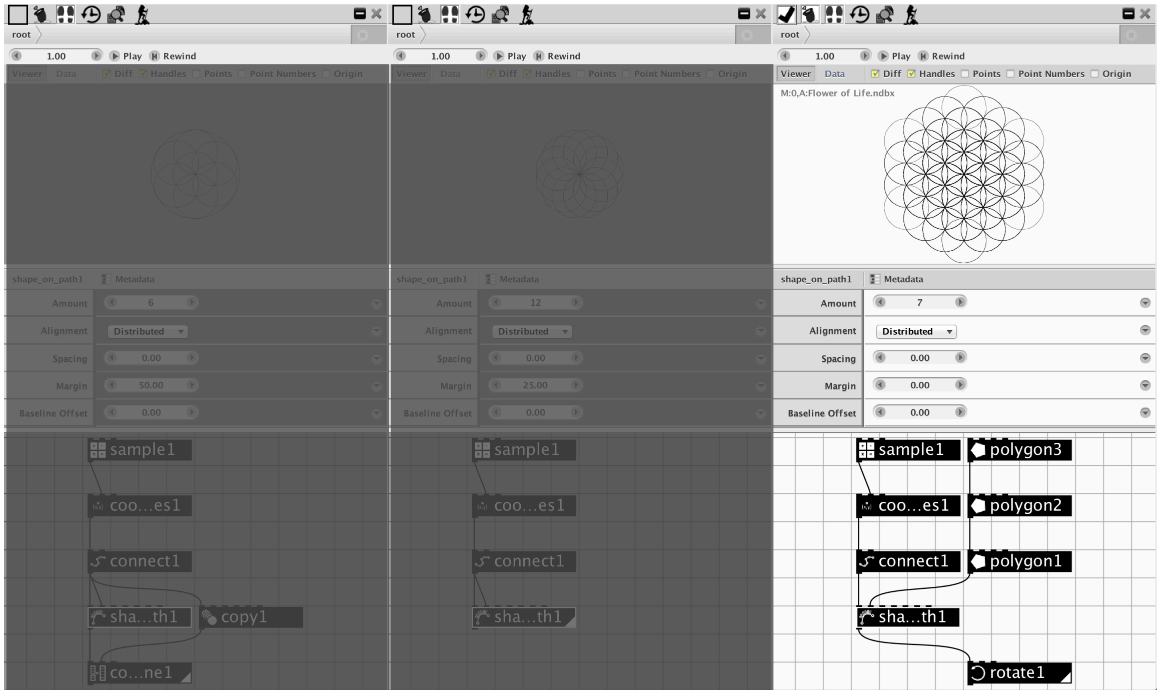
GEM-NI is capable of handling a large number of alternatives, the exploration of which is only limited by screen size, processing power and memory. It is also limited by the complexity of the models and the size of the dependency graphs. Each alternative is hosted in a panel. Panels are contained in one or more *workspace(s)*, which can be saved. Figure 4-1 shows such a workspace with three alternatives. Multiple workspaces may be open at the same time. The panel for each alternative consists of three views: output, parameter, and network view. To facilitate side-by-side viewing of alternatives, *GEM-NI's* panel layout differs from that of *NodeBox 3* (Figure 4-2). In *GEM-NI* views are stacked vertically: output on top, parameters in the middle, and network view at the bottom. The order in which alternatives appear on screen can be re-arranged by drag and drop using a modifier key, with preview and target location highlighting. In the conceptual design phase, designers routinely generate dozens of sketches. That amount of content is difficult to fit onto a single monitor, if all alternatives are still to be viewable and editable. To aid the designer in keeping an overview of all considered alternatives, to organize them, and to view them side-by-side for visual comparison, I support multi-monitor setups in *GEM-NI*. In a preferences menu, the user can select from 1×1 to (currently) 2×3 monitors. The workspace is then re-arranged to spread all alternatives as evenly as possible for the chosen monitor arrangement. Within each monitor, horizontal space is evenly distributed.

In *GEM-NI* the creation of nodes, their positions, parameter values as well as selection state are synchronized by default across all editable alternatives. Thus, moving a node or changing a node parameter affects all of its instances in other editable alternatives. Such parallel editing can be enabled or disabled, see below. I found that uniformity in network layout makes it easier for designers to identify common elements and to compare networks visually across alternatives. E.g., SHAPE_ON_PATH1 in Figure 4-1 was selected in the leftmost alternative and is now selected everywhere with the corresponding parameter views. For the same reasons, zooming and panning on the network and output view are also synchronized. Every operation is accessible through the menu bar. Important ones are also accessible through GUI buttons or keyboard shortcuts.

4.1.1 Parallel Editing

The most common use case for parallel editing is parameter variation in a design. Ann might use parallel editing to change the size of multiple alternatives, which saves having to repeat the operation in each one. Or she might add a new node that adds a background rectangle to all designs. In *GEM-NI* she can control which alternatives are *idle*, i.e., non-editable, through *checkmarks.* Selecting an alternative makes it *active*. All other checked alternatives are *passive* and thus subject to parallel edits. Often, Ann wants to focus only on a single alternative, i.e., work in a *sandbox*.

A workspace typically contains multiple passive and idle alternatives. The active one, Figure 4-1 left, is shown in bright gray. Passive alternatives, Figure 4-1 middle, are shown in a mid-tone gray, and idle (unchecked) ones are dark gray, Figure 4-1 right. An alternative is activated simply by clicking anywhere on its panel, or by switching to it via the TAB key. Newly created alternatives are set to passive, permitting parallel editing. Editing an alternative makes it active and pushes changes to all passive alternatives. Idle alternatives remain unchanged. Pushed changes include all operations in the network view (e.g., creating, renaming, deleting, connecting or disconnecting a node), all operations in the parameter view (e.g., tweaking a parameter of the node), and all operations in the output view (e.g., moving or resizing a shape by direct manipulation). Sandboxing addresses the case when the designer wants to focus her edits on only a single alternative (Figure 4-3). This functionality simply idles (unchecks) all other alternatives. Both checkmarks and sandboxing are accessible through GUI buttons (✓ and , see Figure 4-3) or through modifier keys when clicking on an alternative. The “mute” and “solo” buttons in audio and video software, such as Adobe *Audition CC* and Apple *Final Cut Pro X*, inspired my checkmarks and sandboxing.


shape_on_path1
Amount 6
Alignment Distributed
Spacing 0.00
Margin 50.00
Baseline Offset 0.00

shape_on_path1
Amount 12
Alignment Distributed
Spacing 0.00
Margin 25.00
Baseline Offset 0.00

M:0,A:Flower of Life.ndbx
shape_on_path1
Amount 7
Alignment Distributed
Spacing 0.00
Margin 0.00
Baseline Offset 0.00

Figure 4-3. The alternative on the right is sandboxed. The first two alternatives are therefore idle.

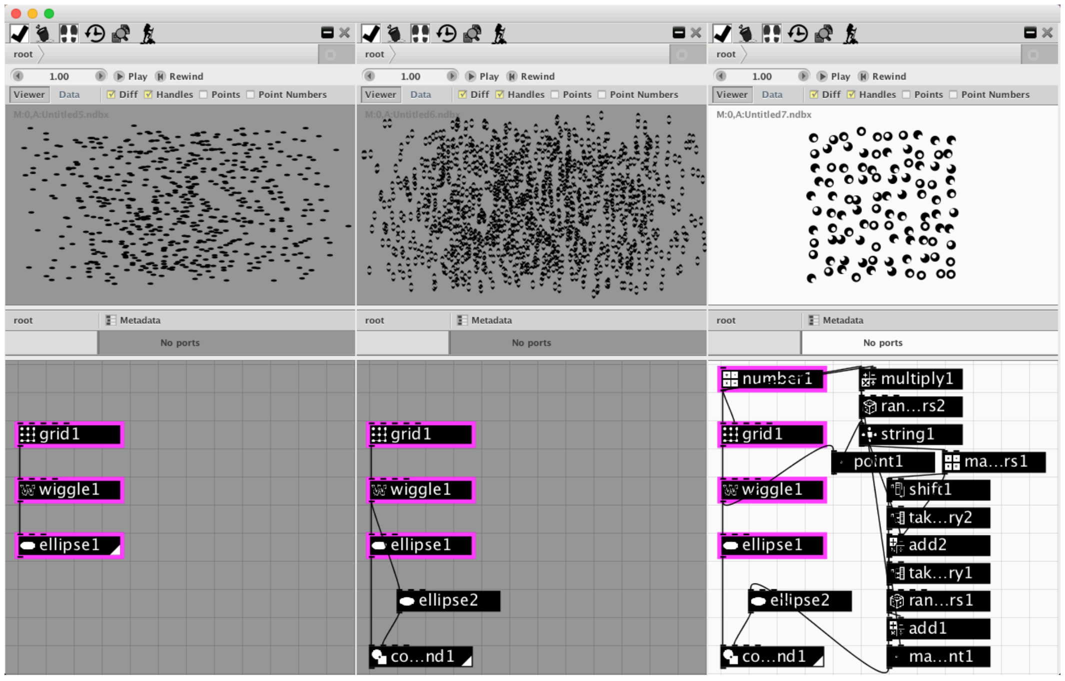
4.1.2 Local and Global Undo

GEM-NI supports two types of undo: local and global. Local undo refers to undo in the currently active alternative. Global undo undoes in all checked alternatives in the workspace. A dedicated global undo and redo stack, in addition to local undo and redo stack, is used to ensure the correct parallel sequence of local undo and redo operations on each involved alternative, which compose the global undo or redo operation. Performing local undo or redo clears the global undo stack to avoid undo synchronization problems. A more powerful undo system, e.g., [33], could address this limitation. I did not implement this for simplicity.

4.1.3 Selective Merging

Designers frequently branch out to explore different alternatives. Sometimes they then want to re-use new parts in other alternatives. Figure 4-4 illustrates a merging scenario in *GEM-NI*. Inspired by Brownian motion, Ann first created a grid with randomly displaced ellipses (Figure 4-4a left). She then created an alternative that uses a compound of an ellipse and a circle (center). Subsequently, she created a slightly more structured 10×10 grid of compound circles (right). Looking at this, she likes the result of the GRID1, WIGGLE1, and ELLIPSE1 nodes in the right design as well as the capability of varying the size of the grid through the new NUMBER1 node. Thus, she merges these four nodes into the other two alternatives. This overwrites the parameters of existing nodes and creates the NUMBER1 node with connections to GRID1 in the other two alternatives. Note that a copy operation would not recreate these specific connections. She then changes the size of the grid in all three alternatives to 15×15 (Figure 4-4b) with parallel editing.

Consider another simple merging scenario in *GEM-NI*. Ann first created the color spectrum design on the left in a 5×5 grid (Figure 4-5a). Subsequently she created two gridded color palettes, each branching from the previous alternative. When working on the last one in sandbox mode, Ann realizes that she can re-use the same number (5) as input for five nodes. Thus, she creates the number node ROWS (highlighted with a red ellipse) and connects it appropriately. This enables Ann to control the grid size and the detail level of her design simultaneously. Instead of manually recreating this node in other alternatives, she *merges* the change into the other ones. This creates ROWS in all other alternatives and also connects it to all common nodes. Note that a copy operation would not recreate these connections. A parallel edit of ROWS to 20 then creates a finer spectrum and palettes (Figure 4-5b).

(a) 

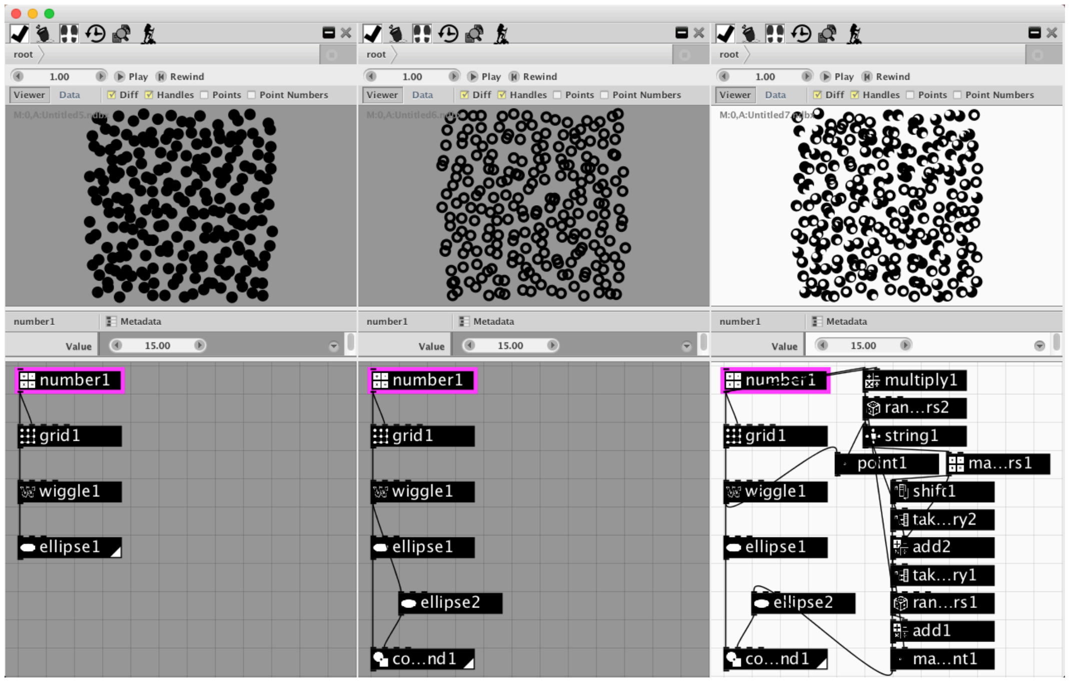
(b) 

Figure 4-4. Merging and parallel editing: (a) Initial state with highlighted nodes selected for merging. (b) Merging replicates new nodes and connections into all other alternatives and overwrites parameters of existing nodes. The user then globally changes NUMBER1 to 15.

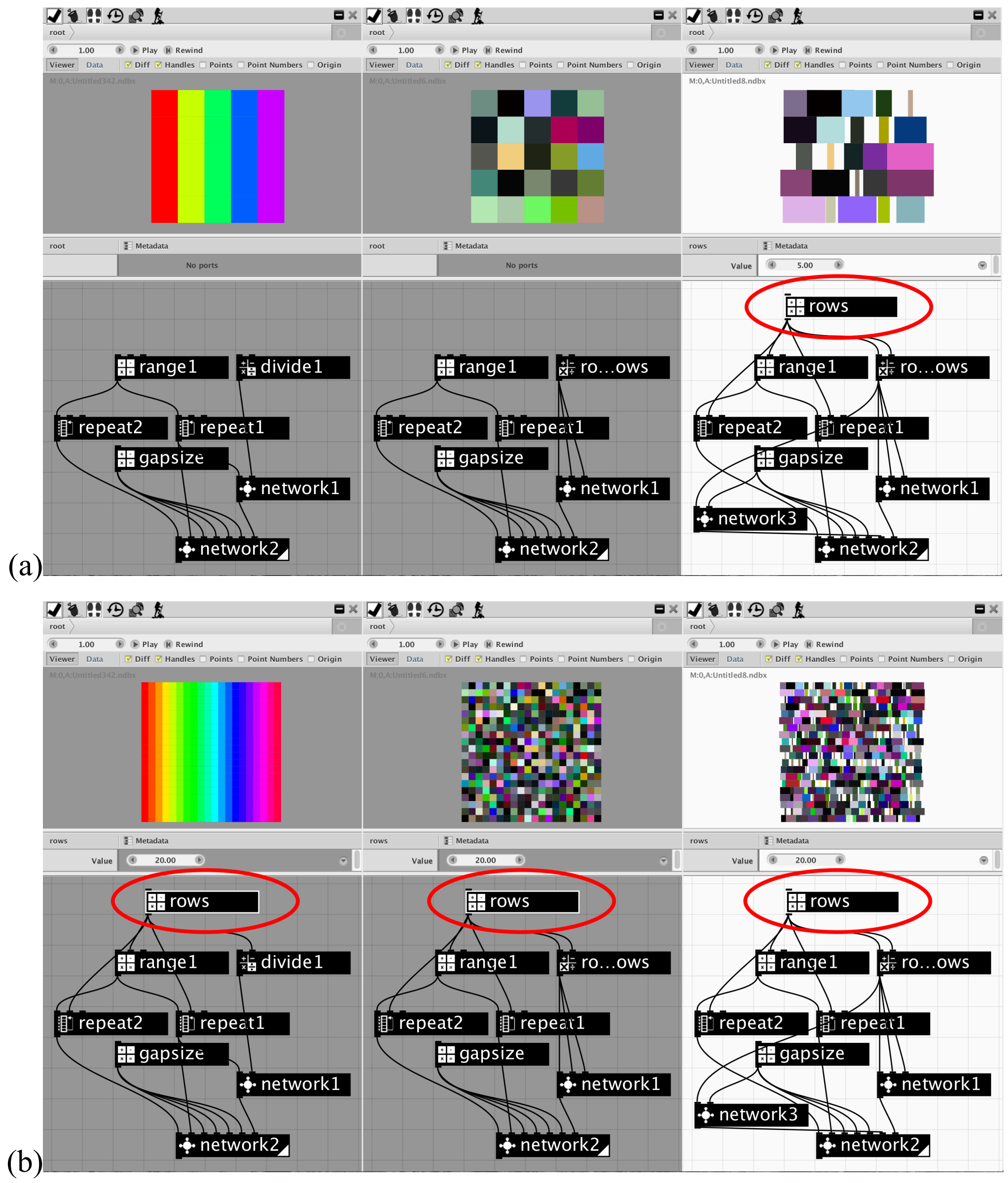


Figure 4-5. Merging and parallel editing: (a) Initial state with new, selected node highlighted. (b) Merging replicates the node and connections into all other alternatives. The user then changed the parameter to 20.

Selective merging is a new mechanism to ensure that parts of a design can be *post-hoc* integrated into other alternatives. *GEM-NI* implements this by *overwriting* the state of the *selected* nodes across all passive alternatives. This is different from standard copy & paste, which will *duplicate* existing nodes. When merging, nodes that do not exist are created and connected suitably in the passive alternatives. Parameters of common nodes are overwritten from the active alternative. This may create conflicts, which the user needs to address later. Performing merging on the complete network essentially turns all alternatives into clones (with potentially different undo history stacks). Ability to selectively overwrite individual parameter states is also supported (see 5.1.4.3). My technique is inspired by the corresponding functionality in source code management, mainly *Git*.

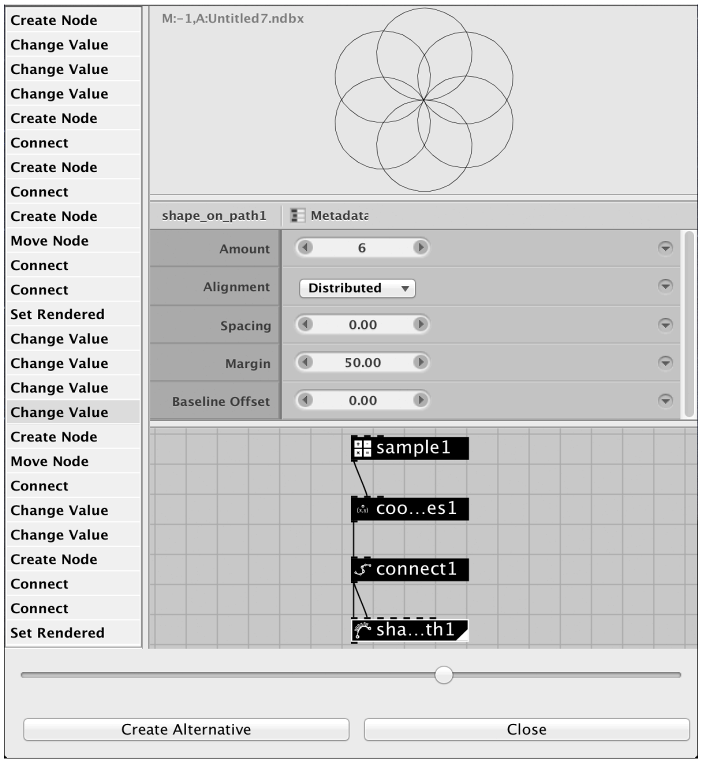
Below is pseudo code for the selective merging algorithm, without undo handling.

```
1: procedure merge()
2:     for all passive alternatives passive
3:         for all selected nodes node in passive
4:             if passive is not idle
5:                 comment: overriding parameters and adding nodes and connectors
6:                 if node already exists in passive alternative
7:                     update node in passive alternative by overriding parameters
8:                 else
9:                     instantiate a new copy of the node (and its children, if applicable) in passive alternative
10:                end if
11:                comment: connect this node
12:                for all inbound or outbound connections of the node in the active alternative
13:                    duplicate connections in passive alternative
14:                end for
15:            end if
16:        end for
17:    end for
18: end procedure
```

4.1.4 Creating Alternatives

Creating new empty alternatives is standard functionality. During branching/cloning, and in contrast to most other work, *GEM-NI* preserves the undo stack, which enables Ann to undo operations in both alternatives. In the example in Figure 4-1, Ann branched an alternative design from an intermediate version of her initial one. Usually this meant either relying on intermediate saves or using (destructive) undo to go back in time. In *GEM-NI,* she can use the resurrection dialog to scroll back in time and select a starting point for a new exploration.

Also, the enhanced interactive design gallery in *GEM-NI* enables Ann not only to explore the variational design space but also to create new variations for the *structure* of the network. This makes it easier for Ann to quickly explore a larger set of designs.



Create Node
Change Value
Change Value
Change Value
Create Node
Connect
Create Node
Connect
Create Node
Move Node
Connect
Connect
Set Rendered
Change Value
Change Value
Change Value
Change Value
Create Node
Move Node
Connect
Change Value
Change Value
Create Node
Connect
Connect
Set Rendered

M:-1,A:Untitled7.ndbx

shape_on_path1

Amount	6
Alignment	Distributed
Spacing	0.00
Margin	50.00
Baseline Offset	0.00

Figure 4-6. Dialog for creating an alternative from history: the history list on the left and the state of the alternative at that time on the right. The current entry is highlighted. The state can be selected from the list directly or by dragging the slider.

4.1.4.1 Branches

An alternative can be created as a branch through cloning, where the entire network from the active alternative is copied to the newly created alternative, along with its undo lineage. This can be interpreted as an adaptation of *skating* [107] to generative design. The new alternative then appears to the right of the active one. Preserving the undo stack upon cloning enables new use cases, as the user can now undo operations in both alternatives.

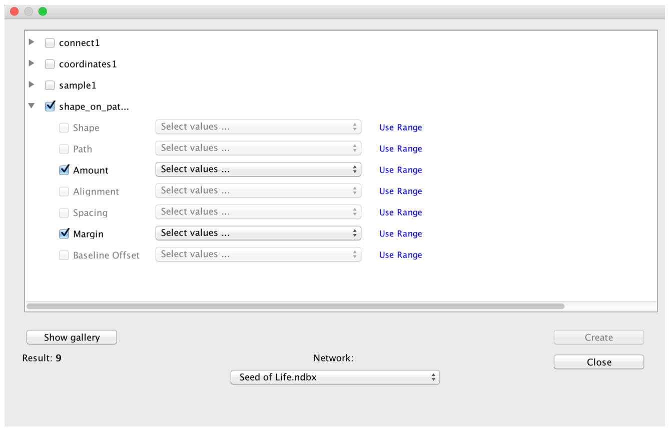
4.1.4.2 Resurrection from History

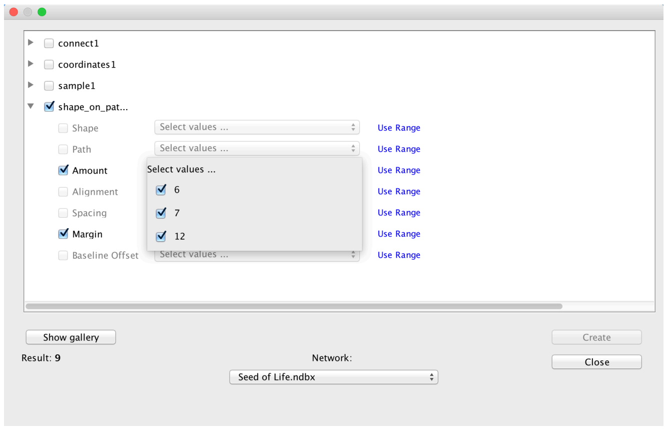
Creating alternatives from history, i.e., resurrecting past states, enables Ann to look through her past work and to select particular points in time from which she intends to “branch out” and to explore new alternatives. This happens in *GEM-NI* through a dialog (Figure 4-6). There, all states from the undo history are listed on the left, with a time slider on the bottom. Clicking on a list item or scrolling shows a preview of the corresponding state on the right. Clicking the “Create Alternative” button then instantiates the selected state as a new alternative in the workspace next to the active alternative. In Figure 4-6, the past state in the history of the left design of Figure 4-1 is highlighted, from which the second alternative was branched out. The dialog enables the user to create more than one alternative at a time. As with branching, *GEM-NI* clones the history stack on a resurrection from history. Together with the history previews this provides an enhanced form of *skating* [107].

4.1.4.3 Design Gallery

I implemented an interface for creating alternatives from a design gallery, inspired by the parametric Cartesian product in *Dialer* [96]. My interface extends *Dialer* in several ways, most importantly by supporting structural products. Figure 4-7 shows the Cartesian product dialog and Figure 4-8 shows a design gallery for Figure 4-1. Starting with the scenario in Figure 4-1, Ann now wants to explore the design space more widely. For this, Ann first selects (with a modifier key) two or more alternatives as the basis for the Cartesian product. This outlines these alternatives with a red frame. In the example in Figure 4-7 and Figure 4-8 all three alternatives from Figure 4-1 are included in the product. Upon modifier key release, the main dialog appears (Figure 4-7a), which shows Ann all nodes of the alternatives in a nested list, with the second level denoting the parameters. To streamline the workflow, only common nodes whose parameters differ between the selected alternatives are selected for the product by default and expanded. SHAPE_ON_PATH1 is the only common node with different parameters (*Amount* and *Margin*) in the three alternatives in Figure 4-1. The GUI elements then permit Ann to include or exclude nodes. Similar to *Dialer* [96], it also permits her to include or exclude parameter values from the set of values that were identified as different among the three alternatives that were included in the Cartesian product. Clicking on the list menu corresponding to the identified differing parameter displays the differing values (Figure 4-7b). In this example *Amount* is differing in all three alternatives, so there are three values to choose from for inclusion/exclusion in the Cartesian product. This mechanism is similar to *Dialer* [96]. To give Ann an idea of how many potential results to expect, *GEM-NI* shows the number of designs that would be generated at the bottom left. In Figure 4-7b, Ann can expect a total of nine alternatives in the hysterical space, which is produced by matching three values for *Amount* {6, 7, 12} with thee values for *Margin* {0, 25, 50}. Thus the hysterical space H in this case is $H = \{\{6,0\},\{6,25\},\{6,50\},\{7,0\},\{7,25\},\{7,50\},\{12,0\},\{12,25\},\{12,50\}\}$. Going beyond *Dialer* [96], *GEM-NI* also enables Ann to specify the range over which parameters should vary. For ranges she can configure the minimum, maximum and step size. In Figure 4-7c, Ann specifies a range of 0 to 50 with step 1 for *Margin*, instead of the initially detected set {0, 25, 50}. Note that the number of expected alternatives has increased substantially to $|H| = 51\times3 = 153$. In general the algorithm for finding the hysterical space is described below:

```
1: procedure findHystericalSpace()
2:      Initialize set $H = \{\emptyset\}$
3:      Initialize set $P = \{\emptyset\}$
4:      find set $N$ of nodes $v \in \{v: v \in N\}$ such that $N = \bigcap_{i=1}^{n} N_i, N_i \in G_i$, where $G$ is a set of $n$ networks $G_i$ that were preselected for inclusion in the Cartesian product
5:      for each node $v \in \{v: v \in N\}$
6:          for each parameter $p \in \{p: p \in parameterOf(v)\}$
7:              Find a subset $G_p \subseteq G$, $|G_p| \geq 2$ of all networks $G_i$ each having unique $valueOf(p)$
8:              Initialize set $S = \{\emptyset\}$
9:              for each $\gamma \in G_p$
10:                 $S.add(\gamma.valueOf(p))$
11:             end for
12:             $P.add(S)$
13:         end for
14:     end for
15:     Build hysterical space $H$ by matching each element of $S \in P$ to the other element of $S \in P$ uniquely for all members of $P$.
16: end procedure
```

(a)


(b)


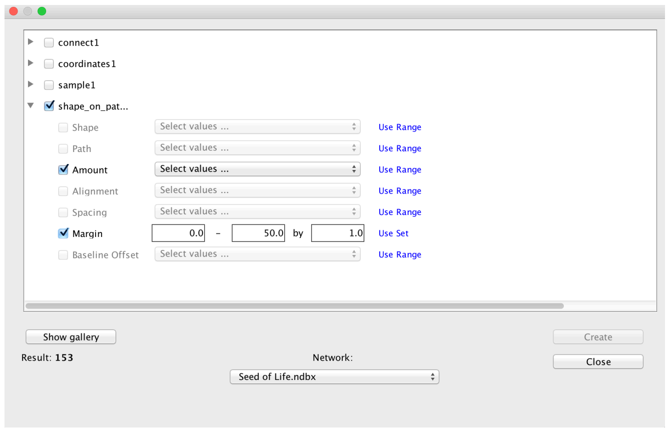
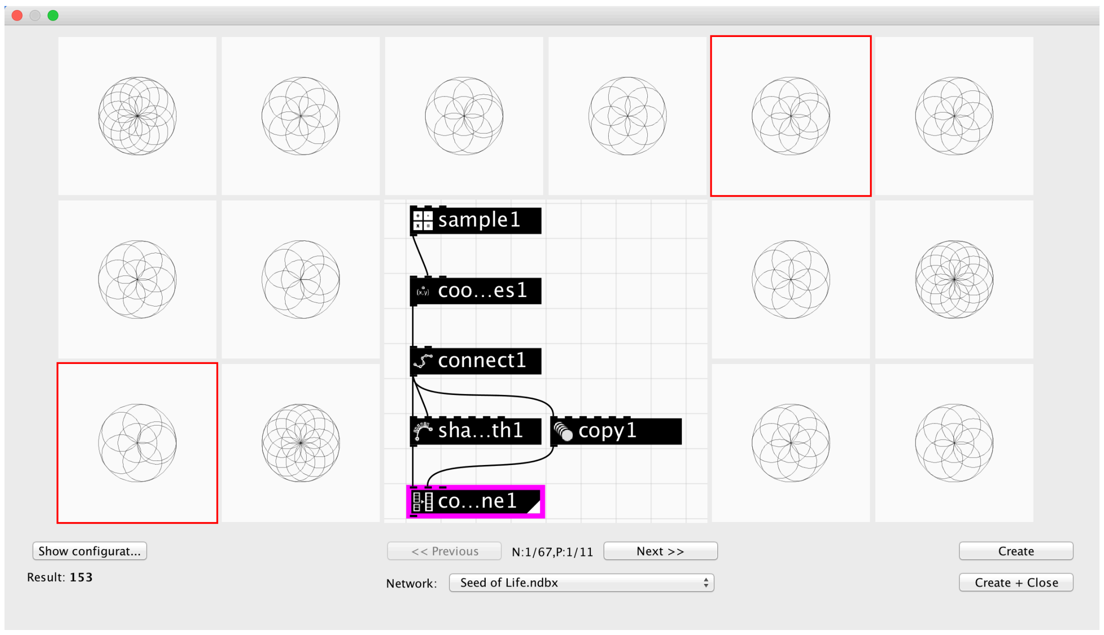
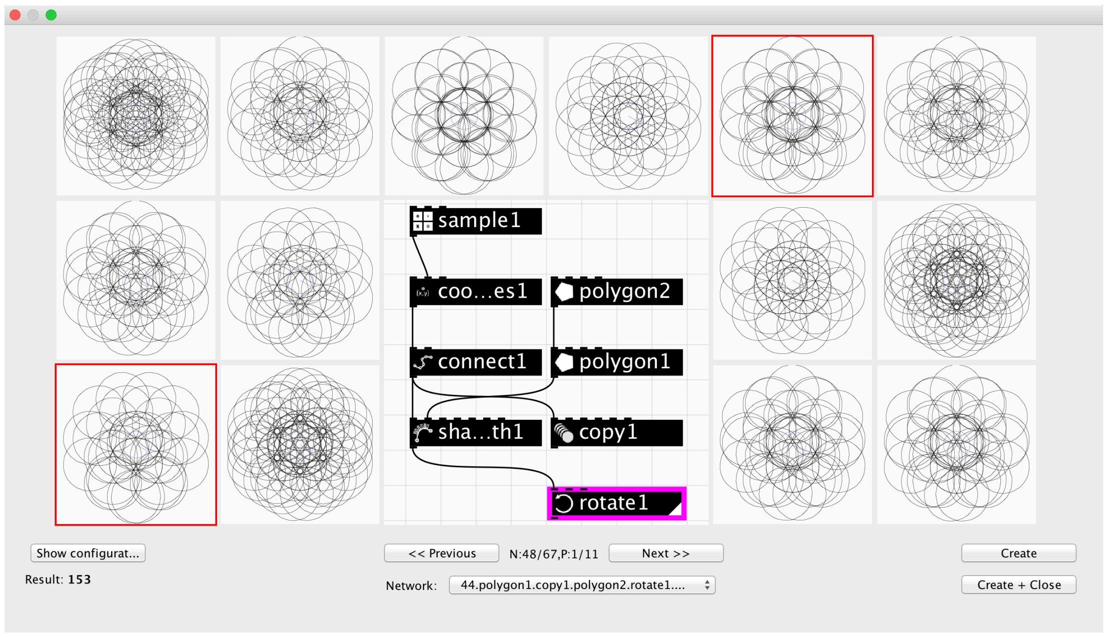
(c)


Figure 4-7. Cartesian product dialog. (a) Cartesian product menu: all nodes of the alternatives are in a nested list, second level denotes the parameters; (b) inclusion/exclusion of parameters in Amount; (c) specifying range for Margin.



(d)



(e)

Figure 4-8. Design gallery. (a) two previewed designs selected in the default network; (b) two previewed designs selected in a network resulted from the product of all three generative networks.

When satisfied with the settings, Ann presses the "Show gallery" button, which displays the results of the Cartesian product (Figure 4-8a) in a dialog that enables the user to scroll through all pages of results with the "Previous" and "Next" buttons. She then selects two previewed designs by clicking on them and presses the "Create" button to instantiate the selected designs as new alternatives, which appends them as the last alternatives on the right side of the workspace. For reference, the design gallery shows the network of the first selected alternative in the middle, but enables Ann also to view other selected networks. Optionally, the *GEM-NI* design gallery can be invoked on a single alternative. In this case the gallery will operate in range only mode.

Finally, Ann can explore even more potential designs by exploring different *structures* for the networks of the generative model. In other words, Ann can create candidates not only for products on parameter values, but also for products of generative networks. For this my new Cartesian product algorithm first identifies all nodes that are different in the alternatives. Then *GEM-NI* constructs their power set and substitutes each into the network common to the alternatives. I implemented this algorithm as follows. In order to create a product of two networks *G* and their nodes *N* and edges *E*, $G_i = (N_i, E_i)$, I create the union $N_{diff} = N_1 \backslash N_2 \cup N_2 \backslash N_1$ of the two sets of node differences $N_1 \backslash N_2 = \{v: v \in N_1, v \notin N_2\}$ and $N_2 \backslash N_1 = \{v: v \notin N_1, v \in N_2\}$. I then calculate N_{diff}*'s* power set $\wp(N_{diff})$ of size $2^{|N_{diff}|}$. Then, for each node in the set $v_j \in \{S: S \in \wp(N_{diff})\}$, I construct a generative network $\gamma_j \in G_1 \times G_2$, where we recreate connections via $connect\left((G_1 \cup G_2) - v_j\right)$. The $connect$ procedure attempts to create connections from every port $p_i \in \{v_i: v_i \in inputNode(v_j)\}$ to all compatible ports $p_k \in \{v_k: v_k \in outputNodes(v_j)\}$. This procedure generalizes to more than two networks via $N_{diff} = \bigcup_{i=2}^{n} N_1 \backslash N_i \cup N_i \backslash N_1$ (all differences are determined relative to the first network G_1), $\gamma_j \in \prod_{i=1}^{n} G_i$, and $connect\left((\bigcup_{i=2}^{n} G_i) - v_j\right)$. It's worth mentioning that group nodes, which represent sub-networks, are treated as completely different nodes between two or more alternatives, if at least one difference in the parameter or structure of the sub-network or sub-sub-network (and so on) is detected. Therefore, they are also part of N_{diff}. The cross product then substitutes them just like any other node from N_{diff}. Since there are a total of six node differences among the three alternatives in Figure 4-1, $2^6 = 64$ networks are created. Ann can then scroll through all designs generated by varying both the network as well as the parameters or select a specific network from a drop-down list. E.g., in Figure 4-8b, she has selected a generated network that consists of three substituted nodes: POLYGON1, COPY1, POLYGON2, and ROTATE1. In the example shown in Figure 4-8 there are 64 generated networks with 153 parameter variations. Thus this design gallery contains over ten thousand potential alternatives.

Below is the pseudo code for the implementation of this algorithm in *GEM-NI*. This code omits the generation of names for each new network created. The implementation consists of two methods, which were added to the code base of *NodeBox 3*. These are *createPowerSets()*, which create power set of alternatives from Cartesian products of networks of selected alternatives, and *deleteAndReconnect()*, a method which deletes a given nodes and reconnects its incoming and outgoing connectors to other nodes whenever possible.

```
1: procedure createPowerSets()
2:     Initialize empty sets newSet, missingSet and diffGroupSet, which will contain new nodes, missing nodes, and group nodes that changed.
3:     Initialize a pointer to referenceAlternative, arbitrarily picked from the Cartesian product list of alternatives.
4:     Initialize an empty set powerSetAlternatives, which will contain the result
5:     for all selected alternatives alternative in Cartesian product other than the referenceAlternative
6:         copyOfAlternative = make a copy of alternative;
7:         Identify all new, missing nodes and changed group nodes of the copyOfAlternative relative to referenceAlternative
8:         for all new nodes n
9:             comment: re-use of the selective merging method
10:            $copyOfAlternative.$overrideAndAddNodesAndConnectors$(referenceAlternative, n)$
11:        Add the found new, missing and changed group nodes to the sets initialized in the beginning (newSet, missingSet and diffGroupSet)
12:    Calculate the power set $\wp(N_{diff})$ of changed group nodes.
13:    Initialize groupNodeOccurences hashtable to keep track of group nodes with identical UUIDs.
14:    for all sets of nodes $v_j$ in the power set $\wp(N_{diff})$
15:        if this is a group node with previously encountered UUID
16:            update groupNodeOccurences
17:            continue
18:        else
19:            initialize groupNodeOccurences
20:        copyOfReferenceAlternative = make a copy of referenceAlternatve;
21:        for all nodes n in $v_j$
22:            if n is not a group node
23:                $copyOfReferenceAlternative.$deleteAndReconnect$(n)$
24:            else
25:                Replace the node with the same name as n in copyOfReferenceAlternative with n
26:        $powerSetAlternatives.$add$(copyOfReferenceAlternative)$
27:    return powerSetAlternatives;
```

```
procedure deleteAndReconnect(Node $node$)
    connections = get all connections for this network
    comment: trying to connect as many connections as possible from the deleted to the new node
    for all $c$ in connections in this network
        comment: incoming connections
        if $c$.input() $==$ $node$
            comment: for all outgoing connectors
            for all $c2$ in connections in this network
                if $c2$.output() $==$ $node$
                    try connect($c$.output(), $c2$.input())
        comment: outgoing connections
        else if $c$.output() $==$ $node$
            comment: for all incoming connectors
            for all $c2$ in connections in this network
                if $c2$.input() $==$ $node$
                    try connect($c2$.output(), $c$.input())
    removeNode($node$)
```

4.2 Evaluating GEM-NI

Evaluating specific features of the system, such as e.g., the difference visualization techniques does little to confirm external validity and the benefits of the system as a tool for generative design and creative work, as these are non-linear processes with a strong creative component. Comparing each new feature in *GEM-NI* with the corresponding feature in existing tools, similar to an evaluation of a new CAD system against another one (e.g., as in [81]), does not seem possible because there is currently no roughly comparable system. So one could only compare against the traditional workflow, where I hypothesize that dealing with alternatives is associated with an increased workload due to the higher management/interaction effort. This becomes evident when one considers the number of operations necessary to achieve tasks associated with creating and managing several alternatives simultaneously.

A more systematic approach for the evaluation of creative work systems has been proposed by Cherry and Latulipe [24]. They developed the Creativity Support Index (CSI), a psychometric survey designed for evaluating the ability of a creativity support tool to assist a user engaged in creative work. It consists of a rating scale section and a paired-factor comparison section. The scale section of the CSI measures six factors of creativity support: Exploration, Expressiveness, Immersion, Enjoyment, Results Worth Effort, and Collaboration. For each factor, there are two agreement statements. Having two statements per factor improves the statistical power of this survey, as it allows researchers to look at the reliability for each factor by examining the similarity of the scores across the two different statements. The paired-factor comparison section consists of each factor paired against every other factor for a total of 15 comparisons. It is designed to reveal important factors. Therefore, the CSI enables researchers to understand not just how well a tool supports creative work overall, but what aspects of creativity support may need attention. From among the CSI usage scenarios identified by Cherry and Latulipe, in my evaluation I am using the scenario of *tool comparison, same task, repeated measures***.** I designed a study in which participants complete a somewhat similar creative task using *NodeBox 3* and *GEM-NI*. Participants complete the CSI's agreement statements after completing the task in each tool and complete the paired-comparison section once, at the end of the study.

4.3 User Study I

To confirm the appropriateness of the presented techniques for the design process, I evaluated *GEM-NI* in two steps: a workshop with an exploratory design study, and follow-up in-depth interviews. The workshop introduced *NodeBox 3* and had the goal to gather feedback on *GEM-NI* from a user group moderately experienced in generative design.

4.3.1 Participants

Five unpaid participants (2 female) from graduate students were recruited through a "session on new generative design tools" announcement at Simon Fraser University. I targeted participants experienced with generative design, since *NodeBox* is challenging to use for non-designers. Coffee and cookies were offered as incentive. Participants design backgrounds were: architectural, sound, visual, and information design, as well as arts. One participant had to withdraw during the workshop due to an appointment. The participants were between 21 and 31 years old (μ=27.2). All were experienced designers (μ=5.7 years). One participant reported experience with generative design tools, namely *Grasshopper*, another knew *Processing*. None knew *NodeBox*. In the pre-questionnaire, all reported that they routinely create multiple alternative designs as opposed to a single solution. All stated that when they design, they regularly keep track of, review, and revisit their design iterations. For that, participants reported the following methods: saving multiple files (even for minor changes), creating files from scratch for major conceptual changes, using a stylus with a note taking application, various combinations of shuffling between files, sketches, tracing paper, and images, and keeping everything in a notebook and/or printouts, including intermediate artifacts.

4.3.2 Apparatus and Procedure

Workstations with dual monitors running *Windows 7* were used. Blank sketch sheets and pens were supplied. The workshop was split into two phases, followed by a one-on-one in-depth interview with participants at a later date. Along with logging and interviews, I used the Creativity Support Index (CSI), a quantitative, psychometric tool in form of a survey to assess how well both systems assist creativity in the design process. In both phases participants completed the CSI questionnaire after the creative task. Collaboration was not rated.

4.3.3 The Workshop

In the first workshop phase participants were taught a basic version of *GEM-NI,* feature-wise equivalent to *NodeBox 3,* i.e., without my new contributions, and called *NodeBox* for the remainder of this section. I picked examples from a generative design book [19] as tasks. I first demonstrated how to create six designs and asked participants to recreate them on their workstations. This took about one hour. This familiarized participants with the system to enable them to perform the main creative task. Said task was a design scenario, where participants had a client that wanted them to come up with an "algorithmic shapes" design for a small front door window, about 20×20 cm. The client expected options to choose from. Participants then used *NodeBox* to create a number of alternative designs and saved them as different files. Participants were free to sketch with pen and paper, as necessary, and were given 30 minutes for the task.

In the second phase, participants first learned how to use *GEM-NI*. All above-presented features of the system were demonstrated on the example in Figure 4-1, which they recreated from scratch. This took one hour. The second task stipulated that their client saw the alternative designs for the door window and liked the designs so much that she asked the participants to extend these designs to cover the entire door. Participants could reuse their designs from the first task. This scenario was chosen for the task because it highlights the iterative nature of the design process, since the designers in this case are required to re-iterate on their previous creations through the feedback from their client. They were given 30 minutes to complete the task and again permitted to sketch. After completing the second CSI questionnaire they also filled the paired comparison part of the CSI. Since the tasks in my study were similar enough, I performed the CSI evaluation as a within subject tool comparison with the same task.

4.3.3.1 Results

The small number of participants limits the strength of my results. Also, I evaluated the tools in a fixed order. Yet, counterbalancing is difficult, as *GEM-NI* is based on *NodeBox.* Looking at the first phase, I noted that several participants had already created alternatives in a *single document* in *NodeBox* (without prompting!) through the ability to create multiple output nodes. This likely reduces the "cool tool" bias and verifies that designers already *plan for alternatives*, even in current tools. These participants had primed themselves to learn *GEM-NI* quickly. Two participants, P1 and P4 created four alternatives with *GEM-NI*. All designs of P1 differed only in parameters, but not structurally. P4 came up with several designs that were structurally different. The logs showed that both P1 and P4 used branching to create their alternatives and worked non-linearly, i.e., went back and forth between alternatives. I also logged five instances where P1 rearranged the order of alternatives.

Another participant, P3, created two alternatives and accessed the history and design gallery, but did not create alternatives with those methods. Only one person was observed to use pen and paper briefly.

4.3.3.2 Results of the CSI Questionnaire and Discussion

Task	Factor \ Scale	Enjoyment	Exploration	Expressiveness	Immersion	Results worth effort
1	Avg. Factor counts (σ)	2.5 (1.7)	3.8 (1.5)	4.0 (0.8)	2.3 (1.3)	2.5 (1.3)
1	Avg. Factor score (σ)	13 (2.5)	11.3 (2.5)	9.0 (4.3)	6.5 (1.3)	11.5 (2.4)
1	Avg. Weighted factor score (σ)	34.8 (30.6)	41.0 (15.5)	36.5 (18.4)	15.3 (9.6)	27.0 (11.2)
2	Avg. Factor counts (σ)	2.5 (1.7)	3.8 (1.5)	4.0 (0.8)	2.3 (1.3)	2.5 (1.3)
2	Avg. Factor score (σ)	14.8 (2.8)	15.8 (1.5)	14.0 (3.2)	10.0 (7.1)	13.3 (5.0)
2	Avg. Weighted factor score (σ)	37.0 (28.9)	59.8 (25.5)	56.8 (20.5)	28.8 (34.8)	32.3 (20.1)

Table 4-1. User Study I: Average results from first task using *NodeBox* (top)*;* second task using *GEM-NI* (bottom).

The CSI analysis, revealed an average score of 51.5 ($\sigma = 13.5$) in the first task and a substantially higher score, 71.5 ($\sigma = 12.84$), for the one where *GEM-NI* was used (N = 4 for both tasks). These results depend to some degree on individual's preferences and their level of expertise with the tool. Similar to [24], I report the results with respect to average factor counts, factor score and weighted factor score (Table 4-1). Average counts express the number of times that participants chose a particular factor as important to the task. Expressiveness and exploration were ranked as most important. The factor score sums both agreement statement responses for a factor. A higher number indicates better supports. Weighted factor scores are more sensitive to the factors that are the most important ones for the given task. In both dimensions, *GEM-NI* scored again much higher for expressiveness and exploration.

4.3.4 In-Depth Interviews

I ran in-depth interviews with three of the participants (P1-3) in the days after the workshop. At the start of the interview, participants were given a short review of the features of *NodeBox* and *GEM-NI*. Then they were asked to continue working on the second task with *GEM-NI*. In a variant of a think-aloud protocol, I asked participants to express their opinions during this, to make comments on the tools, to provide feedback on the overall workflow and experience, and to explain why they made their decisions. P1 and P2 completed the interview in a little over two hours. Participant P3 was only able to dedicate 30 minutes. Overall, participants used many more features of *GEM-NI*.

P1 created two alternatives from history. When asked about this feature, P1 pointed out "creating alternatives from history is superior because I like the idea of being able to pick something from the actual history, which could contain ideas that were not further developed". This is in contrast to the alternative workflow of branching and deleting of unwanted parts of the graph, where he added "[with this] some steps might not be captured, such as creation and deletion of connectors and partial editing of nodes". During the interview, P1 produced designs that were different both structurally and in parameters. In the end, P1 created seven designs in a non-linear way through branching. He also created an alternative from a design gallery and two from scratch. I logged deletion of six alternatives. He re-ordered alternatives 30 times and used global undo once. P2 created five designs in two workspaces and saved some of his alternatives individually and then opened them in a new workspace. He re-ordered alternatives seven times, created two alternatives from scratch and five non-linearly as branches and used merging. P2 deleted six alternatives. P2 was not able to leverage design galleries, as his design had very subtle variations in only two parameters and thus "the results shown in the gallery were [almost] identical". P3 created five alternatives in a single workspace in a short time, through a design gallery, which P3 found to be "a great way to explore possibilities". P3 deleted one alternative and rearranged alternatives 21 times.

All participants were observed using the two available monitors. It was important to their workflow to focus on a single alternative. Therefore, all dragged idle and passive alternatives to the secondary monitor, to increase the workspace for the active alternative. This generated many instances of rearranging. P1 and P2 had programming skills and stated: "*GEM-NI is like version control [systems]*". They drew on their experience with *Git* and used *GEM-NI* somewhat like a version control system for design, which enabled them to experiment more. P3 was not familiar with software version control and thus did not have the corresponding mental model. P2 demonstrated an unexpected use of my system. He created multiple sub-graphs as alternatives, where the output of all sub-graphs was rendered inside a single *GEM-NI* alternative. Then, he started using the panels as means to explore even further alternatives. In the freeform feedback, he later wrote: "*I encountered some unexpected designs while using [GEM-NI], which made things much more interesting than I had first imagined. Interactive [parallel] editing had very interesting results*". P2 worked always on a single alternative at a time and perceived parallel editing of multiple alternatives at the same time "*to be hard*", likely due to the increased cognitive effort required for such parallel tasks. This corresponds to the experience with *Juxtapose* [53], which requires strong coding skills. Only one participant was observed to use global undo.

All participants complained about aspects of *NodeBox* and to a lesser degree about *GEM-NI's* features. Most criticism revolved around the fact that focusing is not automated enough. They found rearranging panels to be hard and wished for an easier workflow. I did not focus on streamlining this specific task. Participants also asked for some difference visualization that "*would highlight changes in the rendered geometry and network*". They also preferred that sandboxing be the default work mode, and that parallel editing only be available on demand (opposite to my default). Finally, participants P2 and P3 wanted to minimize or collapse alternatives, instead of being confronted with all of them simultaneously. They suggested a side window or panel that "*shows alternatives in a way* *similar to the design gallery*". They also identified that they would like alternatives that are collapsed to automatically turn idle.

4.4 Discussion

Here I discuss some of the consequences of the design decisions behind *GEM-NI*, as backed by the outcomes of the workshop and the in-depth interviews. *GEM-NI* supports a number of ways to create alternatives. I include adapted and enhanced variations of results from previous work, such as *Parallel Pies* [107]. I also introduced a new method for creating alternatives from a graphical history with support for lineage duplication, i.e., graphical skating, for generative design tools. The in-depth interviews indicate that this is an ideal feature to easily explore what-if scenarios. Another noteworthy way of creating alternatives in *GEM-NI* is the design gallery. This interface improves previous work [96], by enabling users to select an arbitrary range of parameters and/or parts of the generative network to use. Furthermore, I added the new ability to create alternatives from the product of generative networks, which I believe to be a great addition to design space exploration tools and found to be useful in my evaluation. Notably, participants stated that "*[they] arrived at designs that they did not expect or foresee directly*". They attributed this to both the design gallery and to parallel editing. To control the scope of parallel editing, *GEM-NI* provides checkmarks and sandboxing, which participants found very useful during my evaluation.

In *GEM-NI*, I also introduced a novel method for post-hoc merging of alternatives, inspired by branch merging in *Git*. With post-hoc merging, a designer can easily "import" the knowledge embedded in a sub-network into another alternative. Post-hoc merging is particularly useful when a designer does not remember how he/she arrived at a particular state or if someone else modified the design. Yet, I only observed and logged one participant using the technique, potentially due to the limited design complexity explored in my evaluation. Still, I believe that with time, users will realize the full potential of this feature, similar to its pervasiveness in software projects.

Two participants rearranged alternatives extensively to focus on a single one on one monitor. This justifies my decision to support multi-monitors and to use such systems in the evaluation. Participants requested minimizing and other methods to manage alternatives on dual monitors. Participants also requested difference visualizations for alternatives, and overlaid history steps. Such features have been advocated before [70]. *GEM-NI* was implemented as a branch of *NodeBox 3* by adding multiple-document model support via universal unique identifiers. This enables consistent relationships between alternatives to persist even when they are kept offline. Alternatives can then safely be included back into the workspace at a later stage, without naming conflicts. *GEM-NI* supports versioning in this way and P2 used this during the evaluation.

While the sample size of my evaluation is small, I believe it to be representative for what moderately experienced designers can achieve with *GEM-NI* compared to traditional solutions, in terms of better exploration of a design space and expressiveness. The fact that participants even created alternative-supporting schemes in existing tools, underlines the need for *GEM-NI*'s approach in generative design tools.

4.5 User Study II

My primary motivation to conduct another evaluation was to address the issue of the small sample size in the first study. I also implemented several new features, some of which were requested by participants in the first evaluation. The first feature adds the ability to minimize alternatives and to later retrieve them again through a dialog. Some participants expressed that this would help avoid being confronted with all (or too many) alternatives at once. This dialog shows alternatives in a way similar to the design gallery (Figure 4-9). The second feature enlarges the selected, currently active alternative by redistributing the horizontal space within a monitor, so that the selected alternative occupies a larger part of the space, more concretely, twice as much as other alternatives. This permits users to better focus on a specific alternative. I also added support for L-systems [69], a powerful form of generative graphics, to *GEM-NI*. In the evaluation described below I investigate the usefulness of these three features. This evaluation was conducted in the similar fashion to the first user study, namely, as part of a workshop. In-depth interviews were not performed due to time constraints. The goal of the workshop was to gather feedback from a group of users, moderately experienced in generative design.

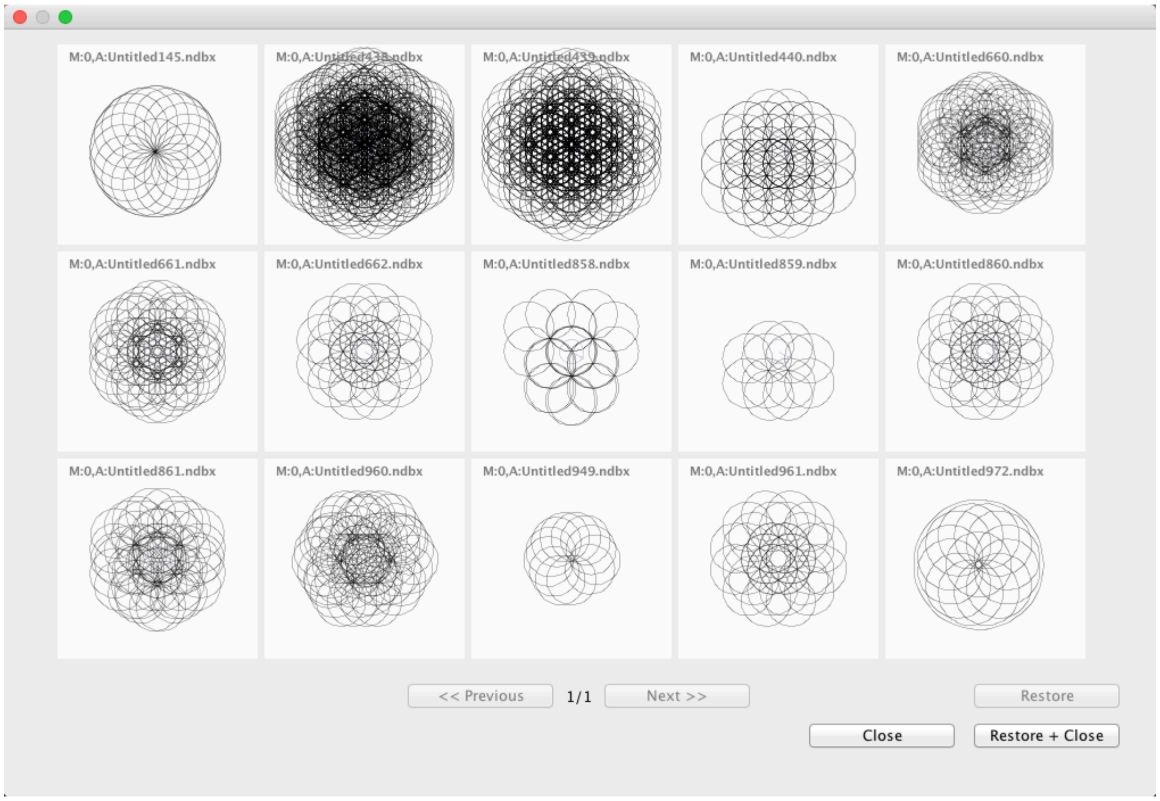


Figure 4-9. The dialog for retrieving minimized alternatives.

4.5.1 Participants

Ten unpaid participants (4 females) were recruited for the workshop from an advanced-level generative design course for graduate students in architecture at the University of Toronto. The workshop was conducted during the lab time of this class. Prior to the workshop, the course instructor notified the participants that they would use a novel generative design tool, perform tasks, and provide feedback. Coffee and cookies were offered as an incentive. The students were targeted because of their experience with design in general and generative design in particular. One participant could not attend the first part of the workshop due to other commitments, so I could not collect his feedback on *NodeBox*. The participants were between 22 and 39 years of age (μ= 27.4). All were experienced with design (μ=8.5 years) and generative design (μ=2.8 years). All were experienced with *Grasshopper*, two with *Processing*. Some were experienced with *Solid Edge*, *Inventor*, *CATIA*, *NX*, *Solid Works*, *Rhino*, *RhinoPython*, *RhinoScript*, *ParaCloud Gem*, *Revit*, *Kangaroo*, and *Weaverbird*. None knew *NodeBox*. This is particularly important because *NodeBox* is easier to use for those familiar with the concept of visual data-flow programming environments, as implemented in systems such as *Grasshopper 3D*. In the pre-questionnaire, 8 participants reported that they routinely create multiple alternative designs, and only 2 reported that they normally create a single solution. All reported that when they design, they keep track, review and revisit their design iterations. For such design iterations, participants reported the following methods: creating scripted outputs of images and model files for later reference, paper and pencil, saving multiple files (mentioned 4 times), saving files with different parameters or definitions, saving multiple files with organized naming conventions to track the history without opening every file, using sketch drawing, recording, pictures, 3D modelling, saving multiple files, drawings, versioning of files, "baking multiple iterations in Grasshopper [3D]", as well as creating a play script with changing parameters in *Rhino.*

4.5.2 Apparatus

We used workstations with dual monitors running *Windows 8*.

4.5.3 Procedure

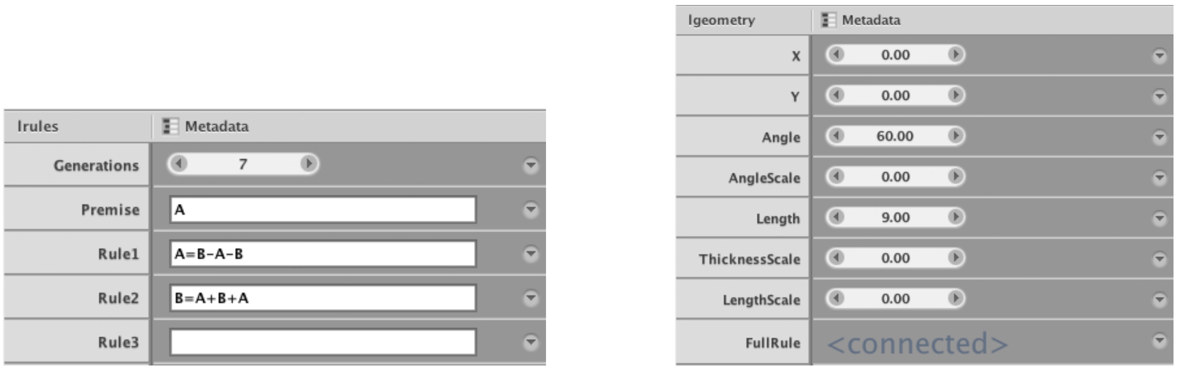
The workshop followed the same procedure as in User Study I (4.3), with the exception that the last demonstrated example involved the use of an L-system. The teaching sessions also took one hour and the tasks 30 minutes each.

4.5.3.1 L-system

During the first phase of the workshop, the last artefact that I asked participants to recreate involved a generative network with two custom nodes (LRULES and LGEOMETRY) that generate an L-system [69]. In the LRULES node, the user specifies the number of generations, a starting premise and up to three rules. In the LGEOMETRY node, the user specifies position, angle and length of the segment, and the scale for angle, length and segment thickness. Figure 4-10 illustrates this with parameters values for LRULES and LGEOMETRY nodes to generate the *Sierpinski Triangle*.

My L-system implementation is based on an existing implementation for *NodeBox* 2 available on *GitHub*[20]. I made the L-system nodes available to participants because they force the user to come up with recursive designs. This imposes further constraints on the creative task and may further increase the internal validity of the experiment. I showed the participants how to generate the *Sierpinski Triangle* and provided them with a set of other examples: *Pythagoras Tree*, *Koch Curve*, *Dragon Curve*, and two variations of a fractal plant (Figure 4-11). I encouraged them to use these examples as starting points in their designs, from which they could branch out. Although all the participants were familiar with L-systems, I recognized that requiring them to use L-systems in *all* their designs could potentially frustrate them. Thus, although I encouraged them to use the L-system nodes in their design, I explicitly identified that this was not required in this study.

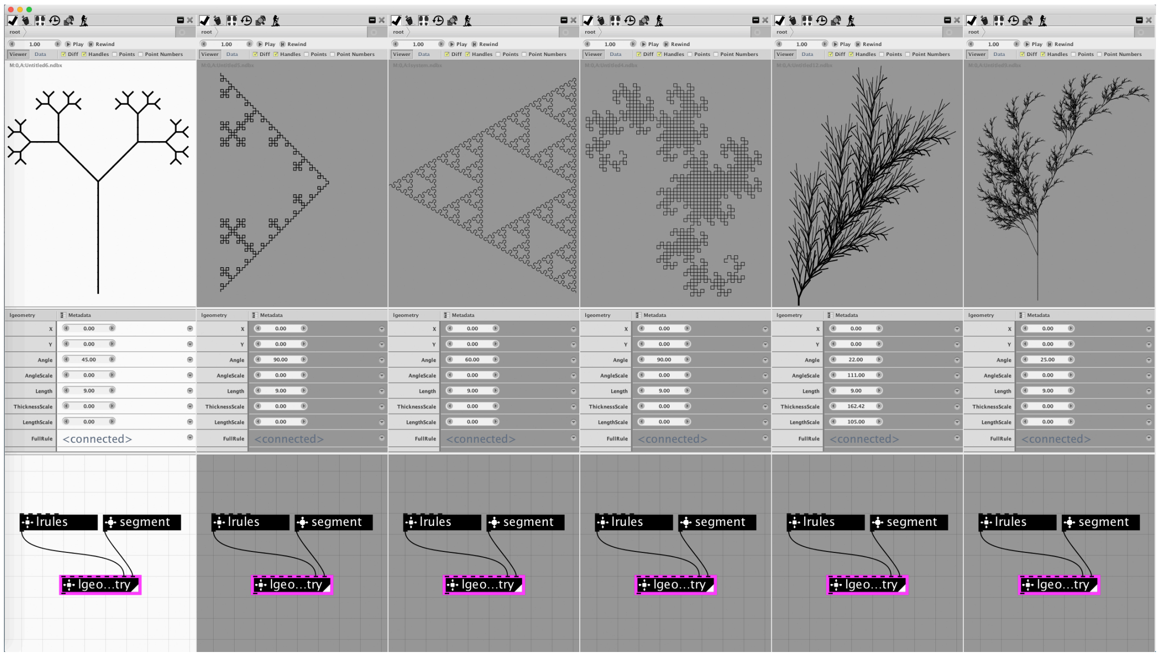
[20] http://github.com/nodebox/nodebox/issues/332



lrules	Metadata
Generations	7
Premise	A
Rule1	A=B-A-B
Rule2	B=A+B+A
Rule3	

lgeometry	Metadata
X	0.00
Y	0.00
Angle	60.00
AngleScale	0.00
Length	9.00
ThicknessScale	0.00
LengthScale	0.00
FullRule	<connected>

Figure 4-10. Parameter values of the LRULES (left) and LGEOMETRY (right) nodes for the *Sierpinski Triangle*.



lgeometry						
X	0.00	0.00	0.00	0.00	0.00	0.00
Y	0.00	0.00	0.00	0.00	0.00	0.00
Angle	45.00	90.00	60.00	90.00	22.00	25.00
AngleScale	0.00	0.00	0.00	0.00	111.00	0.00
Length	9.00	9.00	9.00	9.00	9.00	9.00
ThicknessScale	0.00	0.00	0.00	0.00	162.42	0.00
LengthScale	0.00	0.00	0.00	0.00	105.00	0.00
FullRule	<connected>	<connected>	<connected>	<connected>	<connected>	<connected>

Figure 4-11. The L-System examples that were available to participants for re-use in their designs. The examples are (from left to right): *Pythagoras Tree*, *Koch Curve*, *Sierpinski Triangle*, *Dragon Curve*, *Fractal Plant #1*, *Fractal Plant #2*. The *Sierpinski Triangle* was also the final artefact that participants recreated during the training phase of the workshop.

4.5.4 Results

With *NodeBox*, participants created 2.11 (σ=0.78) alternatives on average. This number excludes all alternatives that were ultimately discarded. Almost all, 6 of 7 (86%), participants created alternatives that were all structurally different, i.e., differed not only in node parameter values but also in the graph structure as well. Two of the three alternatives created by P8 were also structurally different. So, all participants created structurally different alternatives one way or the other. The L-system was used by 6 of 9 (67%) participants. Almost half, 4 of 9 (44%), participants simulated some or all of their alternatives with multiple render nodes and sub-graphs.

Participant No.↓	Total number of alternatives		Number of structurally different alternatives		L-system used in alternatives		Creation of alternatives via multiple rendered nodes in same document
System→	NDB	GMN	NDB	GMN	NDB	GMN	NDB
1	2	4	All	0	0	0	Yes
2	2	3	All	All	0	0	Yes
3	N/A	3	N/A	1	N/A	0	N/A
4	3	5	All	2	1	0	No
5	3	8	All	0	3	8	No
6	1	2	N/A	All	1	2	No
7	1	2	N/A	All	0	2	No
8	3	3	2	2	3	3	No
9	2	3	All	All	1	3	Yes
10	2	8	All	All	1	0	Yes
μ	2.11	4.22					
σ	0.78	2.33					
Summary			7 of 7	8 of 10	6 of 9	5 of 10	4 of 9

Table 4-2. Summary of number of created alternatives with *NodeBox* (NDB – task 1) and *GEM-NI* (GMN - task 2). The larger of the two results per participant is highlighted in red.

Participan t No.	From branching	Non-linear branching	From scratch	By pre-loading from task 1	From history	From Design Gallery
1	0		0	1	4	6
2	1	0	1	1	2	*
3	0		1	0	1	1
4	4	All	1	6	0	*
5	0		0	5	0	1
6	0		2	2	2	*
7	0		0	6	1	*
8	0		0	6	*	3
9	3	0	0	1	0	0
10	N/A	N/A	N/A	N/A	N/A	1
Summary	3 of 9	1 of 3	4 of 9	8 of 9	6 of 9	5 of 10

Table 4-3. Summary of different methods for creating alternatives participants employed in *GEM-NI* in task 2. A '*' designates that the participant used the feature but did not create any alternatives with it. Data for participant 10 indicates the minimum number of alternatives created based on the data recorded before a logging failure.

Participant No.	1	2	3	4	5	6	7	8	9	10
Total Number of Revisited Alternative s	1	3	1	1	3	0	0	6	1	0

Table 4-4. Total number of revisited alternatives by participant.

Partici-pant No.	Merg-ing	Global Undo	Sand-Boxing	Checkmarks	Dual monitors	Rearranging	Min-imizing	Max-imizing	Focusing
1	1	0	3	13	No	0	0	0	0
2	0	8	9	2	Yes	1	0	0	0
3	2	0	0	3	Yes	1	0	0	0
4	0	0	15	29	No	1	3	0	0
5	0	0	6	2	Yes	3	0	0	0
6	0	0	7	1	No	1	1	0	0
7	0	0	4	4	Yes	1	1	0	0
8	1	0	0	31	Yes	3	0	0	0
9	0	0	9	2	Yes	3	0	0	1
10	N/A	N/A	1	7	Yes	6	7	N/A	0
Summary	3 of 9	1 of 9	8 of 10	All	7 of 10	9 of 10	4 of 10	0 of 9	1 of 9

Table 4-5. Summary of other features employed by participants in *GEM-NI* in task 2. Available data for participant 10 indicates the minimum number of times that the feature was used based on the data recorded before the logging failure.

Participant (P3), who could not attend the first part of the workshop, is not included in the results for the first task (*NodeBox*). So all the results in this sub-section are for N=9. See Table 4-2.

With *GEM-NI*, participants created 4.22 (σ=2.33) alternatives on average. A malfunction occurred on the workstation of participant P10 during the second task and I could only recover that participants' session log partially. Therefore, some of the results for the second task with *GEM-NI*, are also reported only for N=9. The partial results for this participant indicate a conservative estimate of the minimum number of alternatives that were created using the corresponding method (Table 4-3) and minimum numbers of times features were used (Table 4-5).

Almost all, 8 of 9 (89%), participants pre-loaded their designs from the first phase as a starting point for the second task. Analysing the logs further reveals that some participants abandoned their designs from the first tasks and created completely new content for the second task.

Creating of alternatives: Branching was used by 3 of 9 participants (33%). Out of these 3 participants, one participant created all his branching alternatives in a non-linear fashion, i.e., branched all designs from a single source. Less than half, 4 of 9 (44%), participants created some of their alternatives from scratch. More than half, 5 of 9 (56%), participants created some of their alternatives from history, and an additional participant used the history, but did not create any alternatives with it. Half, 5 of 10 (50%), created some of their alternatives via the design gallery. Four additional participants were logged using it, without creating any alternatives. Thus, only one participant did not show interest in the feature. See Table 4-3. Besides counting incidents of non-linear branching, another way to observe non-linearity is through the total number of times a participant abandoned an alternative and later revisited it with further editing. Thanks to the checkmarks and sandbox functionality, tracing this activity in the logs is easy. Table 4-4 summarizes such occurrences for each participant. Overall, 7 of 10 (70%) participants revisited alternatives that they temporarily put on hold.

Managing alternatives: Merging was used by 3 of 9 (33%) participants. Global undo was used rarely, by 1 of 9 (11%) participants. Sandboxing was used by most, 8 of 10 (80%), participants, and checkmarks by all (100%). Dual monitors were used by 7 of 10 (70%) participants. Alternatives were re-arranged by dragging at least once by almost all, 9 of 10 (90%), participants. Minimizing was used by 4 of 10 (40%) participants, however no maximizing actions occurred. Only a single participant used focusing once. See Table 4-5.

4.5.5 Discussion

With *GEM-NI*, participants created more alternatives (μ=4.22, σ=2.33) than with *NodeBox* (μ=2.11, σ=0.78). A repeated-measures ANOVA test indicates a significant effect of the tool used, with Wilks' Lamba = .45, $F_{1,8} = 9.75$, $p < .05$, $\eta^2 = .55$, and *observed power* = .78. The data shown in Table 4-2 also confirms, as 7 of 9 participants created more alternatives (highlighted in blue) with *GEM-NI*. Consistent with my first study, almost half (4 of 9) participants created multiple alternatives even in the first task, where they were not prompted to create alternatives. While only one of the tree participants who used branching used the technique non-linearly (and also created all the alternatives that way), a majority of participants (70%) revisited designs that they had worked on previously. This confirms that designers do work non-linearly and that *GEM-NI* is able to support this type of workflow.

The number of structurally different alternatives created is overall consistent between the two tasks. Proportionally they were slightly more popular in the first task with *NodeBox*, but not significantly so. One possible explanation could be that due to the nature of *NodeBox*, only a single alternative at a time can be created. Its interface may thus encourage creating different designs, because participants may be more inclined not to consult previous design. Another reason could be that in the second task, I logged that most of the participants, 89%, pre-loaded existing designs into *GEM-NI*. Thus it is possible that this pre-loading approach could have encouraged the creation of variations rather than structurally different alternatives.

Only three participants did not use the L-system nodes. Those participants who used the L-system in both tasks did create more alternatives with *GEM-NI* than with *NodeBox*. I made L-systems available to the participants because this imposes further constraints on the creative task. This could increase the internal validity of the experiment as participants, in this case, are forced to use a variety of recursive approaches to design. It is fair to note that because of the way I implemented the L-system in *GEM-NI* participants could not take full advantage of the system's comparing features when comparing the networks to each other, since the major components of the L-system, namely the LRULES and LGEOMETRY nodes, retain identical network structure. Using such an implementation of an L-system also limits the usefulness of the *MACE* interface (Chapter 5). However, due to the limiting way *NodeBox* handles support for extensions, I could not come up with a better way to implement L-systems. This also weakened my ability to demonstrate that participants approach design non-linearly in *GEM-NI*: participants 6 and 7 used the L-system nodes, but did not revisit their designs (see Table 4-4). At this moment I do not have sufficient information to tell if this is a causal relation or not. It is also worth mentioning that, despite all the limitations of the implementation of L-systems, one participant used the L-system with other nodes, resulting in more diverse networks (see Appendix B).

The three most commonly used approaches to creating alternatives in *GEM-NI* turned out to be the design gallery, the history dialog, and creation from scratch. The design gallery was undoubtedly the approach that drew the most curiosity: 90% participants were logged using it. Overall, most alternatives were created using this method (11 of 29, i.e., 38%). A total of 10 alternatives were created from history. Creating alternatives as a branch proved to be a bit less moderately popular (28% of created alternatives). This did not confirm my expectations for this approach. Possibly, participants preferred using the history dialog to branching, as both can achieve the same result. The preference could be due to the ability to go back in time and select past states, rather than planning ahead when to branch out. Another possible approach would be to first branch out and then use undo or deletion to get the desired state. Yet, the data I collected suggests that most participants branch out (through history) only in a post-hoc manner, likely after reflection around their designs.

While I did not have high expectations for the merging feature, due to the relative novelty of the concept, merging was interestingly used by at least a third of the participants. This indicates the usefulness of such a feature for the design process. On the other hand, global undo and focusing did not prove to be popular in the study. The same was true for focusing, even though participants in the first user study had requested it. Minimizing, another requested feature, was moderately popular, but none of the participants ever retrieved their alternatives after minimizing. This indicates that participants used this mainly as a lightweight mechanism for storage. It is not surprising to see that checkmarks and sandboxing were used extensively, as these are the mechanisms in *GEM-NI* to control which alternatives are affected by pushed edits. The fact that the majority of the participants used both monitors and re-arranged and minimized alternatives frequently indicates that designers may benefit from more displays than afforded by the dual-monitor setups used during the workshop. This is consistent with Grudin's work [45]. Unsurprisingly, I also logged that participants who created more alternatives tended to also minimize more of them, likely to manage their limited space. This justifies my choice for adding support for up to six monitors in the current version of *GEM-NI*. The popularity of dual-monitor use and re-arranging also confirms previous findings that users tend to dedicate certain regions of the screen for categories [13] and spatial memory [88].

4.5.5.1 Results of the CSI Questionnaire

The CSI questionnaire analysis revealed an average score of 55.7 (σ=13.1) in the first task of this workshop and a higher score, 63.6 (σ=12.1), for the second task where *GEM-NI* was used. Similar to [24], I report the results with respect to average factor counts, factor score and weighted factor score (Table 4-6).

Task	Factor \ Scale	Enjoyment	Exploration	Expressiveness	Immersion	Results worth effort
1	Avg. Factor counts (σ)	1.78 (1.39)	3.78 (1.30)	3.67 (1.22)	2.44 (0.88)	2.78 (0.83)
1	Avg. Factor score (σ)	12.44 (2.55)	12 (3.50)	11.56 (2.88)	9.89 (2.76)	12.11 (3.22)
1	Avg. Weighted factor score (σ)	22.12 (14.44)	44.11 (17.77)	42.89 (20.62)	24.44 (10.62)	34.67 (16.56)
2	Avg. Factor counts (σ)	1.90 (1.37)	3.90 (1.29)	3.40 (1.43)	2.40 (0.84)	2.90 (0.88)
2	Avg. Factor score (σ)	13.10 (3.03)	14.50 (2.46)	12.90 (2.13)	8.90 (4.09)	13.80 (2.20)
2	Avg. Weighted factor score (σ)	24.89 (13.74)	56.55 (22.90)	43.86 (23.56)	21.36 (13.01)	40.02 (15.07)

Table 4-6. User Study II: Average results from first task using *NodeBox* (top)*;* second task using *GEM-NI* (bottom).

The average counts are the number of times that participants choose a particular factor as important to the task. The maximum possible for each factor count is 5. Exploration and expressiveness were ranked as the more important factors. The factor score on the other hand represents the sum of multiple agreement statement responses for a factor. A higher number indicates that the tool better supports that factor. The maximum factor score is 20. Both tools appear to support the factors fairly. *GEM-NI*, however appears to support exploration better. Weighted factor scores are calculated by multiplying a participant's factor agreement scale score by the factor count, in order to make the weighted factor score more sensitive to the factors that are the most important to the given task. The maximum possible weighted factor score is 100. Here again, exploration scored higher with *GEM-NI*. These more qualitative results are consistent with the quantitative results above, such as that more alternatives were created with *GEM-NI,* where the design gallery and history were the most popular techniques for creating alternatives. This further supports the higher ranking of *GEM-NI*'s ability to support exploration.

Even though expressiveness was ranked as important, I argue that the reason this factor was not ranked higher for *GEM-NI* is that participants had different expectations for the tool. Given that my participants work primarily in the architectural domain, they expect more from the tool, such as the ability to create 3D models. This can be contrasted with the results of the first user study where participants from various backgrounds were recruited. Yet, because of the small sample size, I cannot infer this to be a strong conclusion. Yet, *GEM-NI* and *NodeBox*, both are limited to 2D domain. This was confirmed as an issue in the freeform feedback, as discussed below. Results Worth Effort was ranked fairly high in *GEM-NI*. This factor is associated with effort, work, productivity, performance and reward [24]. Arguably, this factor does not directly affect creativity, but does so indirectly by contributing to the motivation of a designer to purpose a task.

In addition to the CSI questionnaire I also added another post questionnaire, where I asked the participants to contrast *NodeBox* with *GEM-NI*. Specifically, I asked how well each tool supports the task with the set of features that were available in each tool.

Participants ranked each tool on a Likert scale from 1 to 9 (1 being poor support, 9 being excellent support). *NodeBox* was ranked on average 6 (σ=1.66), and *GEM-NI* 6.7 (σ=0.82) out of 9.

4.5.5.2 Freeform Feedback

In the freeform feedback section on the post questionnaire I received mostly positive comments. Three participants expressed that they would like to see the functionality available in the tools that they use everyday and are more familiar with. The first participant said: "*[It] was very nice to see all options at the same time, but [I] couldn't help but feel that the improvements made on NodeBox were significantly more useful than NodeBox itself. I would love to see this type of design-space exploration in, say, Grasshopper - the 2D nature of NodeBox is a little limiting.*" Another one speculated: "*not sure if it works on 3D, which I am interested most.*" Yet another one stated: "*there is a robust environment for non-destructive editing and versioning based on history, which I have not experienced in other software, but would be a desirable feature to aid in my workflow. I appreciate [GEM-NI's] feature of side-by-side viewing and capability of editing of multiple alternatives. Additionally, the gallery view and outputs of multiple iterations streamlines an otherwise tedious process of generating options, which tends to be an important part of my workflow when using generative design software*".

Two other comments were also positive in general: "*The idea is excellent ... it would be an extremely useful application*", "*[These are] very useful tools to produce several case studies with the different parameters*".

Three comments were more critical: "*It was easy to create designs based on the functions demonstrated in the tutorial; however, I struggled with using new functions and getting them to generate the designs I wanted.*" This comment may indicate that the learning curve involved may be an obstacle. Another participant said: "*I am very interested in the gallery feature of the [GEM-NI]. It really allows designers to test out various combinations of parameter settings. I think the user interface is a little less intuitive than ideal, and to have a clear workflow is so important in the production process that the user really need[s] to have* *very high level of understanding of the program to maximize the power of it. I see a lot of potential in this program overall! Thanks for showing us this!*" This also emphasizes the need to make a tool easy to learn. Yet another said: "*if the multiple iterations can be changed more intuitive[ly] that would be great. Thanks!* "

4.5.5.3 Design Quality

Similarly to previous work [80,81], I recruited three experts to rate the designs produced by each participant for quality. All were expert designers in academia with at least a decade of experience in practicing design and with grading student work. The designs were ranked by overall and *protean* design quality. Protean means "being able to change easily" or that a design is versatile. Essentially, this quality is used in design to classify how worthy something is to build upon. Ratings ranged from 0 to 5, with 5 being best. The results are summarized in Figure 4-12. Figure 4-13 depicts the averages of these results. The overall design quality of the outcomes with both systems was similar, which may be a consequence of the limited time that participants had to work on their designs. Yet, Interestingly, the results achieved with *GEM-NI* were ranked overall higher in terms of being protean, which I interpret that their creativity potential is higher.

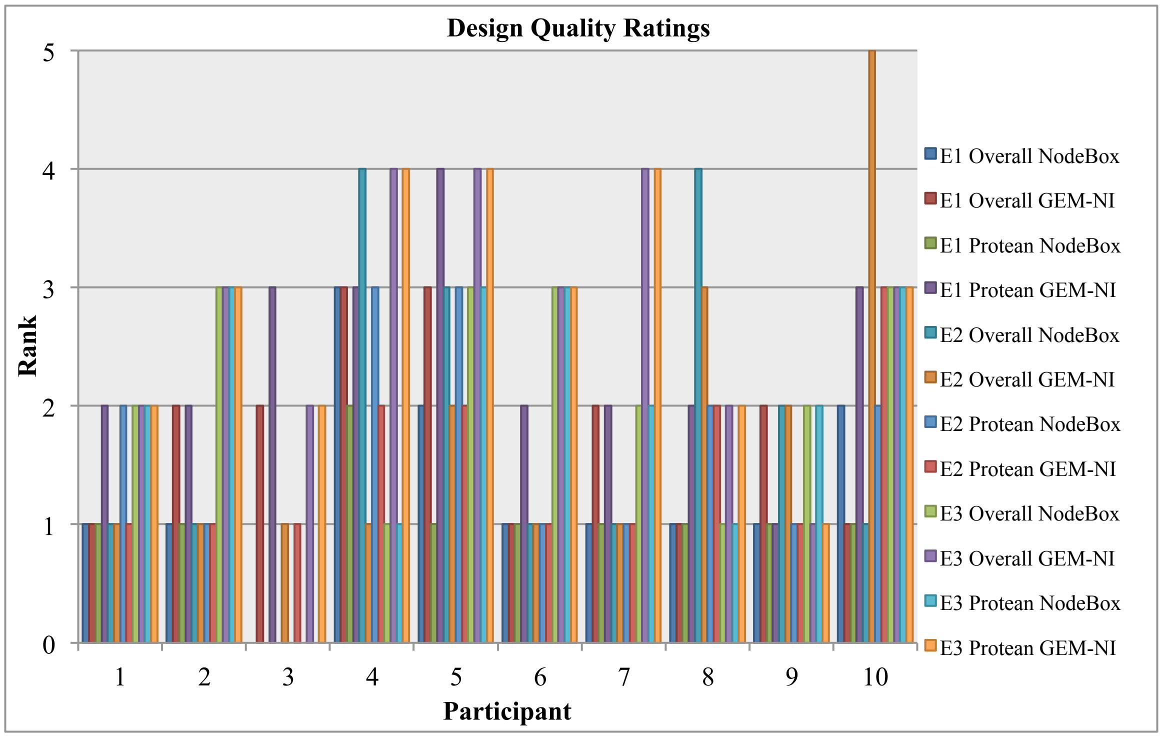


Figure 4-12. Overall and protean quality ratings of participants' designs by each of the experts (E1-3). Higher is better.

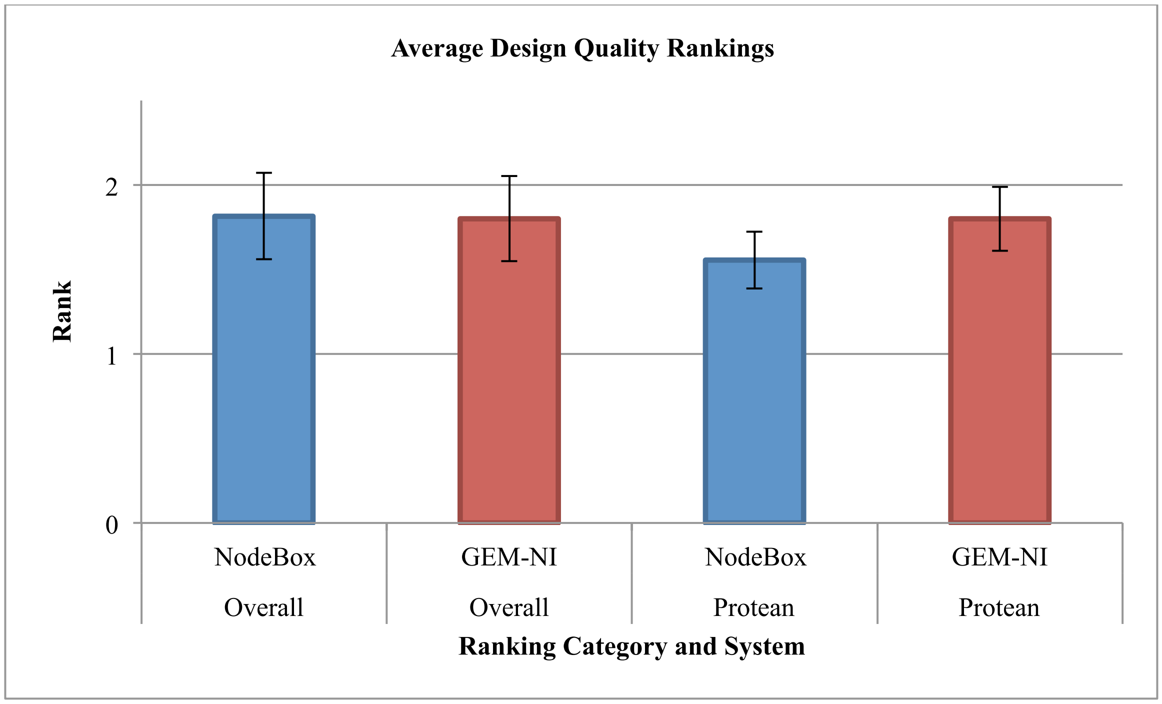


Figure 4-13. Average overall and protean design quality rankings by the three experts (higher is better). Error Bars: ±1 SE.

4.6 Overall Discussion

The results of the second user study shine more light on issues revealed in the first user study. With a larger sample size, *GEM-NI* was confirmed to support exploration better with the new features, as also supported by the results from the CSI questionnaire as well. As in the first user study, a number of participants created alternatives in the first task, where they did not know about *GEM-NI's* features*,* without prompting. In the freeform feedback three participants expressed that they wished they had the features of *GEM-NI* available in the generative design tools they use daily. All this supports my initial hypothesis for the need for *GEM-NI*'s approach in current generative design tools. Some freeform feedback revealed that the learning curve for using a system that fully enables exploration through alternatives, such as *GEM-NI,* is a potential issue.

Interestingly, some features that participants identified as desirable in the interviews in the first study, such as focusing, did not prove to be popular with the participants in the second user study. On the other hand, minimizing, one of the suggested features, was used at least by a part of the participants. This underlines that user interface designers should approach all requested features critically and consider them thoroughly. In contrast, the major features that I decided to implement within *GEM-NI* proved to be more useful, with the exception of global undo. The fact that global undo was not popular may potentially be explained by the fact that few people can simultaneously design multiple alternatives in parallel, due to the increased complexity of such a task. On the other hand, the ability to perform post-hoc merging and resurrection from history was confirmed as useful, which points out that considering multiple alternatives in linear or potentially non-linear fashion is much more realistic. A participant from the interview in the first user study expressed exactly this insight. In hindsight, I believe that if I had designed the user study and logging specifically to reveal instances when parallel editing occurred and contributed to the design, I would be able to state this more confidently. From the current logs it is difficult to say whether parallel editing or global undo was accidental or desired. Merging, a concept novel for generative design, but common in software development as part of version control (e.g., *Git*), received some interest. But as in the first user study only few used it in the second one. One reason could be that the participants I worked with in the second study were not familiar with the concept. In hindsight, I should have asked about experience with version control systems in the pre-questionnaire. That might have enabled me to better analyze this issue. It is also interesting to point out that beyond exploring alternatives, the mechanisms introduced in *GEM-NI* permit designers to use the system as a version control system. Like in source code version control systems, designers do not need to create multiple files and are not restricted by the limitations of copy and paste. As in source code systems, branching and borrowing of ideas is facilitated with the ability to resurrect from history. Through merging, designers can save time by re-using existing parts of the design. I also can point out that in *GEM-NI* alternatives and version control are effectively integrated into one user interface.

Based on these findings I speculate that the user interface of *GEM-NI* for managing alternatives is not specific to generic design. All the newly introduced techniques can be applied to other design workflows. At least one of the participants already expressed the wish that the alternative management techniques should be available in their more familiar 3D parametric modeling workflow. Though, adopting a design gallery into a system like *Processing*, which is purely code-based, would arguably require a new interface.

I also believe that the techniques that were popular in *GEM-NI* in the evaluations will likely also be popular in domains outside of design that involve problem solving, such as visual analytics. Similarly, I expect the unpopular techniques (such as global undo) to be unpopular in other domains as well. Finally, and beside all the benefits of the new techniques, I expect that the obstacles that *GEM-NI*'s interface encountered to transfer as well. For example, parallel editing should not be the default, regardless of domain.

Both user studies may suffer from a hidden skill transfer effect, because *NodeBox* was presented and evaluated first and *GEM-NI* second. However, it is not easy to use counterbalancing with a between-subject study since the two tasks used here are not exactly the same. Moreover, if participants are alerted to the use of alternatives in the first phase through *GEM-NI*, this would likely bias the results for *NodeBox* as well.

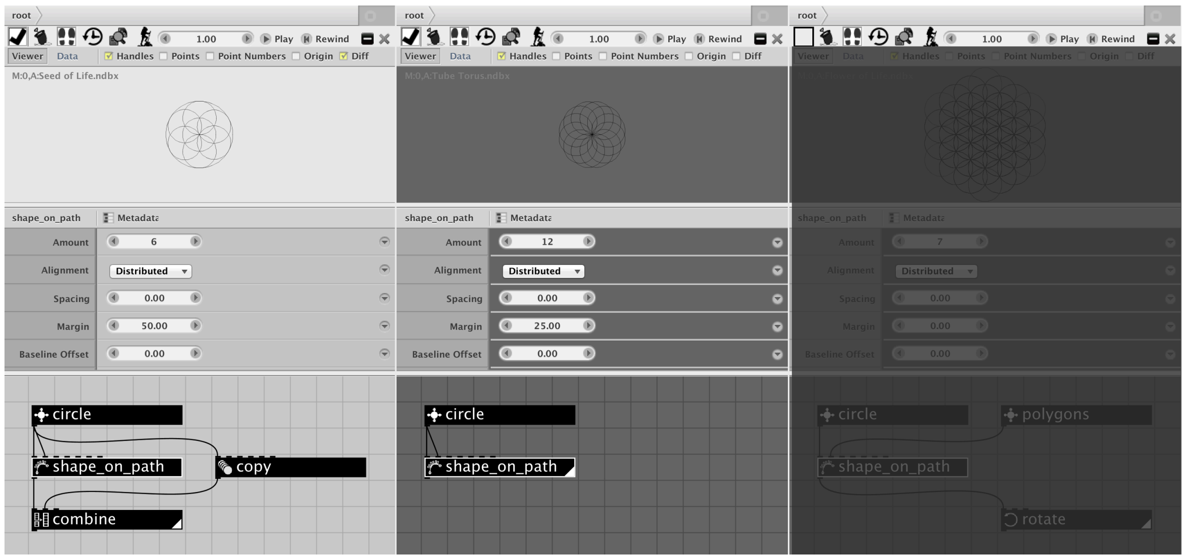
4.7 Summary

In this chapter I presented *GEM-NI*—a new system for creating and managing alternatives in generative design. The system supports parallel editing via checkmarks and sandboxing, two new methods to control which alternatives are affected by a parallel edit. Also, I introduced a novel method for post-hoc merging of alternatives. Moreover, *GEM-NI* provides several methods to create alternatives, including a new method for resurrecting alternatives from a graphical history with previews, with full lineage preservation. Another way to create alternatives is with a new design gallery, which enables users to select which ranges of parameters and/or parts of the generative network model to use for exploration. Moreover, my design gallery supports a new method to explore products of generative networks.

I also conducted two user studies to explore usefulness of the system. These user studies were conducted as part of a workshop where participants first learned how to use the tool.

The feedback from participants in the first workshop and in-depth interviews suggest that *GEM-NI,* and more broadly the approach behind it, indeed enables designers to work more creatively. The results indicate the direct applicability of the presented techniques for the design process also via the CSI questionnaire. While the sample size of my user study is small, it identified the potential for better creativity support through alternatives in design tools. In the second user study, the tasks were refined and revisited with a larger sample of participants. The results resolved the issues raised by the first user study. *GEM-NI* was found to support exploration better due to the newly introduced features, which was also supported through the CSI questionnaire. In the freeform feedback three participants expressed that they wished they had the features of *GEM-NI* available in the generative design tools they use daily. Three expert designers in academia evaluated the quality of the participants' designs. I interpret the rankings as suggesting that the creativity potential of the results is higher with the designs produced with *GEM-NI*.

Chapter 5
MACE: A New Interface for Comparing and Editing of Multiple Alternatives



M:0,A:Seed of Life.ndbx

Amount	6
Alignment	Distributed
Spacing	0.00
Margin	50.00
Baseline Offset	0.00

M:0,A:Tube Torus.ndbx

Amount	12
Alignment	Distributed
Spacing	0.00
Margin	25.00
Baseline Offset	0.00

Amount	7
Alignment	Distributed
Spacing	0.00
Margin	0.00
Baseline Offset	0.00

Figure 5-1. *GEM-NI* enables users to work with alternative generative designs simultaneously. The leftmost alternative is active, the center one is passive, and the rightmost one is idle.

In this chapter I present a new interface for interactive comparisons and editing of multiple alternatives in generative design. The interface is part of *GEM-NI*, a graph-based 2D design tool that supports the exploration of design alternatives in various ways. *GEM-NI* is built on *NodeBox 3*, a graph-based 2D generative design tool. *GEM-NI* adds to *NodeBox 3* a number of novel features and interactions that enable users, among other things, to quickly generate sets of alternative solutions using a variety of mechanisms. *GEM-NI* is described in Chapter 4.

Here, I enhance *GEM-NI* with a novel difference visualization technique, which allows users to compare more than two alternatives at a time. Moreover, my difference visualization technique is fully interactive. To enable editing in difference visualizations, I introduce a new "reveal-to-edit" feature, which I designed to improve parallel editing in *GEM-NI*. I named this interface *MACE* (Multiple Alternatives – Comparing and Editing).

5.1 MACE

I use a design with three alternatives in Figure 5-1 as the main example throughout this paper to demonstrate the features of my system. Yet, *MACE* and *GEM-NI* are capable of handling a much larger number of alternatives, limited only by screen estate, processing power and memory. More examples of difference visualizations are presented in Appendix B.

5.1.1 Design Motivation

Almost all previous approaches to graph differencing discussed in Chapter 2 reduce the problem to showing at most *pairwise* differences. When timelines are compared in dynamic graph drawing the differencing problem also reduces essentially to such pairwise comparisons. Animation is one option that can be used to trace the evolution of a graph. There, it may *appear* as if multiple graphs are compared. Yet, animation relies on the ability of the user to memorize previous frames (time slices), since only a single frame can be displayed at a time and compared against the time frames in the user's memory. Another option is to use superposition for comparing multiple graphs, even for graphs that have not necessarily evolved linearly. Yet, displaying differences between more than two graphs in the same non-partitioned space will result in a scalability problem, even for alternatives. The approach I propose in this thesis is essentially a variation of aggregation where parts that are different from the reference graph are displayed in different partitions or "lanes" corresponding to the alternative, which is compared against the reference graph. This difference visualization technique I present here has its roots in Shireen et al.'s [97] concept for parallel generation and editing of alternatives. Yet, Shireen et al.'s interface was not explicitly intended for difference visualization and misses a visualization of deleted and common nodes and edges. I extend their original concept and thus enable full difference visualization across multiple data-flow networks, i.e., DAGs. Still, the question remains if visualizing all differences across all alternatives at once is overall usable and can scale. I employ subtractive encoding—a complementary approach to the additive encoding identified by Gleicher et al. [39]. Subtractive encoding removes *common* nodes from the compared graphs. This technique reduces visual clutter in the compared view and also reveals and/or highlights changed, unchanged, added and removed nodes in the compared network view relative to the reference. As a result, if there are no differences between a reference and compared network and there is nothing to show in the compared view, visual clutter is non-existent or minimal. On the other hand, if the overall number of changes is too large, then the difference visualization might visually "overwhelm" the content. To characterize this, I use the relative percentage of nodes shown in a given difference visualization between two alternatives in *MACE* as an approximation for readability, *R*:

$$R = 1 - \frac{\min\,(n_{ref}, n_{\neq} + n_{=} + n_{+} + n_{-})}{n_{ref}}$$

where $\mathrm{n}_{\neq}$ is the number of changed, $\mathrm{n}_{=}$—the unchanged, n_{+}—the added and n_{-}—the removed nodes in the compared view, and $\mathrm{n}_{\mathrm{ref}}$ is the total number of nodes in the reference view. If the number of displayed nodes in the compared view is equal to or exceeds the number of nodes in the reference view, readability becomes zero. If the number of differences is small readability will approach one.

In order for my technique to be effective, the average readability *R* of typical designs must be high. I believe that alternatives for a design problem will likely show substantial similarities due to the *shared goal*. As a result, I expect fewer differences among data-flow networks of alternatives compared to the number of similarities. To test this hypothesis I measured the average readability *R* from the dataset of the User Study II (see 3.3.7). For the outcomes I performed all pairwise comparisons of all their alternatives in both orders. Thus, for a participant that generated *n* alternatives, I performed $2\binom{n}{2}$ comparisons and calculated their average readability *R*. Averaging across all participants yielded a fairly high average readability of μ_R=.68, σ_R=.26, N=146. Given that 68% is substantially closer to one, this motivates that showing differences instead of commonalities is an appropriate design choice for difference visualization across multiple alternatives.

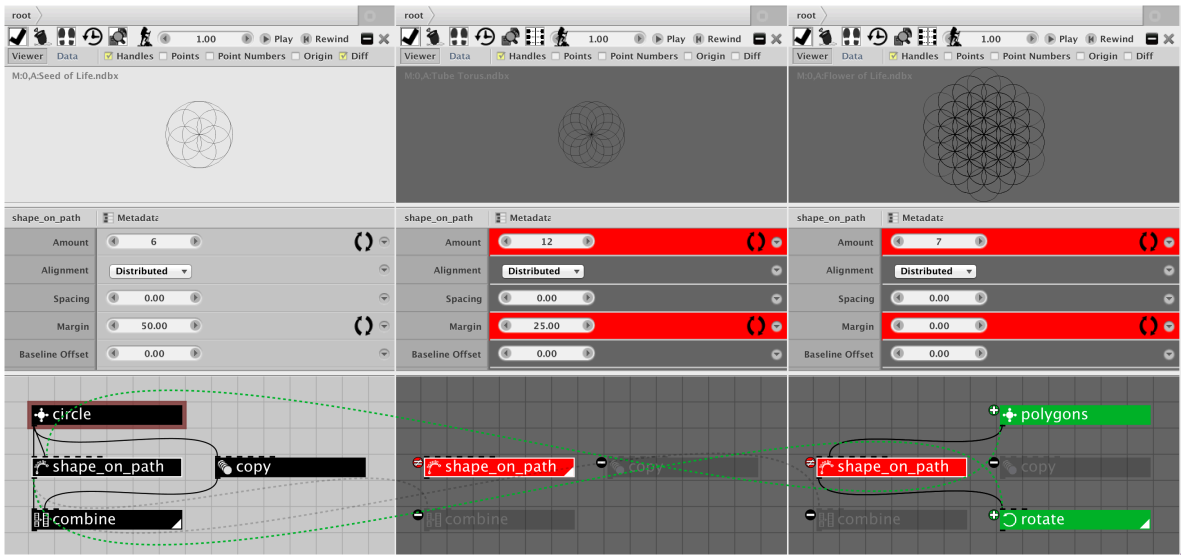
Beyond this I also explore node-focused difference visualization, i.e., showing differences for a single node. This is unlikely to suffer from scalability issues, since only the differences for a single node are shown at a given time.

5.1.2 Mechanisms to Facilitate Comparison of Alternatives

In my implementation, the positions of group nodes are synchronized by default across alternatives. Thus, moving a node in one alternative also moves it in all other alternatives, if it exists. This affects even alternatives that are not editable. In early pilot studies I identified that the uniformity in network layout makes it much easier to visually compare networks across *multiple* (read more than two) alternatives. The default is to keep this feature on. To accommodate use cases where this is undesirable, the user can toggle this feature with a button. One of the scenarios where turning this feature off could be useful is a situation where the user compares networks with a lot of nodes on a small screen. In this case the screen space may not be sufficient to show all encodings without zooming out substantially beyond the threshold of being able to read node labels. In this case moving nodes around, i.e., manual re-layout, at a moderate zoom level could solve this issue to some degree, However, this is an exceptional scenario because I do not expect alternatives to have a lot of changes. And even if a lot of changes appear, I expect the user to use node grouping to reduce the visual complexity of the networks.

Selecting a node in one alternative also selects it in all other alternatives if the node exists there, again to make it easy to identify commonalities. It also brings up the parameter view for the selected node everywhere as well. In Figure 5-1 the node SHAPE_ON_PATH was selected in the leftmost alternative and is thus selected in all other ones as well. The corresponding parameter views are also shown. This also makes it easier for the user to identify common elements between alternatives. Zooming and panning operations on the network view and output view are also linked, again to facilitate visual comparison.

(a)



(b)

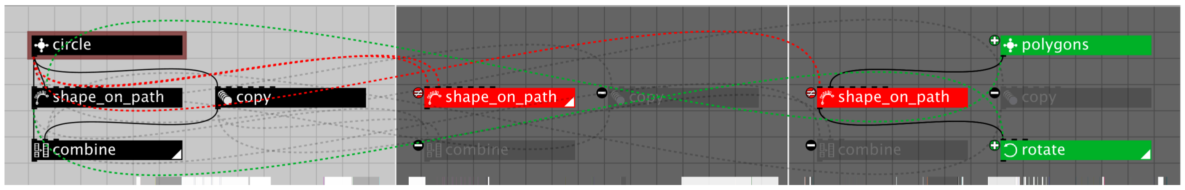


Figure 5-2. a) Node-focused difference visualization of SHAPE_ON_PATH. Left document is the reference and is also active. (b) Difference visualization for the network panels of the same content without node focusing.

5.1.3 Difference Visualization

In *GEM-NI* interaction with alternatives happens in the default visualization shown in Figure 5-1. In *MACE* I added *diff mode,* which shows the differences of all the alternatives relative to a reference alternative instead. The user can freely select which alternative to use as reference. See Figure 5-2. This mode was inspired in part by the subjunctive interface proposed (but not implemented) by Shireen et al. [97]. The power of diff mode is its ability to show differences between multiple alternatives at the same time. To get into this mode, one alternative has to be designated by the user as the *reference* through a GUI button, clicking on a menu button, or a key short cut. The other alternatives (further referred to as *compared alternatives*) are then compared to it. In diff mode, differences are visualized in all three views (output, parameter and network), as applicable. While Shireen et al.'s proposed GUI shows differences only for nodes that are common, my implementation also visualizes nodes and edges that have been added or deleted.

In Figure 5-2a, the leftmost alternative was chosen as reference. Its network starts with a group node CIRCLE that is fed as both shape and path to the SHAPE_ON_PATH node generating a circular formation of six circles. Moreover, two copies of the circle are then created at the center, one of which is scaled up to form the outline of the design. The output of SHAPE_ON_PATH and COPY are then combined into a single design through the COMBINE node, which is the rendered node.

The center alternative starts with the same CIRCLE. This node is unchanged and thus is not shown (as described below). The generative model increases the number of circles to 12 in SHAPE_ON_PATH, which now shows up as a changed node. The COPY and COMBINE nodes were removed in this design, leaving the SHAPE_ON_PATH node as the rendered node. The right alternative substitutes the path input of SHAPE_ON_PATH node (and only that input) with a triple-recursive hexagon arrangement (shown in green with group node POLYGONS). Instead of the COMBINE node, the whole design is also rotated by 30° with a final ROTATE node.

5.1.3.1 Network View

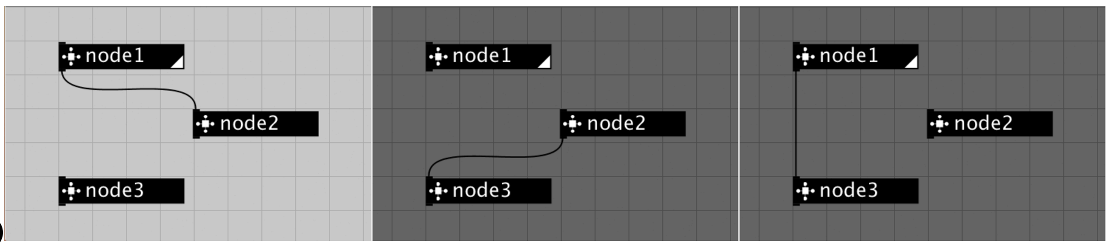
Nodes common to the reference and at least one other alternative are only shown in the reference. Phrased differently, for every compared alternative and in the network views, all nodes that are common with the reference and which have identical parameter values are not shown to reduce visual clutter. This potentially hides entire unmodified sub-graphs. In Figure 5-2, the CIRCLE node is an example. It exists in all three alternatives. Common nodes are highlighted with a brown (de-saturated red) outline in the reference.

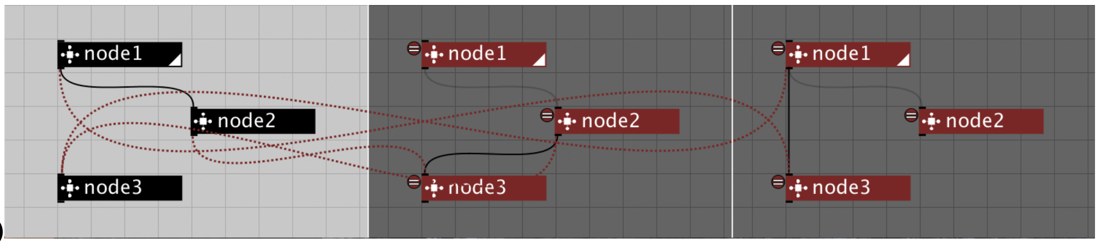
Nodes that are common with the reference but have one or more different parameter value appear in red color. A "≠" sign is displayed to the top left of the node to emphasize this further through an inequality metaphor. If such a node has any incoming or outgoing connectors, they are connected to the corresponding nodes in the reference with lines that cross the panels. The connectors are displayed in the same red color and appear as a dashed curve. This style differentiates them from solid “within-document” connectors. In Figure 5-2a, node SHAPE_ON_PATH in both compared alternatives is an example for a node with changed parameters.

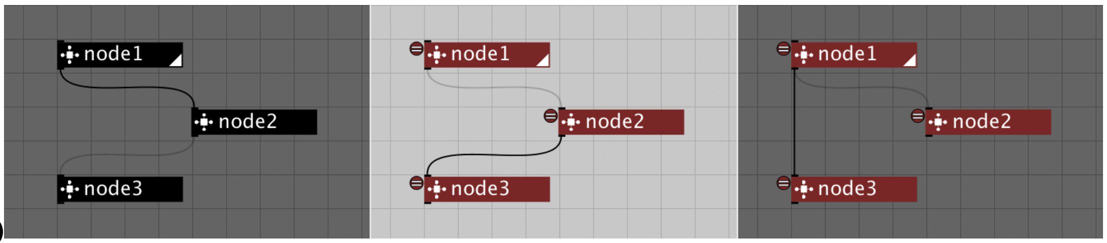
This also works for group nodes, which contain sub-networks. If at least one difference in either a parameter or structure exists between the sub-networks, then in the corresponding compared views these group nodes also appear highlighted in red with a “≠” displayed next to them. If a group node contains another group node, the same technique is applied recursively. This is described in more detail in 5.1.3.5.

Nodes that do not exist in the reference are highlighted with a green color and are again connected with dashed connectors to the reference. A “+” sign is displayed in the top left of the node to emphasize this through an addition metaphor. In Figure 5-2a, nodes POLYGONS and ROTATE in the rightmost alternative are such additions.

Nodes that exist in the reference, but don’t exist in a compared alternative are displayed in a background semi-transparent layer and are connected with semi-transparent connectors to the reference. A “–” sign in the top left of the node emphasize this further through a reduction/subtraction metaphor. In Figure 5-2a, COPY and COMBINE in both compared alternatives demonstrate this visualization technique.

(a)


(b)


(c)


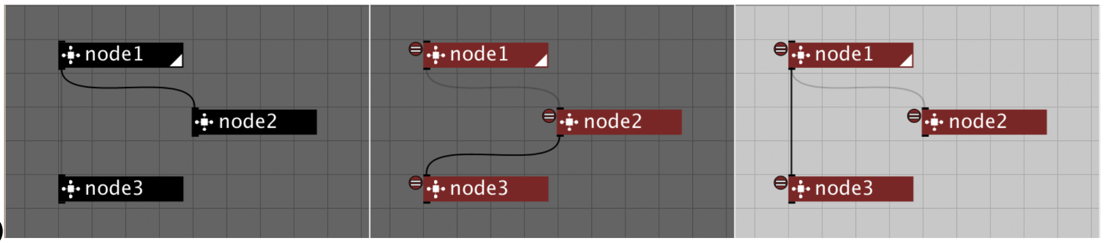
(d)


Figure 5-3. Difference visualization for changed connections. (a) no difference visualization, (b) diff mode, (c) diff exclusion with cross-alternative connectors turned off, middle alternative is active, (d) diff exclusion with cross-alternative connectors turned off, right alternative is active.

I also implemented a new technique to illustrate differences in connections between nodes. In this visualization, I highlight unchanged, common nodes that have one or more changed connections, in brown (de-saturated red) color. An "=" sign is displayed in the top left of such nodes to emphasize their unmodified state further. Figure 5-3 shows this technique using dummy nodes. In this figure, four views of the network are presented as follows: In the default mode shown in Figure 5-3a, the unenhanced networks of three alternatives are presented. In Figure 5-3a, I show a scenario without difference visualization, where one of the connectors exists only in the reference, while others exist only in the compared alternatives in the middle respectively right. In Figure 5-3b-d, I illustrate two variants of my new connector difference visualization technique. In Figure 5-3b, the *diff mode* visualization, the alternative on the left is the reference. All the cross-alternative connectors are displayed. In diff mode, all three nodes are identified as common in the middle and right alternatives. The changed connectors are then shown as dashed connectors across panels. While this presentation emphasizes all the differences in connectors in the three networks, it may appear confusing due to the number of cross-alternative connectors. This leads to a more and more cluttered display with an increasing number of alternatives.

Below is the pseudo code for the implementation of the difference visualization in *GEM-NI*. Cross-alternative connectors are painted onto the Java `GlassPane`, which is in front of all GUI elements. The new method is `paintGlassConnections()`. The pseudo code omits the details of the (earlier) creation of various sets of nodes, i.e., `sameNodesInReference`, `newNodes`, `sameNodesThatChanged` and `missingNodes`. The pseudo code also handles the implementation of node-focused difference visualisation, a feature that is described below.

```
/**
 * This method paints cross alternative connectors with node-focused visualization.
 */
void paintGlassConnections(){
        Initialize pointer to singleNodeSelectedSomewhere. Non-null means active node-focused difference visualization.
        //this segment is for cases of node-focused difference visualization
        if active alternative ≠ reference {
                // singleNodeSelectedSomewhere is empty but a single node is selected
                if selectedNodes.size() == 1 and singleNodeSelectedSomewhere == null {
                        Reinitialize newNodes, sameNodesThatChanged, missingNodes, missingNodes, and
                                                draggedNodesThatDidntChange to empty sets
                        add the selected node appropriate sets and update singleNodeSelectedSomewhere.
                }
                // singleNodeSelectedSomewhere is not empty, sets needs to be re-initialzed
                else if singleNodeSelectedSomewhere ≠ null {
                        Reinitialize newNodes, sameNodesThatChanged, missingNodes, missingNodes, and
                                                draggedNodesThatDidntChange to empty sets
                        add singleNodeSelectedSomewhere to appropriate sets.
                }
        }

        //the actual visualization of differences of connectors for new, changed and dragged nodes
        for all connections c in the network {
                for all nodes n in sameNodesInReference{
                        //input in newNodes
                        if c.output()== n{ //output is in reference
                                Set connection color to NEW_NODE_COLOR
                                Draw connection to the node output in reference for all newNodes
                                Set connection color to CHANGED_NODE_COLOR
                                Draw connection to the node output in reference for all sameNodesThatChanged

                                Set connection color to DRAGGED_NODE_COLOR
                                Draw connection to the node output in reference for all draggedNodesThatDidntChange
                        }
                        //input in newNode
                        if c.input()== n{ //input is in reference
                                Set connection color to NEW_NODE_COLOR
                                Draw connection to the node input in reference for all newNodes

                                Set connection color to CHANGED_NODE_COLOR
                                Draw connection to the node input in reference for all sameNodesThatChanged

                                Set connection color to DRAGGED_NODE_COLOR
                                Draw connection node to the input in reference for all draggedNodesThatDidntChange
                        }
                }
        }
        //the actual visualization of differences of connectors for missing nodes
        for all connections c in reference{
                for all nodes n in reference {
                        //input in missingNodes
                        if c.output() == n { //output is in reference
                                Draw a connection to the node output in reference for all missingNodes
                        }

                        //output in missingNodes
                        if c.input()== n { //input is in reference
                                Draw a connection to the node input in reference for all missingNodes
                        }
                }
        }
    }
```

Certain changes such as, e.g., a change in the reference relative to all other alternatives (in other words when the user modified the reference without pushing changes to all other alternatives) create visual clutter proportional to the number of alternatives in the visualization. To address this kind of visual clutter, we designed a new variant, called *diff exclusion*, accessible through a GUI button or a shortcut. This mode does not show all cross-alternative connectors to and from the excluded alternative. This makes missing connectors more visible and we show them transparently in the compared alternatives relative to the reference and other missing elements. Figure 5-3b, illustrates the clutter created by cross-alternative connectors. In Figure 5-3c,d the missing connectors between NODE1 and NODE2 in the compared alternatives relative to the reference are more visible when diff exclusion is applied to both compared alternatives. Another use case for diff exclusion is if the user wants to see all differences between a small, say up to three, set of alternatives. Otherwise, the user can temporarily hide undesired alternatives in the difference visualization or compare one node at a time with node-focused difference visualization (described below). Another option is to use group nodes, but this changes the structure of the network.

One way to see missing connectors in the reference relative to the compared alternative is to select one of the compared alternatives as reference. To remove this extra step of switching the reference, I implemented another technique where the system shows missing connectors in the reference instead. The user simply switches the active alternative to the desired compared alternative against which s/he wants to see missing connectors in the reference. The missing connectors in the references, if such exist, are then shown transparently. In Figure 5-3c, the middle alternative was set as active. The missing connector between NODE2 and NODE3 is displayed transparently in the reference (on the left). In Figure 5-3d, the compared alternative on the right was set as active. The missing connector between NODE1 and NODE3 is displayed transparently in the reference. While the idea of showing missing connections was previously presented in the *DARLS* system (Chapter 3**)**, that technique could only handle two graphs at a time. The new diff mode and diff exclusion techniques presented here generalize *DARLS* methods to more than two networks.

To further reduce visual clutter, I do not show connections between all combinations of deleted and common nodes inside each compared alternative. E.g., the connector between COPY and COMBINE is not shown in the compared alternatives in Figure 5-2a (and b). The user can toggle this via a menu command.

5.1.3.2 Node-focused Difference Visualization

Graham and Kennedy [41] point out that a potential disadvantage of using edges for a visual comparison of two trees is that if there are too many lines displayed at once then individual edges become impossible to distinguish from the mass of drawn lines. Such visual clutter is a known concern in graph visualization. *MACE* includes a novel interaction method to overcome this problem. Whenever the user selects a node (via clicking on it) in diff mode, the system hides all the cross-alternative connectors that are not connected to the selected node. Figure 5-2a illustrates an example where SHAPE_ON_PATH is selected in the reference alternative. Thus, only connectors involving the SHAPE_ON_PATH node in the reference are shown. If there are still too many dependencies visible, the user can apply diff exclusion to exclude certain unwanted alternatives to reduce visual clutter further. Deselecting the node (by clicking on any empty area) then shows all other connectors again. See Figure 5-2b.

5.1.3.3 Parameter View

In the parameter view, I emphasize parameters changed relative to the reference for the currently selected node. For this, each changed parameter "row" is highlighted in the compared alternatives. In Figure 5-2a, the "Amount" and "Margin" parameters are different in both alternatives relative to the reference and are thus highlighted in red.

5.1.3.4 Output View

To illustrate the differences in the output of the generative design, the geometry produced by the rendered node of the reference is displayed transparently in the output view in a bottom layer for all compared alternatives. This directly superimposes the geometry of compared alternatives over the reference to enable simple visual comparisons. To deal with cases where this is visually too intrusive, I provide an option to disable this functionality by unchecking the corresponding "diff" checkbox. Figure 5-2a shows a case where the direct overlap of the curves makes it advisable to turn this feature off. Figure 5-7c shows a case where the difference visualization in the output view is not as intrusive. Here the offset parameter of the WIGGLE node was changed. The default option is to keep this checkbox on. I leave it up to the user to determine when this feature gets too intrusive since it depends on the content that the user is working with.

5.1.3.5 Recursive Group Node Difference Visualization

I implemented a technique to visualize differences between group nodes. The technique supports visualization of differences between recursive/nested variations of these nodes as well. Figure 5-4 demonstrates an example where three alternatives were created from an earlier "Flower of Life" design from Figure 5-1. The top part of the figure shows the status of the workspace with difference visualization turned off. The bottom part of the figure shows a difference visualization highlighting the node POLYGONS in the network view as described above. This indicates that there is a difference between these nodes. However, on this level, it is not revealed. Entering the POLYGONS presents the view in Figure 5-5. All three views are now displaying the contents of the POLYGONS node in each alternative. The top part of the figure shows contents with difference visualizing turned off. The bottom part shows a difference visualization highlighting the node POLYGON1 and POLYGON2_3. POLYGON1 appears in all three alternatives and is also selected, which enables node-focused difference visualization on it. This highlights the "Sides" parameter emphasizing that the value of 3 is different from the reference value of 6. The "Sides" parameter of POLYGON2_3 also has the same value of 3 in the middle alternative (not shown). POLYGON2_3 is the last network not in this branch. Entering it presents the view in Figure 5-6. Here, the right alternative is completely disabled because the node doesn't exist there. This is indicated by highlighting the whole alternative in red. Note that the alternative is highlighted in both the regular mode (shown on top) and the difference visualization mode (shown at the bottom).

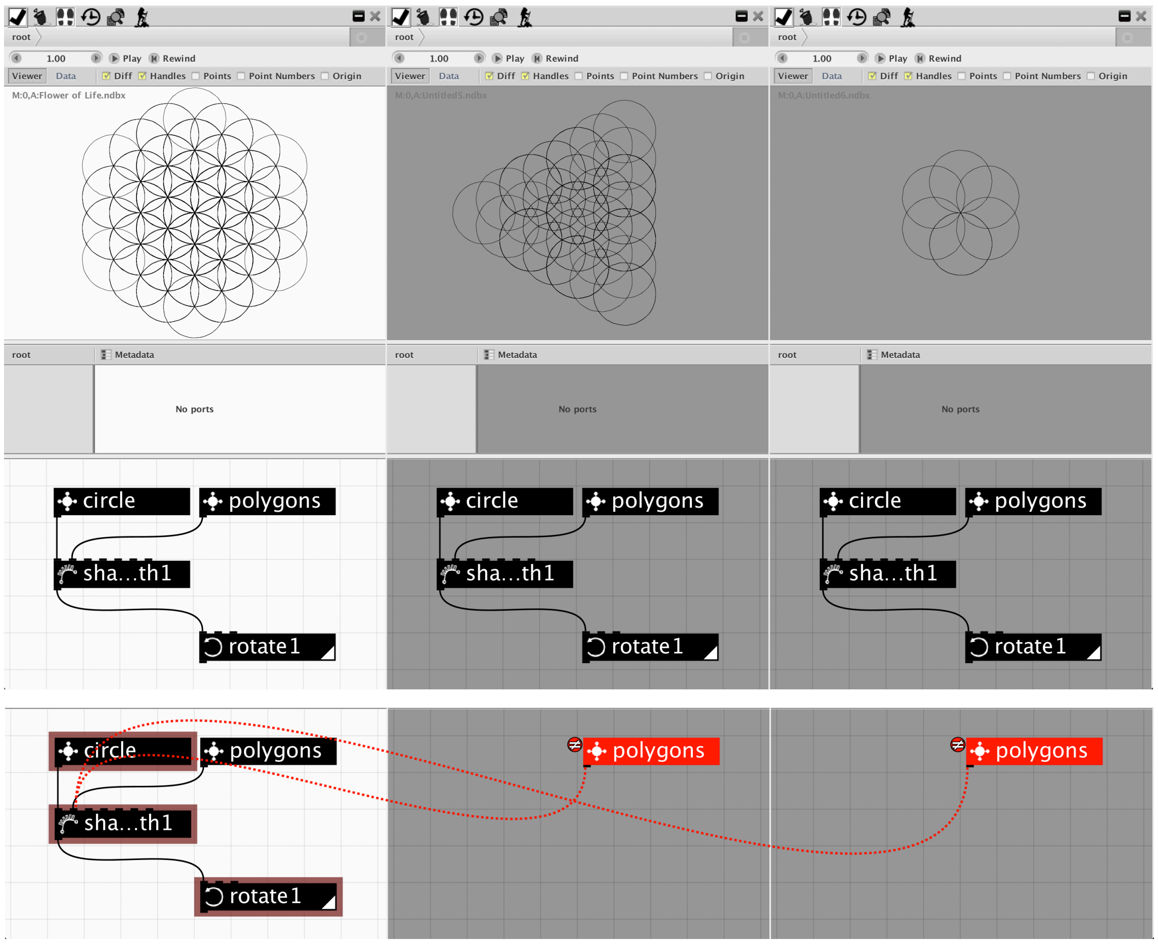


Figure 5-4. Three alternatives of Flower of Life. The design differs in the POLYGONS node at level 1.

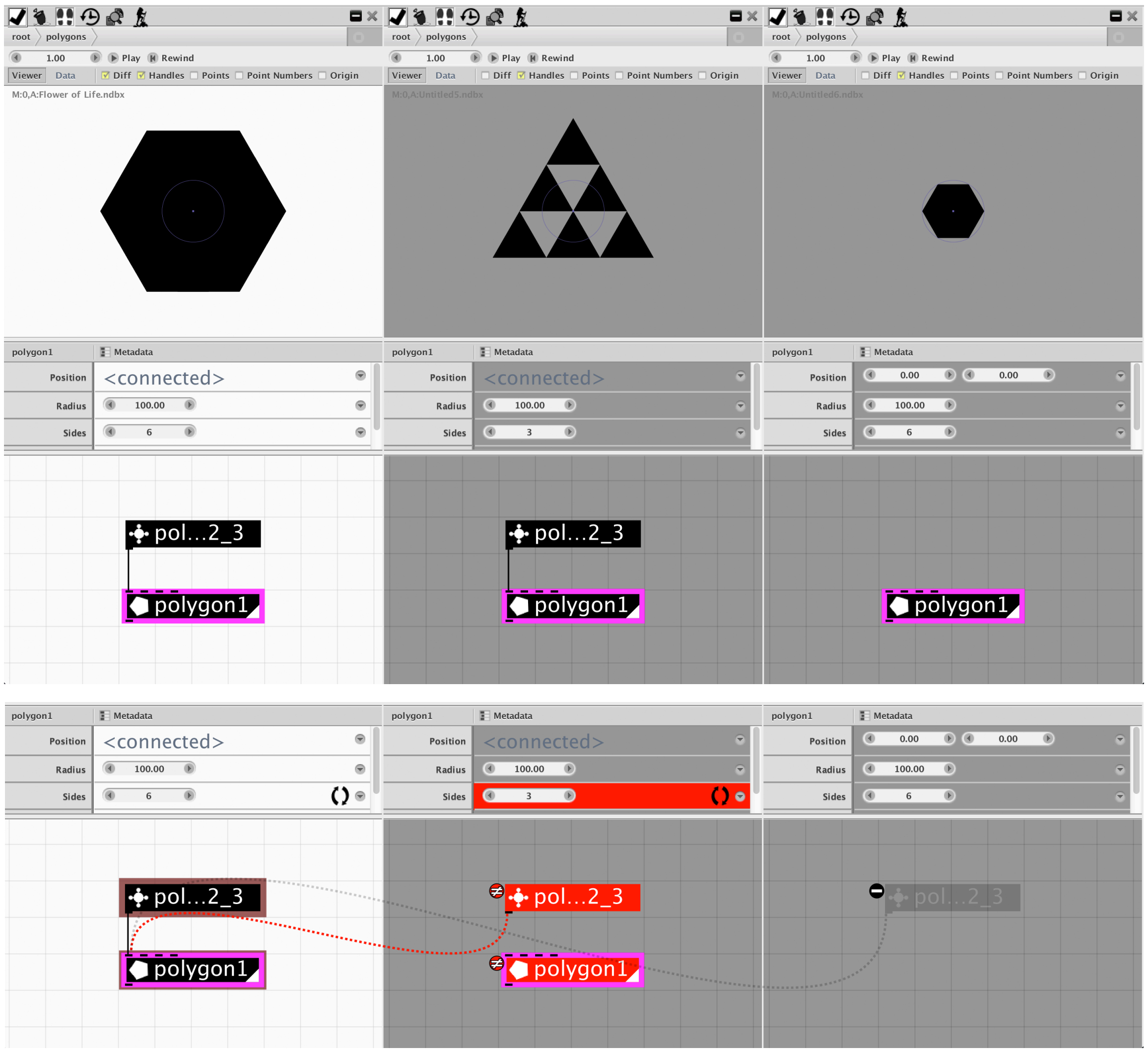


Figure 5-5. Difference visualization at level 3 inside POLYGONS node.

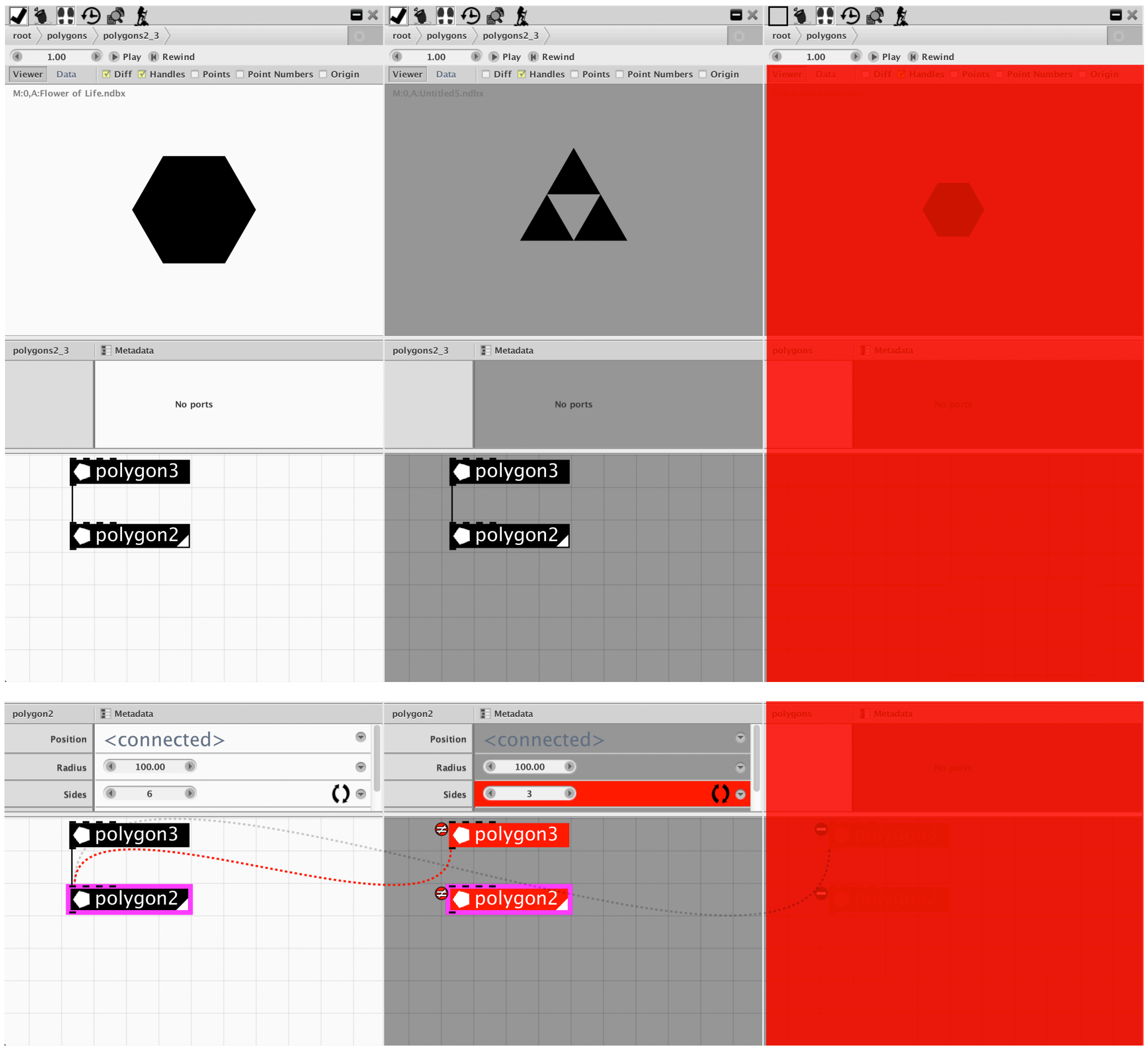


Figure 5-6. Difference visualization at level 2 inside POLYGON2_3 node. The right panel is disabled, because the corresponding node does not exist in the network.

Below is the pseudo code for the implementation of the recursive comparison method for group nodes in *GEM-NI*. The code consists of a single `static` method `groupNodesEqual()`, which was added to the code base of *NodeBox 3*.

```
/**
* The method compares if the two group nodes are identical, or there exist difference in at least one parameter of a node, or missing/new
node or connection
 * @param groupNode1 is in the compared alternative
 * @param groupNode2 is the reference
 */
boolean groupNodesEqual(Node groupNode1, Node groupNode2) {
        Initialize empty sets: newNodesInGroup1, changedNodesInGroup1, missingNodesInGroup1
        Initialize subgroupNodesEqual = true; //initially we assume that subSubNetworks are equal

        //look for new and changed nodes
        for all nodes group1Node in groupNode1.getChildren() { // all nodes in this groupNode1
                Initialize foundSameNode = false;
                for all nodes group2Node in groupNode2.getChildren()) { // all nodes in groupNode2
                        if UUID of group1Node == UUID of group2Node{
                                Initialize foundSameNodeThatChanged = false;
                                for all nodes inputs g2Input of group2Node {
                                        If g1Input not g2Input{
                                                foundSameNodeThatChanged = true;
                                                break; //node was matched
                                        }
                                }
                                if (not foundSameNodeThatChanged) {
                                        changedNodesInGroup1.add(group1Node);
                                }
                                else if (group1Node is a group node) {
                                        subgroupNodesEqual &= groupNodesEqual(group1Node,group2Node);
                                }
                                foundSameNode = true;
                                break;
                        }
                }
                if (not foundSameNode) {
                        newNodesInGroup1.add(group1Node);
                }
        }

        //looking for missing nodes
        for all children of group2Node { //for all nodes in reference document
                Initialize found = false;
                for all children of group1Node { //for all nodes in this network view
                        if UUID of group1Node.child == UUID of group2Node.child {
                                found = true;
                                break;
                        }
                }
                if (not found){
                        missingNodesInGroup1.add(group2Node);
                }
        }


        // comparing connections
        connectionsNewInGroup2 = Find all connections that are in groupNode1 but not in groupNode2
        connectionsNewInGroup1 = Find all connections that are in groupNode2 but not in groupNode1

        return subgroupNodesEqual and newNodesInGroup1.isEmpty() and changedNodesInGroup1.isEmpty() and
                        missingNodesInGroup1.isEmpty() and connectionsNewInGroup1.isEmpty() and
                        connectionsNewInGroup2.isEmpty();
}
```

5.1.4 Editing Alternatives in Diff Mode

My difference visualization mode is fully interactive. This means that all above-mentioned visualizations are not just static, but can be used directly during parallel editing.

5.1.4.1 Autosandboxing

In diff mode, switching to another alternative automatically sandboxes the newly active alternative (making all others idle). This feature can be enabled in the preferences. Autosandboxing saves the user an extra step when editing alternatives in diff mode. Currently, the default is to keep this feature turned on, because many users work with one alternative at a time. After all, non-sandboxed, i.e., parallel editing is more challenging.

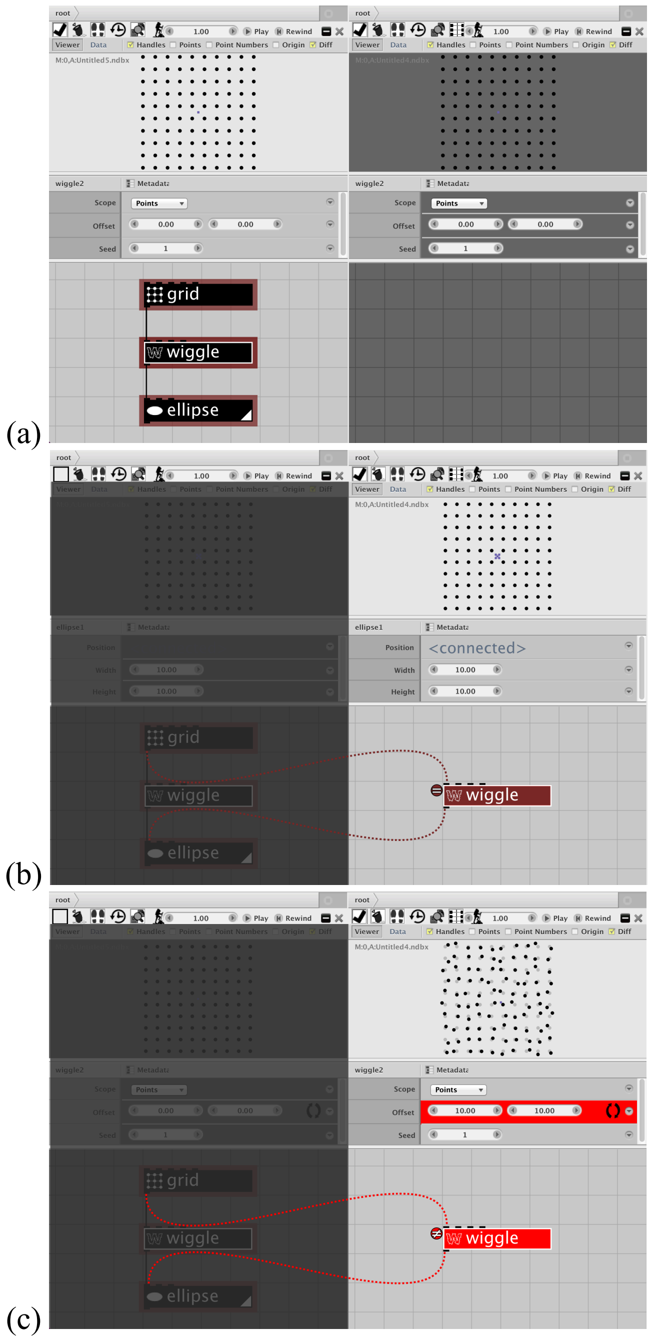


Figure 5-7. Reveal-to-edit feature. (a) Initial state. (b) A common node, highlighted in brown (de-saturated red) is revealed via a clicking with a modifier key in the alternative on the right. That (compared) alternative is then active and the reference is made idle through autosandboxing. (c) A parameter change results in a red difference visualization.

5.1.4.2 Reveal-To-Edit

One drawback of any difference visualization that hides common nodes is that these nodes are then inaccessible for editing and other operations. To address this shortcoming and inspired by the user interface concept proposed by Shireen et al.'s [97], I implemented a new *reveal-to-edit* feature. Shireen's concept used dragging of nodes to reveal them. Yet, dragging of objects has a different meaning in GUI's and does not scale well to multiple alternatives and monitors. Thus, I implemented a new reveal-to-edit feature through clicking while holding down a modifier key in a compared alternative. This action shows the selected nodes in the active and compared alternatives (temporarily) in brown (de-saturated red) and with a '=' sign in the top right to emphasize the commonality. This visualization is consistent with other visualizations of common nodes mentioned above. Alternatively, the user can click while holding the modifier key on nodes in the reference alternative to reveal the selected nodes in all alternatives. This interface is only accessible in diff mode.

Consider the following typical scenario. The user starts with a design consisting of three nodes: GRID, WIGGLE and ELLIPSE connected to each other in a chain. This network produces a 10×10 grid of ellipses. The user then creates a clone through branching and enables the diff editing mode with the alternative on the left as reference. As a result, all the elements of the cloned alternative become hidden (as described above). See Figure 5-7a. To edit the parameter for the selected WIGGLE node in the other alternative, the user then clicks in the compared (right-hand) alternative while holding the modifier key. This then changes the display to Figure 5-7b, also because autosandboxing makes the reference alternative idle. Subsequently, the user can now edit the "offset" parameter of the WIGGLE node of the compared alternative on the right (Figure 5-7c). In this scenario, only the WIGGLE node is revealed because it is the only selected node in the reference alternative.

5.1.4.3 Parameter Synching

To facilitate post-hoc (re-)synchronization of parameters, I offer a simple shortcut for nodes with changed parameters. For each changed parameter, a "sync" button is shown to the right of the field (Figure 5-2a). Clicking it synchronizes the state in all passive alternatives to the state of the current alternative. Higher level synchronization on the structure of the graph is possible through merging and is described in Chapter 4.

5.2 Multi-Monitor Support

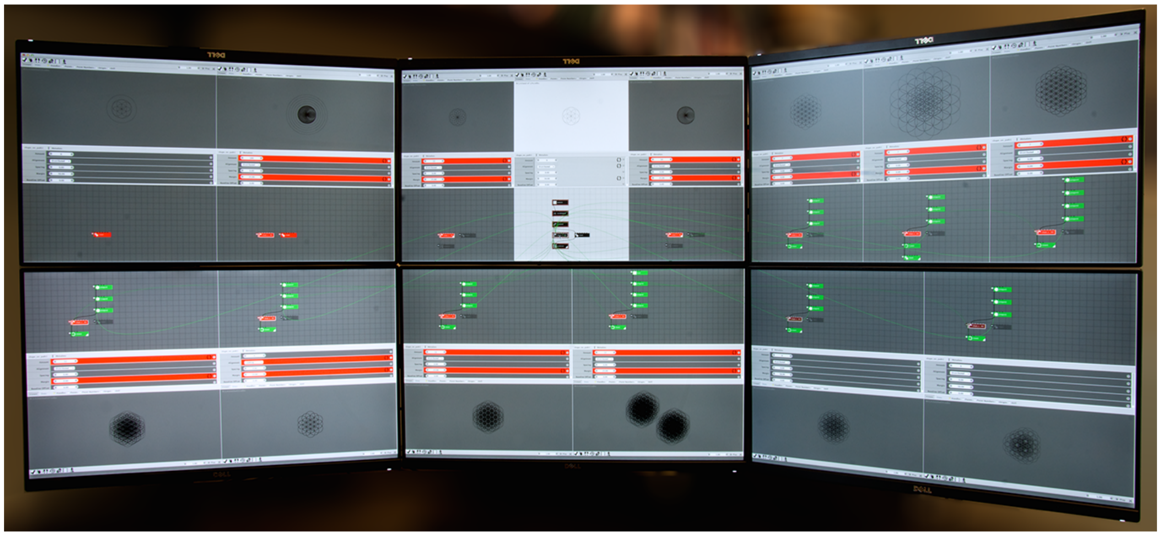


Figure 5-8: My 2×3 multi-monitor setup displaying a total of 14 alternatives in a difference visualization relative to the top middle (reference) alternative.

In the conceptual design phase, designers routinely generate dozens of alternatives. That amount of content is difficult to fit onto a single monitor, if all alternatives are still to be view- and editable. Consequently, I extended *GEM-NI* to support multiple monitors to help the designer keep the overview of all alternatives they are considering. Multi-monitor support in *MACE* helps to support scalability as more alternatives can be shown at full scale at the same time.

I enhanced *GEM-NI* to take advantage of the increasingly popular multi-monitor setups. In the preferences menu, the user can select the preferred monitor usage from between 1×1 and (currently up to) 2×3 monitors. The workspace is then re-arranged to spread all alternatives as evenly as possible according to the newly chosen monitor arrangement. Within each monitor, horizontal space is evenly redistributed depending on the number of alternatives in that monitor. In a sense, this is an adaptation of the *Spread* technique of Bi et al. [17] to tiled applications. The user still has thus the flexibility of using only a subset of available monitors.

For all monitor layouts with two rows, i.e., 2×1, 2×2 and 2×3, the model and network views are swapped on the bottom row. That way, cross-alternative node connectors in diff mode do not cross the model and parameter views of the bottom row alternatives.

To demonstrate how *GEM-NI* works on more than one monitor, I created a multi-monitor setup with six Dell U2414H monitors, in a 2×3 formation in an Ergotech multi-monitor stand (Figure 5-8) with a total resolution of 5760×2160 pixels. These monitors have thin bezels on three sides. To minimize the overall seams, I rotated the top row of monitors 180°. In Figure 5-8, 14 alternatives are being edited in *GEM-NI* on this system.

5.2.1 Managing Alternatives in Multi-Monitor Environment

Alternatives can be dragged across different monitors to rearrange the layout. Each time an alternative is dragged between monitors, the horizontal space in the two involved monitors gets redistributed accordingly. When an alternative is dragged from a monitor on the top to a monitor at the bottom and vice versa, the model and network views swap places. If all alternatives are dragged out of a monitor, or if a setup in the preferences is chosen leaving some monitors empty, a plus sign is displayed in the middle of the empty monitor. This widget enables quick creation of a new empty alternative. Instead, an alternative from another monitor can be dragged into this empty area.

Figure 5-8 shows an example when an alternative in the middle was chosen as reference. This reference is the *Seed of Life* from Figure 4-1, which was initially positioned as the first alternative in the top left corner. In fact, this alternative was first dragged to the middle to demonstrate how placing the reference alternative in the middle makes it easier to compare it against all others in the diff mode.

5.2.2 Jamming Spaces

Ball and North [13] identified that users tend to dedicate certain regions of a large display for certain applications and then rely on spatial memory. I believe this can be generalized to how screen space can be used for alternatives in *GEM-NI* and consequently implemented a corresponding feature that supports the adaptation of the space to the current use case. Moreover, space is an important resource in parallel exploration tasks. In *GEM-NI,* I permit users to "jam spaces", i.e., monitors, into the following states: idle/non-idle; enable/disable display of cross-alternative node connectors; and all combinations thereof.

This functionality is available through a menu and directly affects all alternatives in a given monitor. When a monitor is jammed, a red frame is displayed around the border as a visual clue (Figure 5-9). Dragging an alternative into a "jammed" monitor affects the state of said alternative corresponding to the "jam" settings. In Figure 5-9 the two monitors at the left and right bottom respectively are both jammed. The one on the left is jammed in an idle state. The one on the right is jammed in the state where cross-alternative node connectors are not displayed.

5.2.3 Limitations

It is important to point out that the approach for multi-monitor support in *GEM-NI* and *MACE* does not scale to a large number of alternatives, say substantially more than 20. The reason for this is the physical limitations of the average user to see sufficient detail. Objects appear smaller proportionally to their distance from the user due to perspective. Thus, a user can only keep track visually of all alternatives that appear in the center of the field of view. In order to accommodate hundreds of alternatives, a different interface will be necessary.

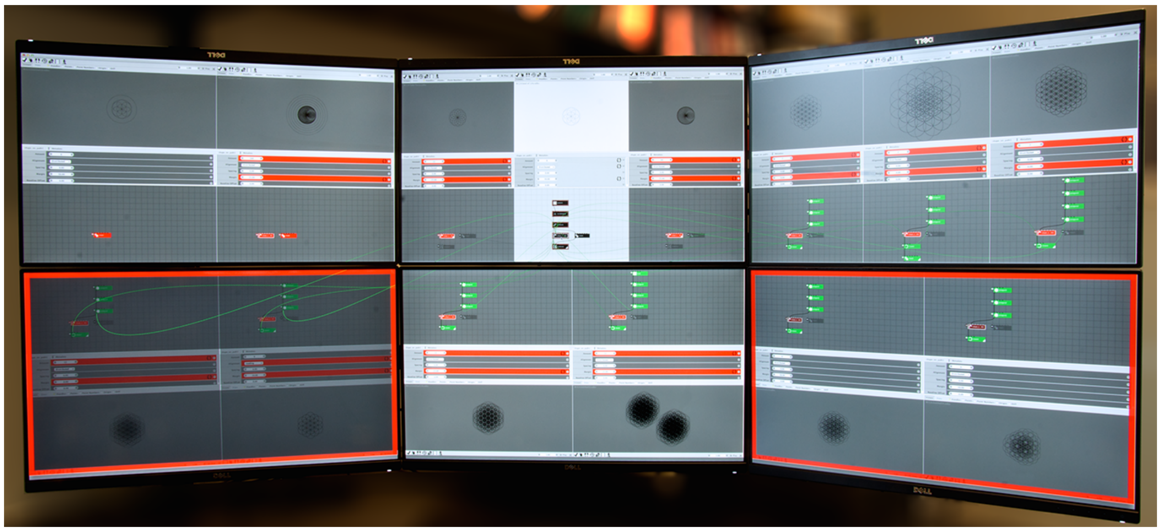


Figure 5-9. The same example as in Figure 5-8 with the bottom left monitor jammed into an un-editable state and the bottom right monitor jammed into the state where cross-alternative connectors are not displayed.

5.3 Implementation

MACE builds on *GEM-NI*, which in turn was implemented as a major branch of *NodeBox* 3 by adding support for a multiple-document model based on universal unique identifiers (UUIDs) for nodes. Such UUIDs enable us to perform robust comparisons and difference visualization between alternatives. UUIDs also enable consistent relationships between alternatives to persist even in the situation when certain alternatives are kept "offline" (i.e., stored on disk during editing sessions). These stored alternatives can then safely be re-included in the workspace at a later stage without naming conflicts.

5.4 Discussion

Here I discuss the differences to previous work and the consequences of the design decisions behind the difference visualization interface of *MACE* in more detail.

The problem of showing differences is important for generative design because designers typically create several alternatives based on a single idea, which they use as a reference. Designers also tend to work on multiple design alternatives concurrently [70]. Then management of these alternatives becomes an issue. Transferring ideas among alternatives and saving multiple files or creating multiple designs in a single document are current solutions for this. Yet, these approaches make it harder for the designer to compare designs. *MACE* presents a solution to difference visualization for alternative graphs: added, deleted, (un)changed and recursive group nodes in both the reference and all compared graphs as well as added and deleted connections. As my technique is fully interactive, it permits editing directly in the difference visualization, which reduces the number of mode switches.

I have previously presented pair-wise difference visualization for directed graphs with nodes identifiable by name in *DARLS* (Chapter 3). Comparing more than two such graphs of the evolution of a *single* data set can be done with animation and/or time slices, e.g., [90]. In generative design where parallel and non-linear creation and editing of alternatives is the norm we deal with situations well beyond the evolution of a single graph. Thus animation and other traditional techniques are not directly applicable. Agglomeration is also not appropriate because I am dealing with DAGs, not trees. My work is the first to propose a solution to the problem of showing differences between more than two such graphs. In other words, *MACE*'s approach extends a) the layering approach used in several instances of previous work, such as [6,26] and *DARLS*, by hiding unchanged nodes to reduce clutter and drawing connectors to the reference to enhance juxtaposition; b) side-by-side views [46,76,77] by going beyond pair-wise comparisons; c) existing work on subjunctive interfaces [97], *TreeVersity* [47–50] and *TreeVersity2* [50,51] to show a larger variety of difference visualizations; and d) the parallel editing interface of *GEM-NI* (see 4.1.1) to allow the user to keep difference visualization enabled during editing. *MACE* also shows a difference visualization of multiple group nodes. This supports scalability to generative networks with many nodes, where node grouping becomes a necessity as otherwise the graph becomes much too large for a single screen.

Also, my technique proposes subtractive encoding—a new form of explicit encoding where members of the intersection are removed from the compared graph. This extends Gleicher et al.'s taxonomy work [39]. As a result, this improves the readability of my difference encoding by keeping visual clutter low. Subtractive encoding is as an extension to Shireen et al.'s [97] concept for parallel creation and editing of alternatives. Given that alternatives for a design problem will likely be similar due to the shared goal, I expect fewer differences among the data-flow networks of alternatives compared to the number of similarities. This assumption underlies the design of the *MACE* interface. I performed an analysis on the alternatives obtained through a user study to test this assumption. Using an introduced readability measure, based on the measuring the similarity of the alternatives networks, I obtained a fair degree of readability of the difference visualizations, which confirms the appropriateness of the design choice of the technique (for at least this dataset). I also presented a new user interface mechanism to interact with omitted unchanged nodes in difference view visualizations, via a "reveal-to-edit" feature. In part, these techniques were inspired by Shireen et al.'s [97] conceptual sketch of a user interface to enable parallel generation and editing of design alternatives as an extension to existing variational CAD tools. *MACE* is the first realization of these concepts and includes several substantial extensions. Shireen et al.'s prototype only concentrated on changed nodes. Their work was focused on the creation of alternatives and not truly on visualizing differences. *MACE* suggests a solution to both issues and thus can be used for creating alternatives and for visualizing differences or both together. I also introduced new difference visualizations for edges and parameters as well as a parameter post-hoc synching method within the difference visualization. In *MACE* differences are illustrated in all: the output, parameter and network views in different ways. The "reveal-to-edit" feature is also an improvement relative to Shireen et al.'s work, as it avoids the problem that dragging of nodes to reveal them does not scale to multiple alternatives. Clicking while holding a modifier key is a better option and is also more consistent with standard conventions. Creating and editing alternatives via the *MACE* interface has the advantage over the visually unenhanced parallel editing (see 4.1.1) in that the differences between the original (reference alternative) and the compared alternative are immediately visible. Finally, by tuning the interface for multi-monitor setups I demonstrate that our approach is scalable.

In my difference visualization technique, nodes in a compared alternative view with any type of change (new, deleted or modified) are connected with the corresponding nodes in the reference view. Unless a connector to an unchanged node is added or removed (relative to the reference), I chose to omit unchanged nodes from the difference visualization, as we expect more commonalities among the alternatives compared to differences. After all, a designer will generally work on alternatives for a single design goal. I believe that this design choice, along with synchronized node positioning, zooming and panning, substantially reduces the eccentricity effect [112] when comparing networks. This effect suggests that the farther two pieces of information are from each other in the visual field, the harder it is to divide attention between them. In multi-monitor environments, compared alternatives may be located far apart from each other. This effect was also one of the motivations why I reversed the positioning of the network and output views in the bottom monitor row. By favoring close positioning of networks, I put the output views at a relative disadvantage because they are now further apart. The ability to re-arrange the alternatives suggests a solution to this problem when side-by-side comparison of models is needed.

The difference visualization technique that I propose here can scale to displaying differences of many alternatives with any number of changes, thanks to the node-focused visualization and diff exclusion. However, the effectiveness of the approach decreases as the number of changes and alternatives increases because of the clutter that is generated as a result of comparing many alternatives with multiple changes. The user still can perform comparisons but may be required to use the node-focused visualization and diff exclusion extensively.

To investigate the usability of my approach I conducted an exploratory interview with three expert designers having 5–30 years of experience in generative design on an earlier version of *MACE*. I first introduced the interface and its components, let them experiment with it, and then asked for feedback on each feature. Most of their feedback was positive and confirmatory towards the major motivations for this system. A number of issues were pointed out, which were addressed. These included the need for fine-tuning of the GUI. One expert suggested that beyond node coloring it would be nice to add “+” and “-” symbols, for added and removed nodes respectively. I took this thought further and added the “=” and “≠” symbols to highlight parameter changes better. This then supports red-green colorblind users as well. When playing with the reveal-to-edit and other features of our interface, one of the users pointed out that parameter synching at the node level would be useful and I added this feature. All the experts rearranged the alternatives within the workspace and selected different alternatives and/or nodes to more rapidly identify differences between the models. The idea of jamming spaces as realized in our system was also very well received. Users more or less immediately identified how this was useful to their workflow. One commented: “This way I can easily focus only on a subset and don’t have to see every [difference] at the same time”.

I believe that the ideas behind *MACE* generalize to other visual programming environments, including 3D modeling (e.g., *Grasshopper 3D*, *Houdini*). For other types of media, such as video or audio (e.g., *Max/MSP*), a different approach to illustrating differences may be necessary.

5.5 Summary

In this chapter I presented *MACE*—novel interface for differencing and editing alternatives in a generative design system. This was implemented as an extension of *GEM-NI*—a system for creating and managing alternatives in generative design. My new difference visualization technique enables comparison of *more than two* alternatives at a time. The technique is based on the idea of subtractive encoding which I identified as being useful in data that has more similarities than the differences, such as alternatives. I used a readability measure to confirm the appropriateness of the approach for at least one dataset of alternatives produced by designers. My new user interface enables the user to interact with omitted unchanged nodes in difference view visualizations, via a new “reveal-to-edit” feature. This feature improves parallel editing in that the differences between the original (reference alternative) and a clone are immediately visible during editing. The autosandboxing further facilitates alternative exploration I introduced new ways to emphasize added, deleted, (un)changed nodes, recursive group nodes, as well as edges. Finally, I implemented multi-monitor support to demonstrate that my difference visualization technique scales well to up to 20 alternatives. Finally, I introduced a new “jamming spaces” technique for assigning individual monitors into different visualization states. This makes organization of a large workspace easier.

Chapter 6
Additional Discussion

Beyond the discussions mentioned in the above chapters, I discuss here a couple of additional insights from my presented work.

6.1 Parallel Exploration of Alternatives in *GEM-NI*

In Chapter 1 as identified by Krish [65], I stated that *GEM-NI* (together with the *MACE* interface) through explicit support for parallel exploration of alternatives complies with all the requirements that need to be met for computer-aided design tools to support conceptual design. Here, I clarify how I achieved this.

- ***GEM-NI makes minimal demands on and minimal disruption to the designer's work processes.*** Alternative creation, checkmarks and sandboxes along with merging, minimizing and retrieval are mechanisms that are minimally intrusive to the designer's workflow for alternatives. While in my findings checkmarks and sandboxes happen to be used quite extensively, this could potentially become intrusive. But this issue can be resolved (see Section 6.4)
- ***GEM-NI is flexible in allowing the designers to navigate the design space in the way they see fit.*** The decision to use stable network layouts with synched zooming and panning enable seamless navigation of many design options simultaneously. The *MACE* interface further makes comparison of these design options much easier. The ability to quickly generate new alternatives, to minimize and retrieve them as well as the multi-monitor support facilitates the organization of the workspace. The design gallery and history interfaces further enable easy exploration of "what if" scenarios without commitment.
- ***GEM-NI is able to support chaotic and unstructured work processes.*** *GEM-NI* supports such non-linear processes by enabling the generation of alternatives through branching and resurrection from history. Merging further enables post-hoc reintegration

of changes across alternatives. All these mechanisms support unstructured work processes in a seamless manner.

- ***GEM-NI is an assistive tool, giving the designer the choice to either use it or not use it.*** All the features that define *GEM-NI* and *MACE* do not interfere if the designer chooses to use the tool for creating a single design document, i.e., if s/he chooses not to take advantage of the explicit alternatives support the tool provides.
- ***GEM-NI supports and enables emergence in order to stimulate the creativity of the designer.*** In the second user study, participants created more alternatives with *GEM-NI*. The analysis of the CSI questionnaires in the user studies underscored that *GEM-NI* was particularly highly ranked for exploration. It can be argued, that this in turn enables emergence. Another feature that supports emergence is the novel design gallery.
- ***GEM-NI enables an efficient transition of design content from the conceptual to the detailed design phase.*** Elements of the conceptual design process are supported in *GEM-NI* through the support of alternatives. *Nodebox*, and consequently *GEM-NI*, which inherits its functionality inherently supports detailed designs. First, it is fairly easy to construct simple designs. Yet, the large palette of computational nodes in *NodeBox 3* together with the seemingly limitless possibility for combinations enables almost limitless refinement of any given design. Furthermore, the ability to implement custom nodes with Python scripting permits users of *GEM-NI* to create even more detailed designs. In fact, the L-system functionality described in Chapter 4 is an example where custom created extensions were employed. Appendix B presents examples of some of the noteworthy designs that were created by participants in a short amount of time allocated for the workshop. Some of them already show signs of detailed design.

Besides, *GEM-NI* through explicit support for parallel exploration of alternatives addresses the following obstacles for conceptual design support of computer-aided design as also identified by Krish [65]:

- ***The invasiveness of frameworks impedes the thinking effort making it difficult to automate conceptual design.*** To counter this, *GEM-NI* gives the designer the “freedom to create, modify and discard” (Krish [65]). Freedom to create is enhanced with a selection of alternative generation methods. Editing is enhanced with merging and the *MACE* interface. *GEM-NI* supports both: destructive discarding and non-destructive minimizing of currently unwanted content.
- ***CAD in its current form is unsuitable for representing and considering vague concepts and forms.*** *GEM-NI* introduces support for creating and managing multiple alternatives, which reduces the need for premature commitment. Yet, I acknowledge that the system in its current form cannot yet approach the vagueness of sketching.
- ***CAD does not provide the creative stimulation that designers derive from the process of hand sketching. Essentially the tools ignore that designs are developed based on reactions to previously generated concepts.*** *GEM-NI* addresses this by supporting a highly non-linear workflow through branching, resurrection from history, the design gallery and merging. All these features are used to enable designers to react to and build on previously generated concepts.
- ***Design is an iterative process of searching the design problem space as well as the solution space. Designs and solutions co-evolve, during the design process. This is not supported.*** *GEM-NI* supports iterative and parallel exploration of design options. The link between the design and solution spaces is always guaranteed, as changes to the model always immediately update the output view. *GEM-NI* supports iterative exploration through its ability to branch off, merge, and reorganize alternatives, as well as their minimization and retrieval.
- ***Many possibilities are considered and most of them are discarded at the early stages of design. In this context, designers need to represent a wide range of concepts efficiently. They are, therefore reluctant to invest the additional effort required to represent such concepts in CAD.*** History, branching, the design gallery and merging

are the mechanisms that aim to ensure that concepts created with *GEM-NI* are "cheap" to create in terms of effort.

6.2 *GEM-NI* as a Subjunctive Interface

GEM-NI also supports the three design principles on which *subjunctive interfaces* are built, as identified by Lunzer and Hornbæk [70]:

- ***Enabling setting several, perhaps totally different scenarios independently.*** This is primarily achieved through the support for multiple alternatives, which can potentially be totally independent. In fact, one of *GEM-NI*'s strengths is that it seamlessly supports the full spectrum from completely independent to fully identical alternatives.
- ***Displaying multiple scenarios simultaneously to facilitate comparison.*** This is supported explicitly through juxtaposition. Moreover, the *MACE* interface is designed to further facilitate comparison.
- ***Synchronous adjustment of multiple scenarios to escalate the exploration process.*** This is achieved through parallel editing, using checkmarks and sandboxes.

6.3 Revision Control

GEM-NI was designed with the goal of supporting alternatives. However, the same ideas can also be used for revision control, similar to Doboš and Steed's [28,29] approach for 3D models and Chen et al.'s [23] approach for images. In this sense, alternatives can be thought of as significant events, which can be committed. Workspaces are then equivalent to repositories. The *MACE* interface, designed to compare alternatives, can then be re-envisioned as a tool to compare versions.

6.4 Guidelines for Re-implementation:

GEM-NI and the *MACE* interface were implemented as a branch *NodeBox 3*. For convenience, I chose *NodeBox 3* as a foundation because of the many provided features. *NodeBox 3* is representative of a generative design system. It uses dataflow programming. It has been previously used for visualization and generative art [101]. This choice enables the potential use of my results in a wider spectrum of applications, compared to a tool more targeted at a single domain.

Unsurprisingly, *NodeBox 3* was not designed with supporting alternatives in mind. The code follows, what Terry and Mynatt [106] refer to as, the *single state document interaction model* which recognizes and requires a document to be in one, and only one, state at any particular time. This is a poor match to the non-linear, experimental processes characteristic of creative endeavours [106]. To work around this limitation, I had to implement the features of *GEM-NI* and *MACE* in an intrusive manner, where I sometimes had to violate good software-engineering principles. E.g., each method that affects the state of the document had to be modified to push changes to all alternatives. This was further made worse by the fact that some alternatives may be idle. Global undo adds another layer of complexity. As a result, the implementation was not efficient. Because *NodeBox 3* follows the single document state model, I also had to introduce UUIDs for the nodes to distinguish the states of nodes in different alternatives. In hindsight, this approach is only suitable for retrofitting into existing systems.

A better approach is to design the system from scratch by including support for alternatives from the start. One example of such an approach, currently work-in-progress, is the Shiro[21] dataflow programming language designed to be embedded into applications that support reuse and the exploration of alternatives. The language provides designers with syntax to describe alternative designs or analysis solutions. In Shiro nodes can be subjunctive, i.e., exist in multiple states. This allows a cleaner implementation with less shared data. This approach should be considered by those re-implementing *GEM-NI's* approach in their application domain.

NodeBox 3 utilizes the standard undo manager from `javax.swing.undo`. To enable undo history duplication, I created a custom undo manager, which supports duplication of the undo stack. This functionality is used when creating branches and alternatives from

[21] http://github.com/jrguenther/shiro

history. To support global undo, I use another stack, which keeps track of every undoable operation that was done and the alternatives that were affected by this to enable me to identify potential undo conflicts and to clear the global undo stack if such a conflict occurs. This is a simplified implementation that may not handle all use cases. Yet, in the user studies, global undo was used only infrequently, also because participants did little parallel editing. Thus, I currently see little need for a more sophisticated global undo/redo-method in a system such as *GEM-NI*. The majority of the participants focussed on one design at a time, and if necessary, re-integrated ideas from previous work through merging. Thus, I believe that one area for future development in *GEM-NI* should focus on better methods for post-hoc merging, e.g., by coming up with visualizations that identify which parts of the merge could not be completed.

During the workshops some participants pointed out that *GEM-NI*'s interface is unintuitive with regards to parallel editing. In a future re-implementation parallel editing should be offered as an option rather than imposed on the user. Passive alternatives should appear only when desired explicitly by the user and not by default. This will leave merging as the main mechanism of pushing changes. To make the merging mechanism more versatile, future implementations should introduce the concept of a timeline and allow the user to merge the timeline of one alternative with that of one or more other(s). The history mechanism is currently limiting in that it only permits the creation of alternatives from history and not the merging of parts of history. Also history is based on undo and, as a result, the history of edits from earlier application sessions is not available, as the undo stack is currently not preserved during saving and re-opening.

Finally, there are limitations in *NodeBox 3* that future implementations should address. One example is the inability to embed recursion into the data-flow programming model that is employed in *NodeBox 3*. As discussed in Section 4.5.5 this prevented me from taking full advantage of the *GEM-NI*'s comparison features when relating networks with recursive nodes to each other. Moreover, *NodeBox* contributors decided to abandon the support for the "tweaking" of existing nodes since version 3. In *NodeBox* 2, it was possible to directly modify and display the python code, which stands behind each node in the system. Although I acknowledge that this may not be a feature that the majority of designers must have, I disagree that it was necessary to remove this feature from the latest version. Power users generally appreciate such a feature and use it to solve many interesting problems. In addition to that, I could have added in *GEM-NI* the ability to merge differences between different alternatives directly in python code. Then, I could also have augmented the *MACE* interface to perform difference visualization also on the code of the python-based nodes.

Chapter 7
Conclusions

The work towards this dissertation started with the objective to address the lack of previous quantitative research on generic diagram visualizations that support merging of diagram versions. To investigate this, I introduced a new system for differencing and merging diagrams that use of Dual View, Animation, Re-Layout, Layers and a Storyboard, abbreviated *DARLS.* The system is targeted at diagrams with node and edge attributes. Such diagrams, among other areas, are used frequently in generative design for dataflow programming. I ran two user studies to investigate the benefits of the introduced difference visualization techniques and found that naïve dual-view visualization was not well received. The dual-view option with a difference layer was most preferred for comparing diagrams with matching node positions. For diagrams with non-matching positions, I found evidence that animation is beneficial, but that the combination with a difference layer was liked best. In summary, this dissertation reveals that the difference layer technique is useful and a good complement to animation. This had positive implications for the diagram merging method that was introduced. The findings of the user studies suggested that stable layouts across the network views of alternatives in *GEM-NI* should be used for facilitating comparison of dataflow programming. As a result, I implemented this technique. Also, I implemented the merging method of *DARLS* in *GEM-NI* in the context of generative design and multiple alternatives to support merging of dataflow programming models. I evaluate the technique later. The evaluation revealed that the technique could be useful for complex models. The layering technique that I explored with *DARLS* I revisited in *MACE* and adopted it for showing differences for more than two alternatives.

This dissertation investigated how introducing various forms of exploration with design alternatives into generative design seen in manual sketching affects creativity support. To address this, I introduced the techniques in *GEM-NI*—a graph-based generative-design tool that I built, which supports parallel exploration of alternative designs. These techniques were: parallel editing, recalling history, branching, merging, comparing, and Cartesian products of and for alternatives. Further, I introduce a modal graphical user interface and a design gallery, which both allow designers to control and manage their design exploration. Many of the introduced techniques are novel in the context of generative design and in general. I investigated the usefulness of my approach through user studies and interviews. The feedback from participants in the first study and in-depth interviews suggest that *GEM-NI,* and more broadly the approach behind it, indeed enables designers to work more creatively. The results indicate the direct applicability of the presented techniques for the design process also via the CSI questionnaire. While the sample size of my first user study was small, it identified the potential for better creativity support through alternatives in design tools. I repeated the study with a larger sample of participants. *GEM-NI* was found to support exploration better with the new features. This was clarified in the CSI questionnaire. In the freeform feedback, three participants expressed that they wished they had the features of *GEM-NI* available in the generative design tools they use daily.

One of the missing features that I identified early on as necessary in *GEM-NI* was the ability to compare alternatives effectively and easily. I identified that it would be useful to have the ability to compare more than two alternatives at the same time because in the open-ended design tasks a lot of alternatives are created and being able to compare and edit them in an interactive manner is important. To offer a solution to this I extended *GEM-NI* with *MACE* – novel interface for differencing and editing alternatives in a generative design system. My new difference visualization technique enables comparison of *more than two* alternatives at a time. Using an introduced measure I confirmed the appropriateness of the approach for at least the dataset of alternatives produced by designers in my studies. My new user interface enables the user to interact with omitted unchanged nodes in difference view visualizations, via a new "reveal-to-edit" feature. This feature improves parallel editing in that the differences between the original (reference alternative) and a clone are immediately visible during editing. The autosandboxing further facilitates alternative exploration. I introduced new ways to emphasize added, deleted nodes, (un)changed nodes, recursive group nodes, as well as edges. Here, my work builds on a previously introduced, but never implemented concept [97]. The approach extends previous approaches for layering, side-by-side views by going beyond pair-wise comparisons, and shows larger variety of difference visualizations. It also improves my previous parallel editing approach by allowing parallel editing and difference visualization simultaneously in an interactive manner. In the second user study involving *GEM-NI*, I found evidence that users might benefit from more display space than afforded by a dual-monitor setup. As a result, I implemented multi-monitor support in *MACE* to demonstrate that my difference visualization technique scales well to up to 20 alternatives. My novel jamming space feature takes advantage of the multi-monitor support to ease organizing a large workspace by assigning individual monitors into different states. It has been already known that users tend to organize their space [13,88]. The jamming space technique, therefore, takes this natural human behaviour to the next level by supporting forced states to enable better organization. To investigate the usability of my approach I conducted an exploratory interview with three expert designers having 5-30 years of experience in generative design on an earlier version of *MACE*. The comments I received were confirmatory towards the major motivations of the interface. Their feedback resulted in the addition of the sandboxing, autosandboxing, parameter synching and the improvement of the visualization that addresses color-blind users.

7.1 Generalization of the Introduced Approaches

I am confident that the techniques introduced in this work can be used not only for generative design in 2D vector graphics, but in other domains as well. This has been confirmed in the second user study of *GEM-NI*, since some participants expressed their desire to have the features available in their everyday workflow. This, first of all, applies to visual programming environments in 3D modeling (e.g., *Grasshopper 3D*, *Houdini* and *GenerativeComponents*). Here, different visualization techniques would have to be employed for comparing the 3D output. Generally speaking, any system where graph driven visual programming is used, including multimedia (e.g., *Max/MSP*), could benefit from my approach. But for comparing other types of media, such as audio or video, a different approach to output difference visualization may be necessary.

Moreover, outside generative design, some of the concepts used here, such as e.g., parallel editing, checking and sandboxing can be used in other domains as well. In fact, recently a system called *CAMBRIA* [64] has been introduced, where the authors apply the idea to regular 2D vector graphics design.

7.2 Limitations and Future Work

I envision several extensions as follows.

7.2.1 DARLS

Some of my findings indicate that the interaction between differencing techniques and layouts is a rich area for future work. In other words, a closer look is needed at the combined effect of layout techniques, such as my optimal layout method, and specific visualization features. Another direction is the generalization of the work to UML diagrams, with their information-rich nodes and edges. The storyboard can be investigated in more details, e.g., if it can be directly used for difference visualization, similar to small multiples. One idea is to use highlighting on the small views *in combination with* difference layers in the large ones. Yet another direction is to investigate merging. My findings are positive for animation, but more can be done. With larger sets of changes, animating all changes at once may be counterproductive. It can also be investigated whether it makes general sense to break change visualizations into smaller sets for easier comprehension. Currently the system is targeted at diagrams with up to 50 nodes. However, I do not see any major obstacles to enhancing the system to deal with larger diagrams, such as the hierarchies described in [22,76].

7.2.2 GEM-NI

Currently, the network layout is not kept consistent across versions if merging or other editing occurs. The design gallery creates far too many candidates that are too similar. One solution could be to filter candidates by structure and visual similarity. It would also help to display the design gallery next to the Cartesian product menu, so that the changes in the Cartesian product are reflected interactively instead of switching between the two views. Erhan et al. [35] proposed a method based on similarity metrics for making it easier to manage the design space. The method includes parameter selection, computation of similarity between pairs of design alternatives and visualization of their similarity on various forms, clustering and applying filters on the clusters to narrow the scope. One future option is to integrate this method into the system. Also, the multi-monitor aspects of *GEM-NI* can be evaluated on a 2×3 multi-monitor setup through further experiments and interviews.

One direction of future research could be to investigate how versioning can be made more explicit and integrated with alternatives in a design system. One idea is to show the history of how alternatives were created through a tree visualization.

Currently, *GEM-NI* allows parallel editing of all operations and selective merging of all types of states. While all of these operations and types of merging are usable, it remains an open question if supporting all of them makes sense. Future research can target this question. It would also be interesting to investigate how to deal with merging conflicts, and if detecting them helps the users.

7.2.3 MACE

Given that my preliminary usability analysis produced confirmatory results towards the major design decisions, I believe that investigating the effect of the difference visualization techniques in *MACE* would most likely produce trivial results. Also, I had already learned from the user studies with *DARLS* that unenhanced juxtaposition is less effective than highlighting. Moreover, most of the features in *MACE* explicitly highlight things that are otherwise not easily visible and/or have to be understood by repeatedly glancing back and forth, which is less efficient. One potentially interesting user study would be to investigate the scalability of the difference visualization technique to more than 18 alternatives. This number corresponds to three alternatives each, on 2×3 monitors. On the other hand, I believe that such large numbers of alternatives are not that frequent in design. In my user studies, for example, I observed that eight was the maximum number of alternatives participants produced. However, in a different context, such as longer design sessions, the number of alternatives may well exceed this. Another potential study could also investigate if and how the effectiveness of the basic juxtaposition visualization, the diff visualization with and without node focusing, as well as the diff exclusion mode all deteriorate as the number of alternatives increases. Yet another study could investigate the effectiveness of the edge drawing technique in *MACE* that shows connectors back to the reference alternative in comparison to the side-by-side visualization technique with highlighting in *DARLS*. However, this last technique would need to be generalized to more than two views. Another idea is to evaluate the usefulness of the reveal-to-edit approach when creating alternatives.

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Appendix A
Version Pairs of a Course Prerequisites Diagram Used in the *DARLS* User Studies

Most Frequent False Negatives in User Study I

Incremental Layout		Optimal Layout	
Node	**Frequency**	**Node**	**Frequency**
COMP 3403	64	COMP 3403	12
COMP 3481	47	COMP 3481	12
COMP 3214	45	COMP 3214	12
COMP 3431	18	MAST 1025	10
MAST 1025	13	COMP 3431	10
MAST 1310	10	MAST 1310	10
ENGR 3150	2		
COMP 3215	2		

Table A-1. Most frequent false negative nodes.

Incremental Layout		Optimal Layout	
Edge	**Frequency**	**Edge**	**Frequency**
COMP 2031 -> COMP 3215	40	COMP 3213 -> COMP 3481	28
COMP 3213 -> COMP 3481	32	COMP 2031 -> COMP 3215	21
MAST 1025 -> COMP 3431	20	MAST 1025 -> COMP 3431	19
MAST 1310 -> COMP 3101	10	MAST 1310 -> COMP 3451	18
MAST 1310 -> COMP 3451	8	MAST 1310 -> COMP 3213	18
MAST 1310 -> COMP 3213	5	MAST 1310 -> COMP 3101	14
COMP 3201 -> COMP 3215	2		
ENGR 3150 -> COMP 3201	2		

Table A-2. Most frequent false negative edges.

Optimal Layout Heuristics

Heuristic	Value
Minimal Node Distance	20 (pixels)
Minimal Edge Distance	10 (pixels)
First Minimal Segment Length	20 (pixels)
Orientation	Top to Bottom
Node Placement	Linear Segments
Node Ranking Policy	Hierarchical – Tight Tree
Node Order Weight	Barycenter
Transposition	Yes
Removed False Crossings	Yes
Randomization Rounds	40

Table A-3. Summary of optimal layouter heuristics that were used during the User Study I.

Version Pair Summary

No.	**1**	**2**	**3**	**4**	**5**	**6**
Version Pair	1→3	3→4	4→5	5→8	8→10	10→12
Num. of Node in Left View	24	28	28	26	27	26
Num. of Edges in Left View	23	25	25	22	24	23
Num. of Nodes in Right View	28	28	26	27	26	29
Num. of Edges in Right View	25	25	22	24	23	26
Num. of Common Nodes	23	28	25	23	26	23
Num. of Common Edges	23	25	25	23	26	23
Num. of New Nodes	5	0	1	4	0	6
Num. of New Edges	5	0	0	4	2	6
Num. of Deleted Nodes	1	0	3	3	1	3
Num. of Deleted Edges	3	0	3	4	3	3
Total Added	10	0	1	8	2	12
Total Deleted	4	0	6	7	4	6

Table A-4. Version Pair Summary.

Optimal Layout Snapshots

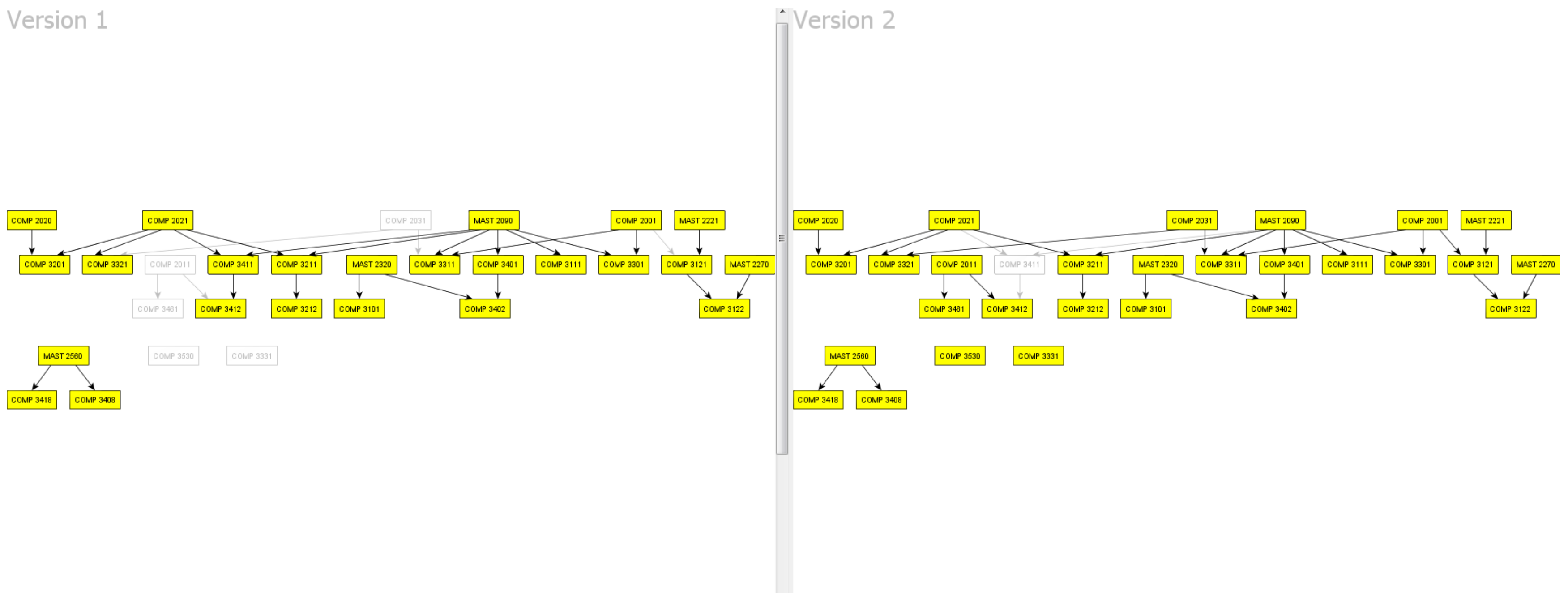


Figure A-1. Optimal Layout, Version Pair #1 (1→3).

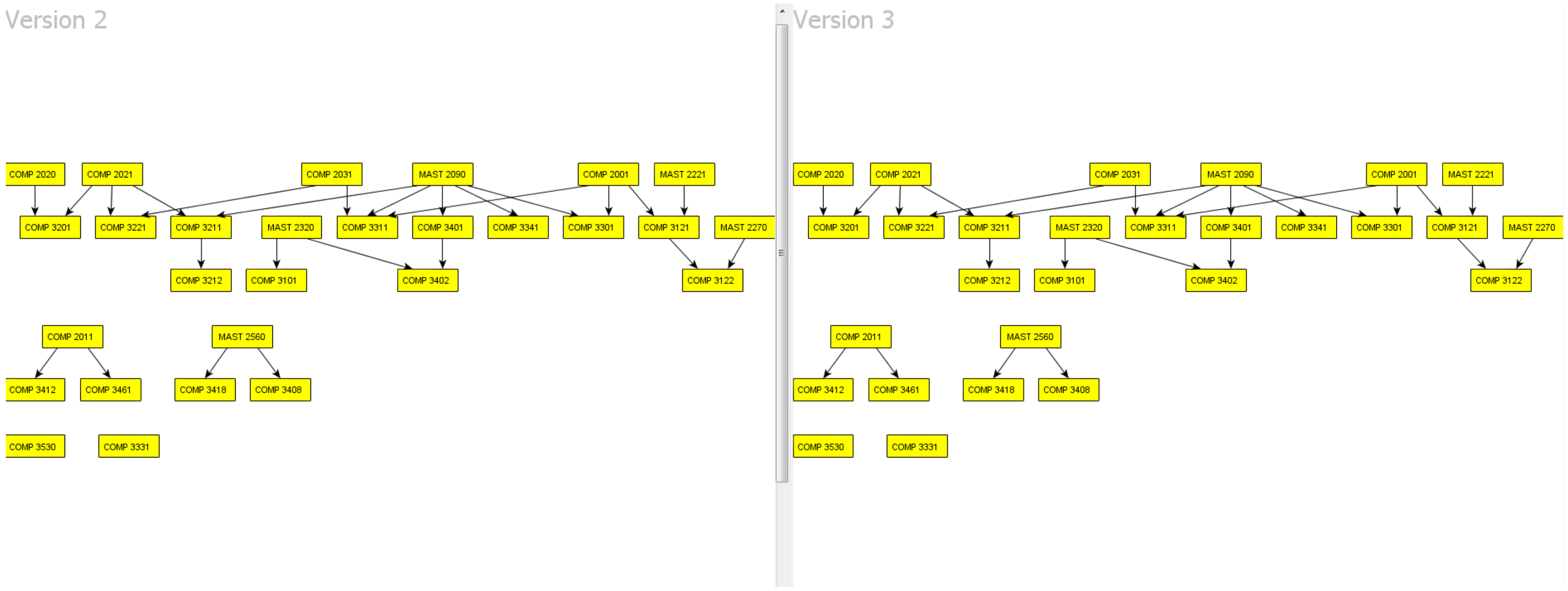


Figure A-2. Optimal Layout, Version Pair #2 (3→4).

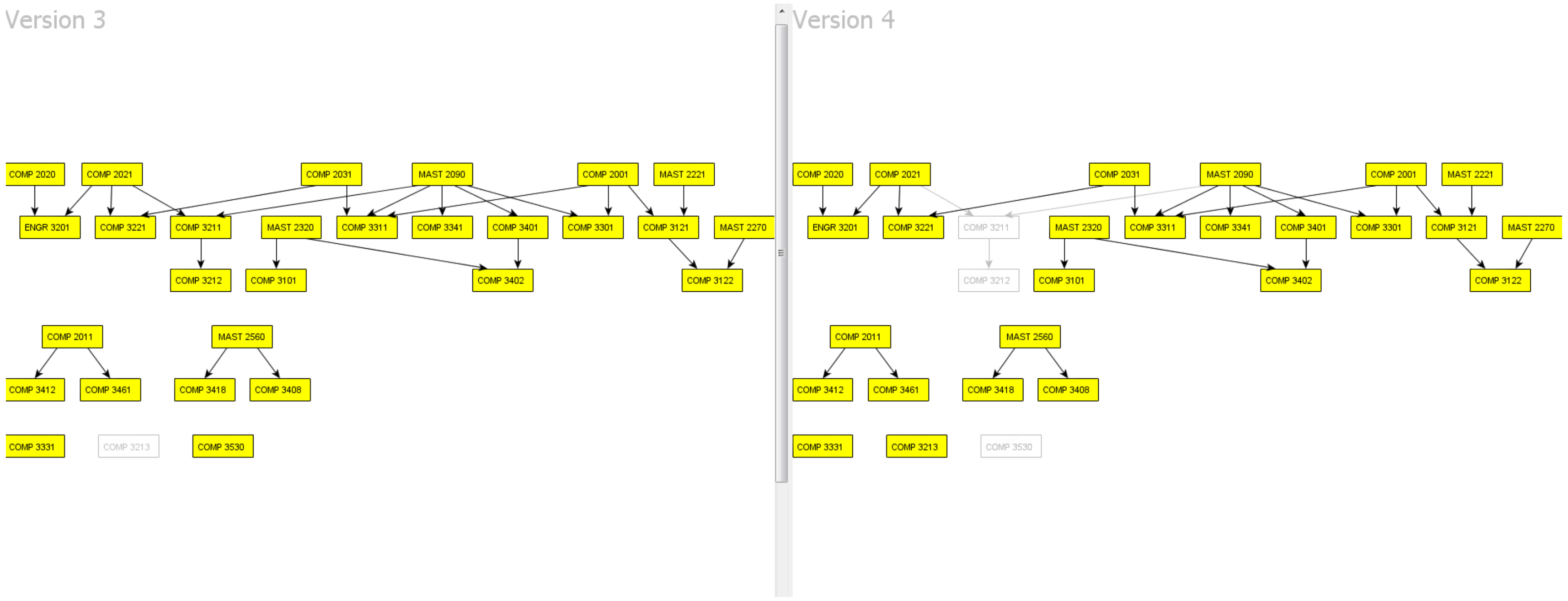


Figure A-3. Optimal Layout, Version Pair #3 (4→5).

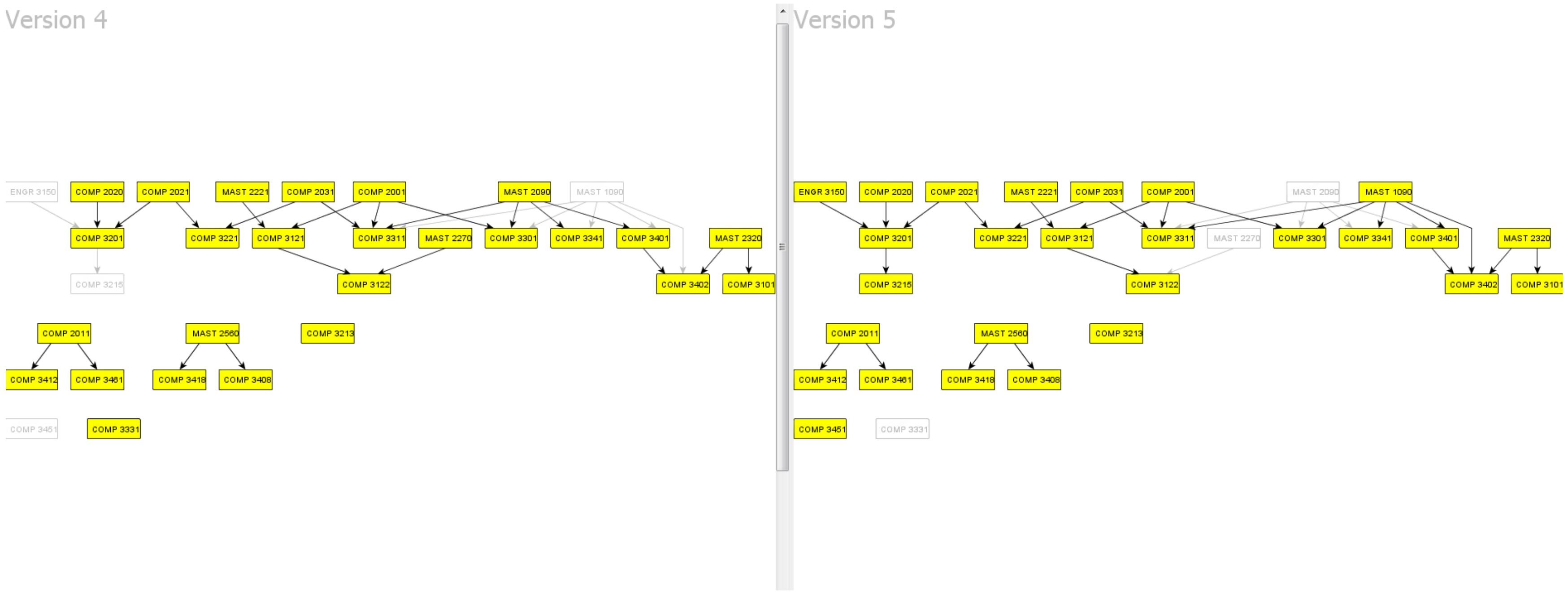


Figure A-4. Optimal Layout, Version Pair #4 (5→8).

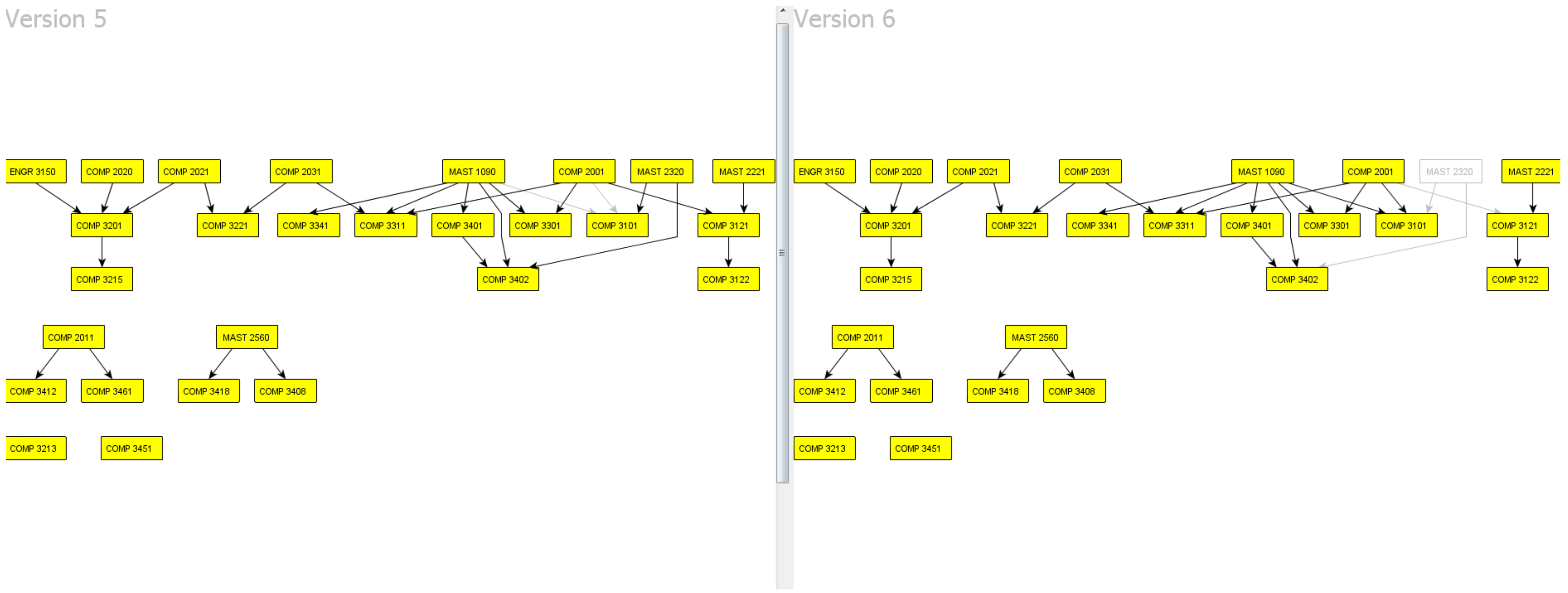


Figure A-5. Optimal Layout, Version Pair #5 (8→10).

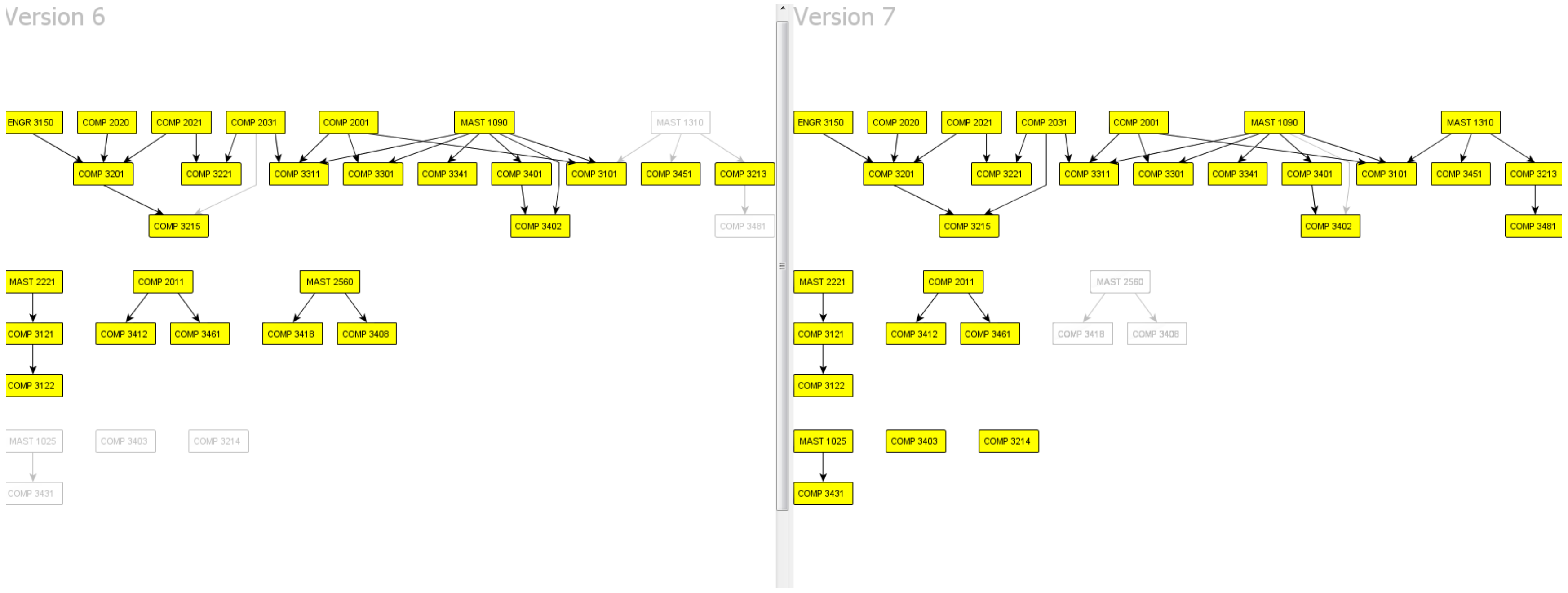


Figure A-6. Optimal Layout, Version Pair #6 (10→12).

Incremental Layout Snapshots

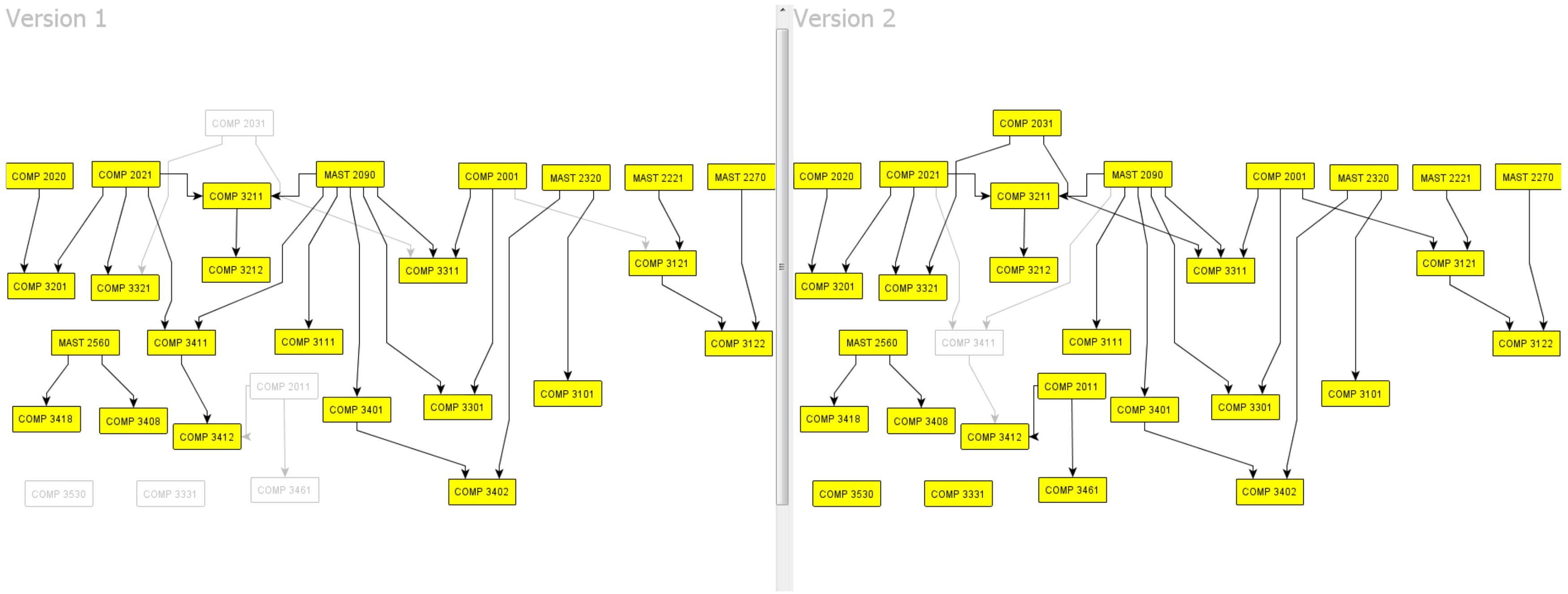


Figure A-7. Incremental Layout, Version Pair #1 (1→3).

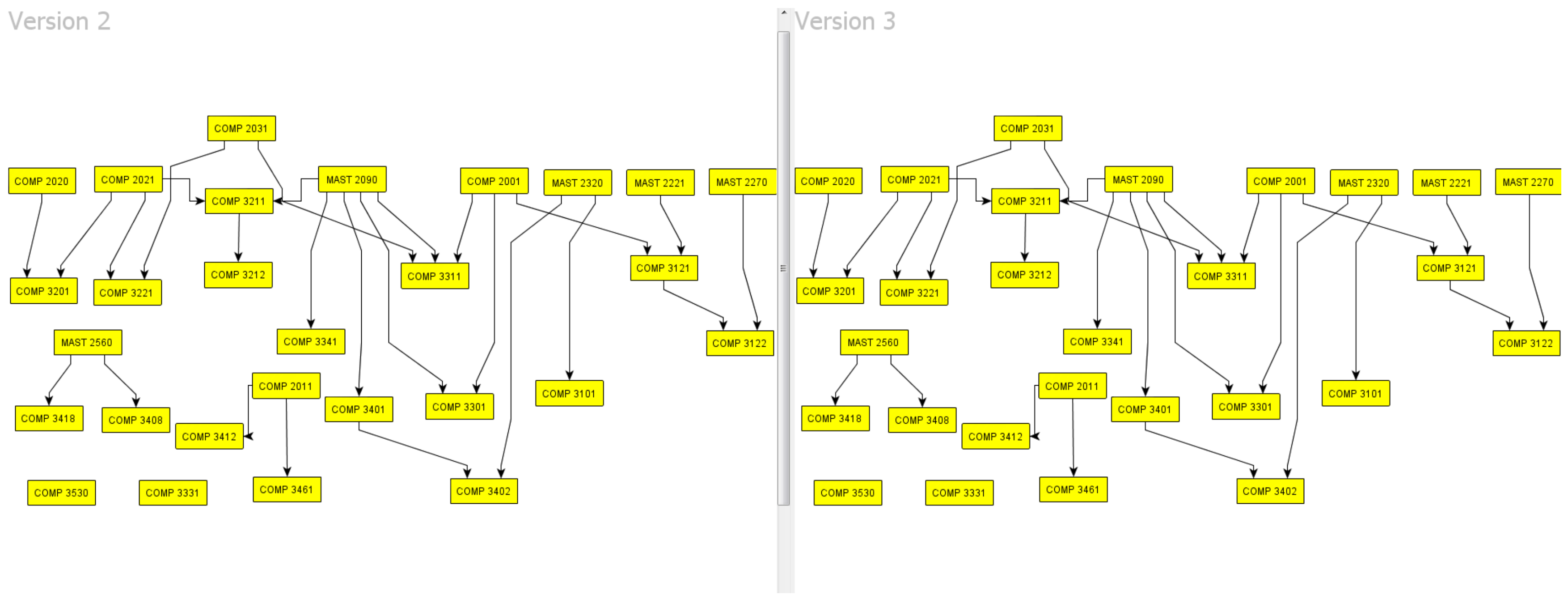


Figure A-8. Incremental Layout, Version Pair #2 (3→4).

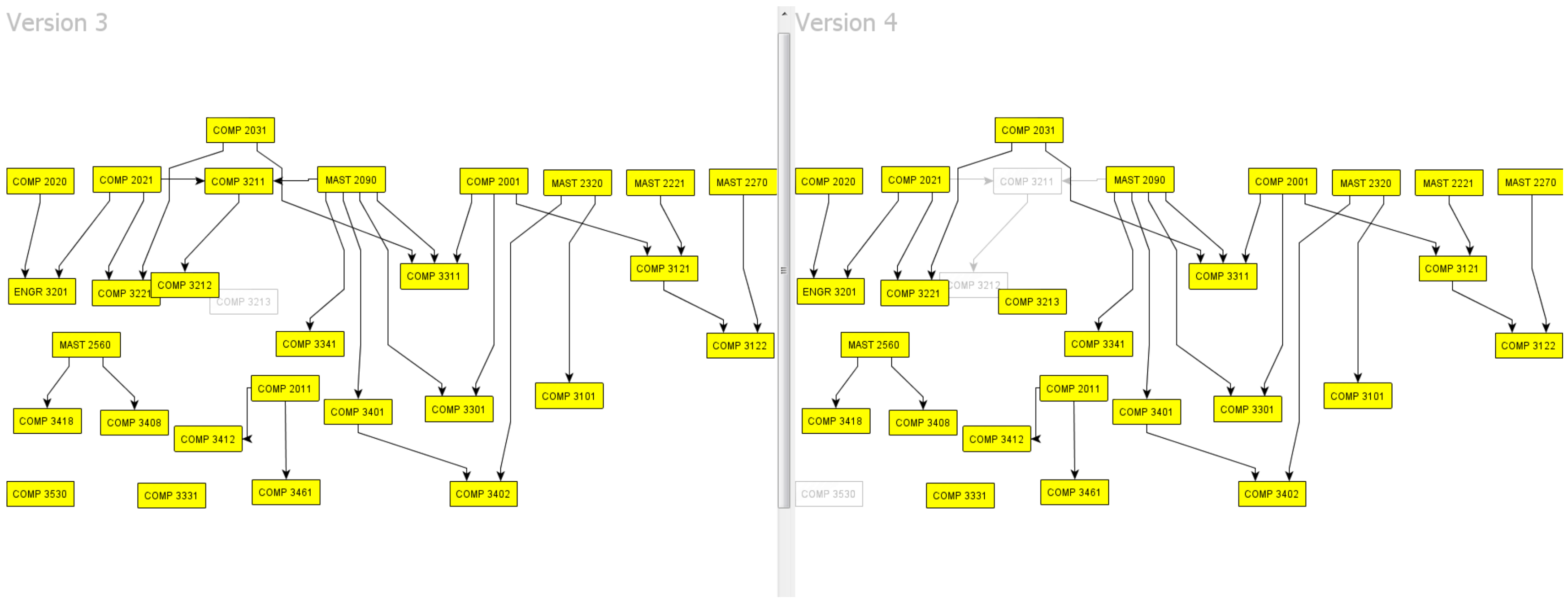


Figure A-9. Incremental Layout, Version Pair #3 (4→5).

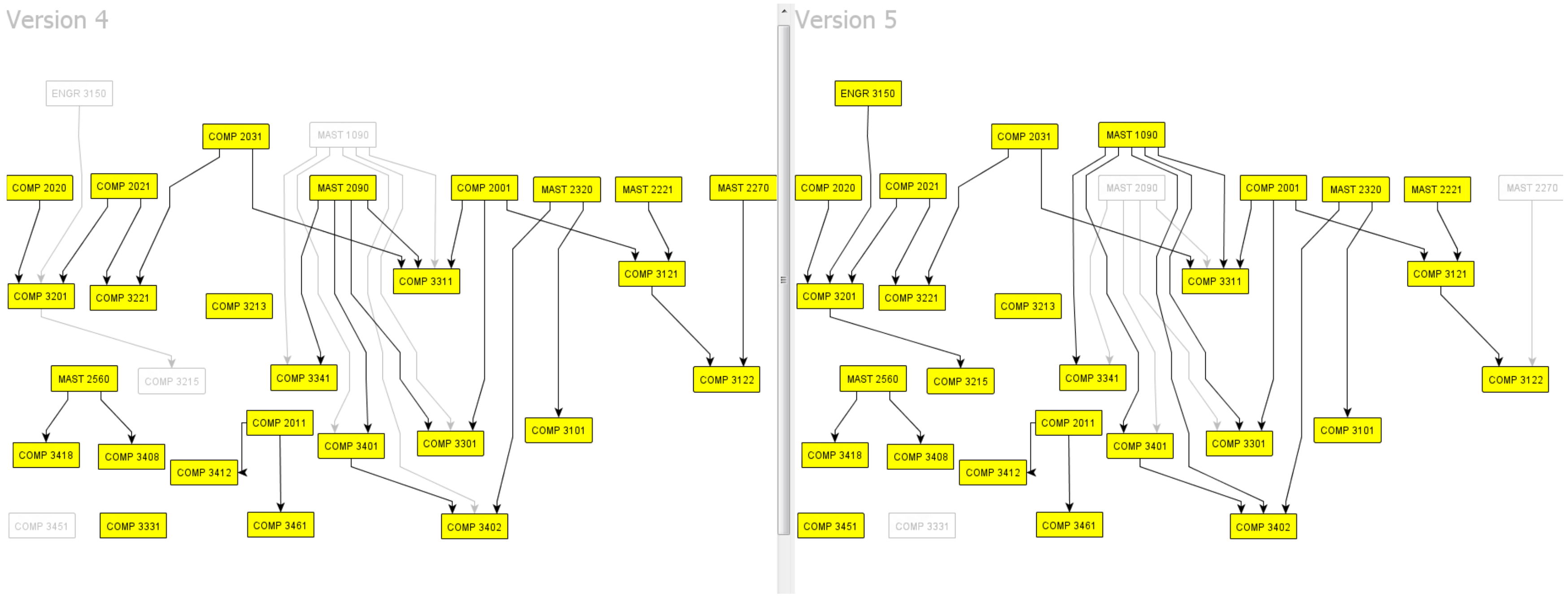


Figure A-10. Incremental Layout, Version Pair #4 (5→8).

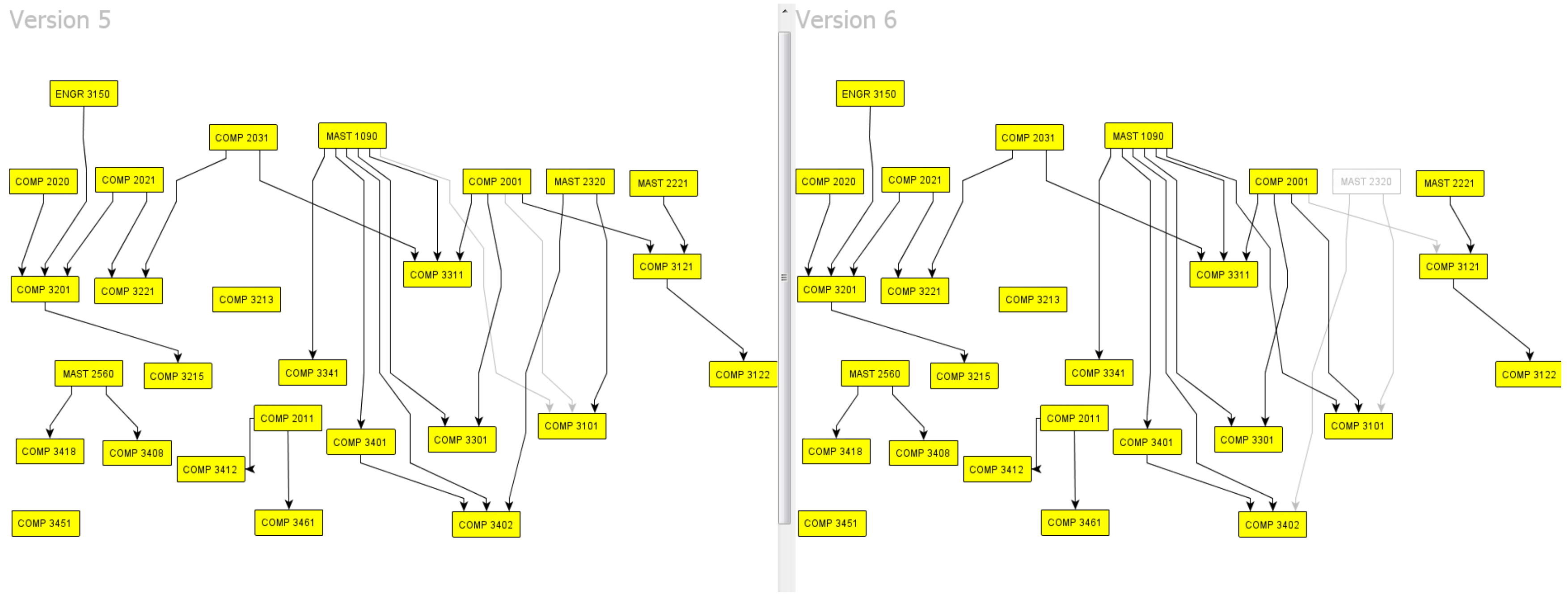


Figure A-11. Incremental Layout, Version Pair #5 (8→10).

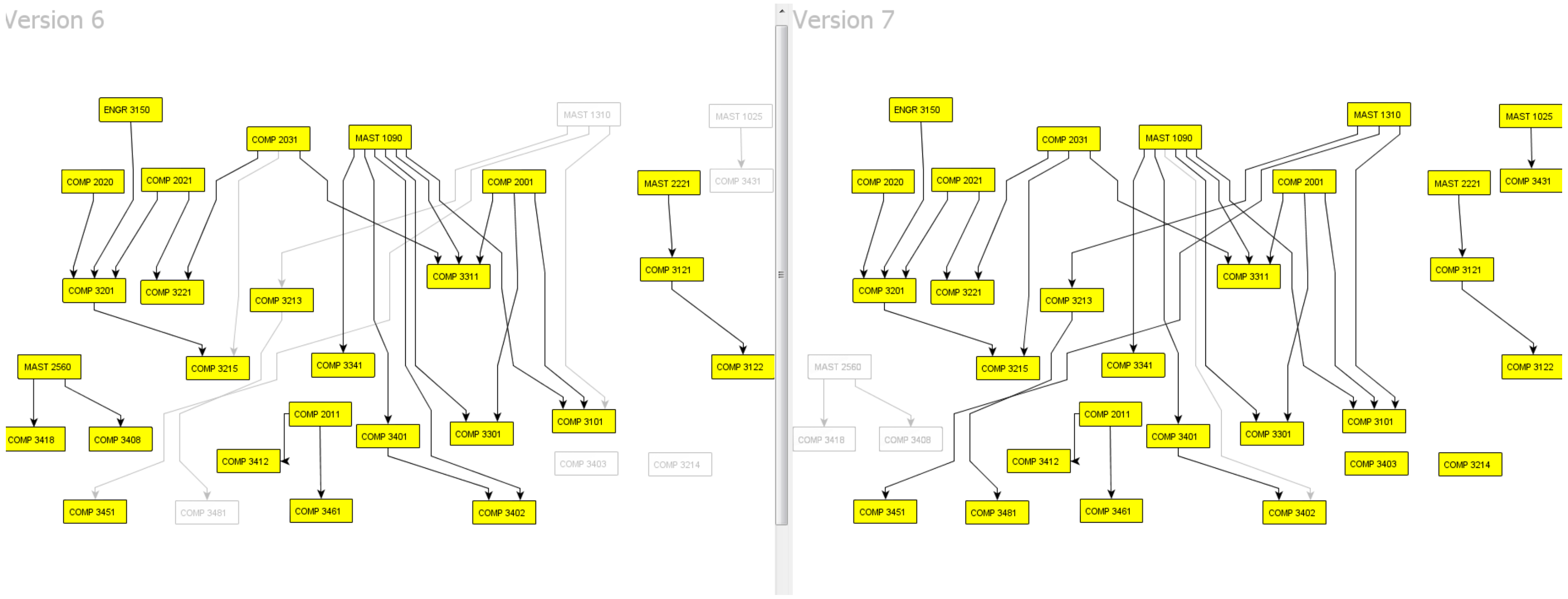


Figure A-12. Incremental Layout, Version Pair #6 (10→12).

Appendix B
Noteworthy Designs of the Workshop Participants with Difference Visualizations

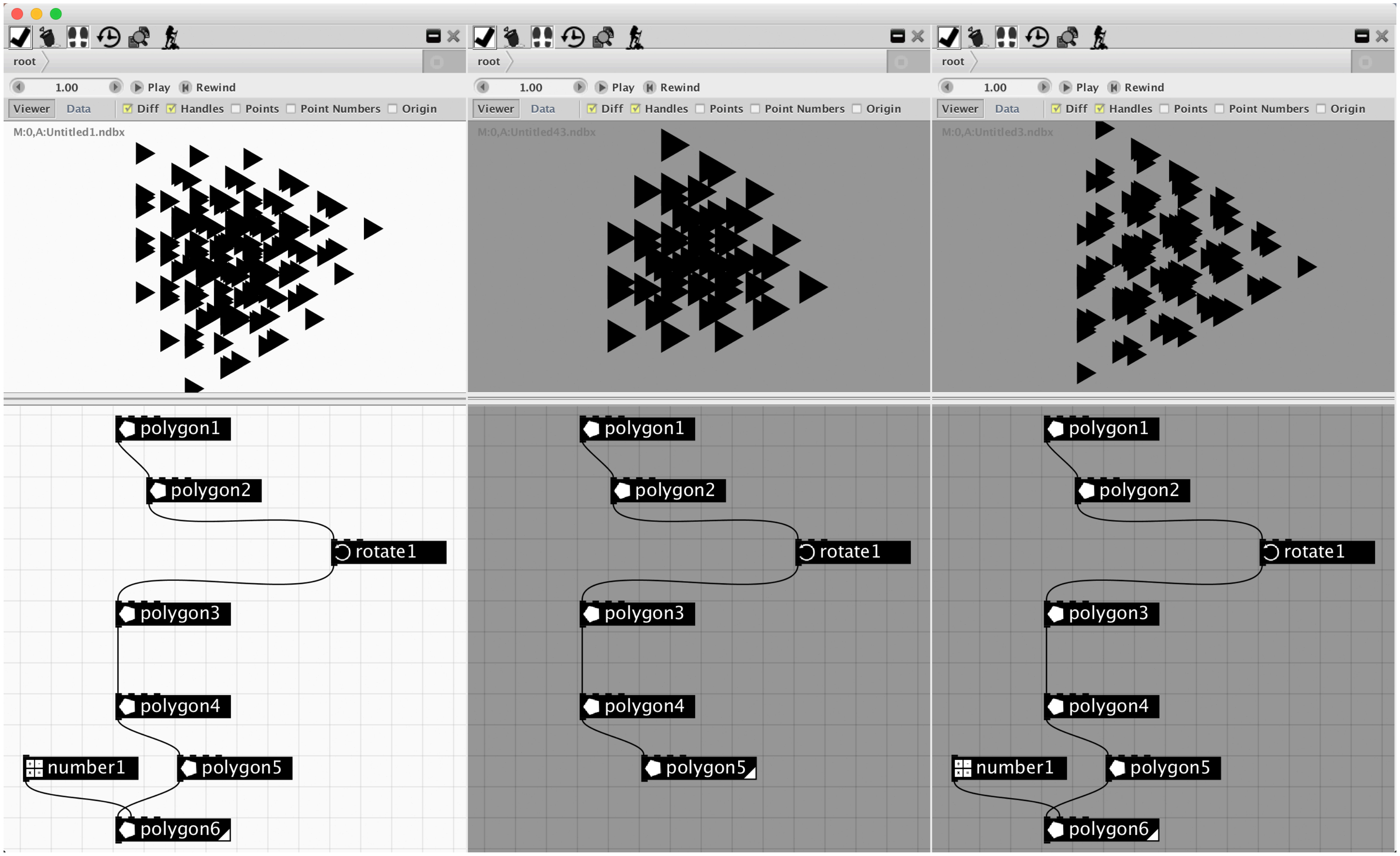


Figure B-1. Design 1: unenhanced view.

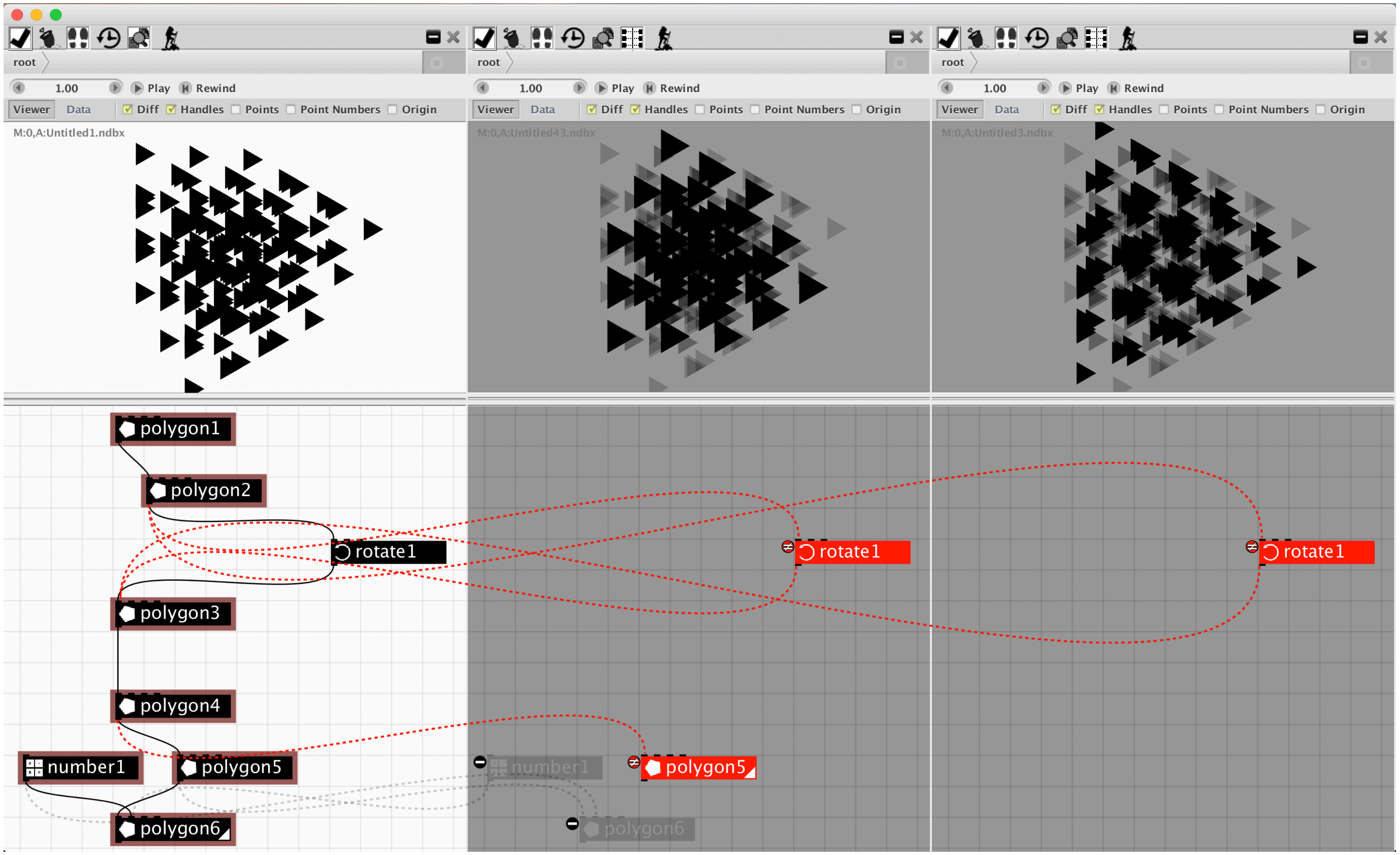


Figure B-2. Design 1: difference visualization view (with subtractive encoding).

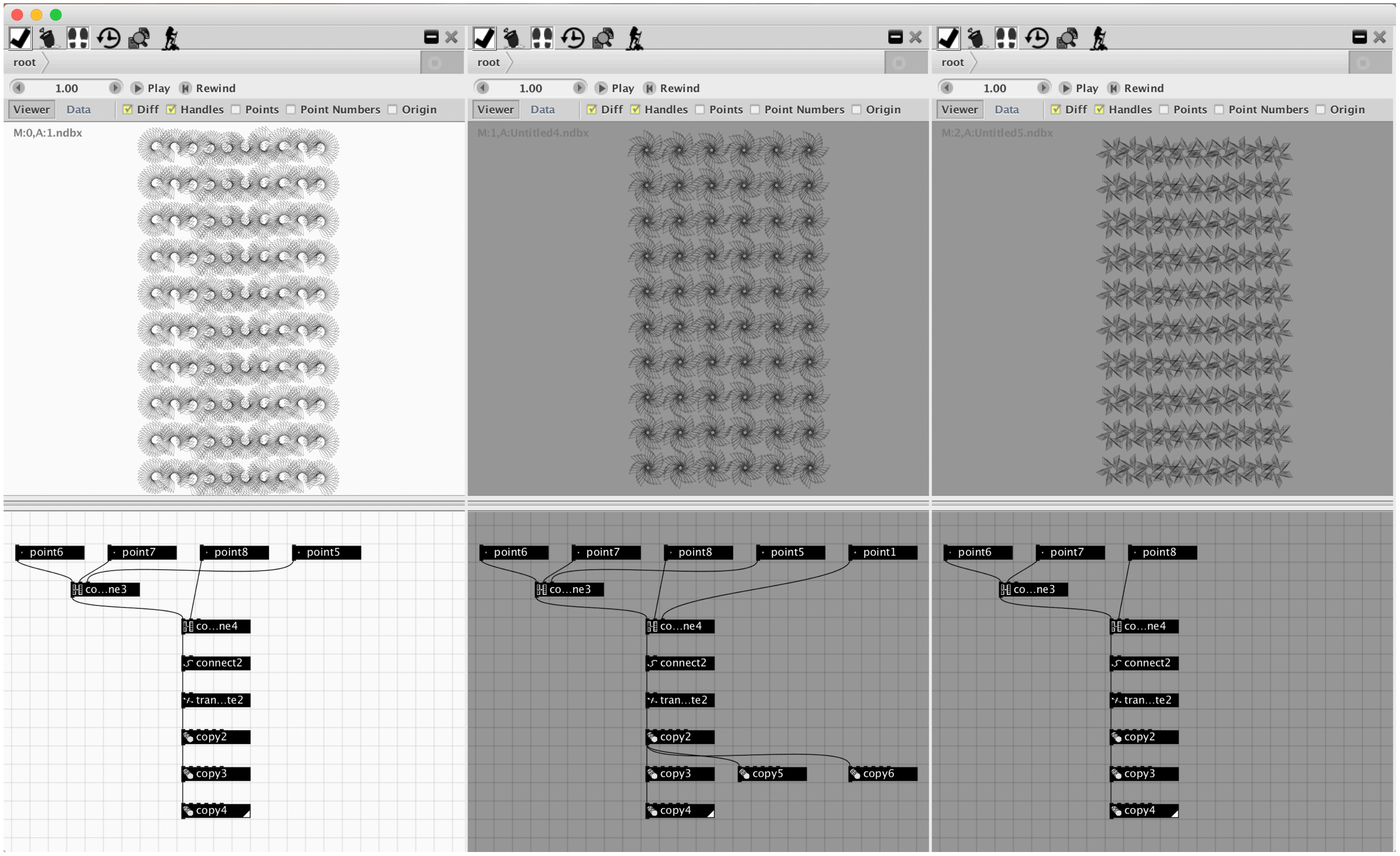

root
1.00
Play
Rewind
Viewer
Data
Diff
Handles
Points
Point Numbers
Origin
M:0,A:1.ndbx
M:1,A:Untitled4.ndbx
M:2,A:Untitled5.ndbx
point6
point7
point8
point5
point1
co...ne3
co...ne4
connect2
tran...te2
copy2
copy3
copy4
copy5
copy6

Figure B-3. Design 2: unenhanced view.

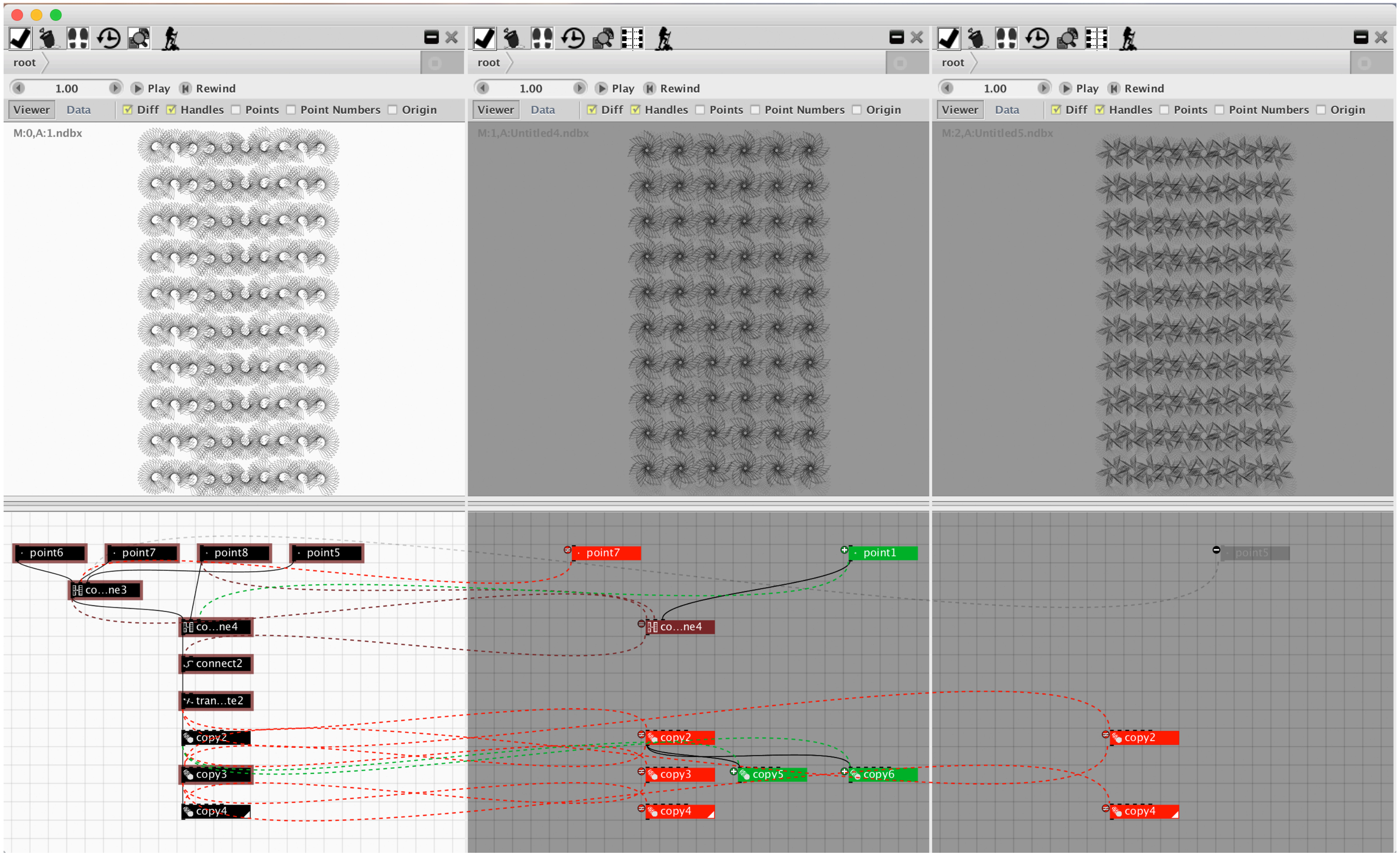


Figure B-4. Design 2: difference visualization view (with subtractive encoding).

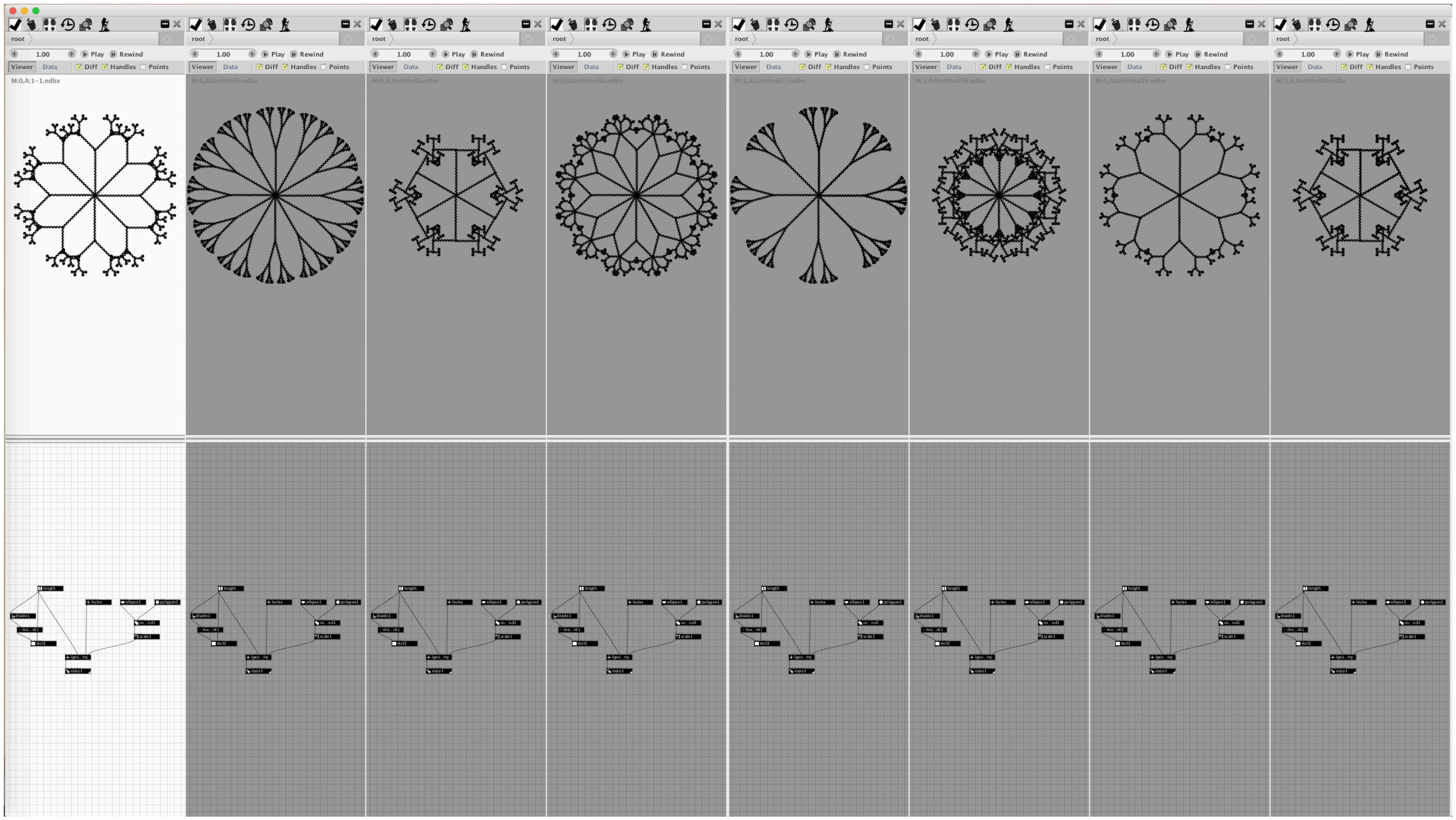


Figure B-5. Design 3: unenhanced view.

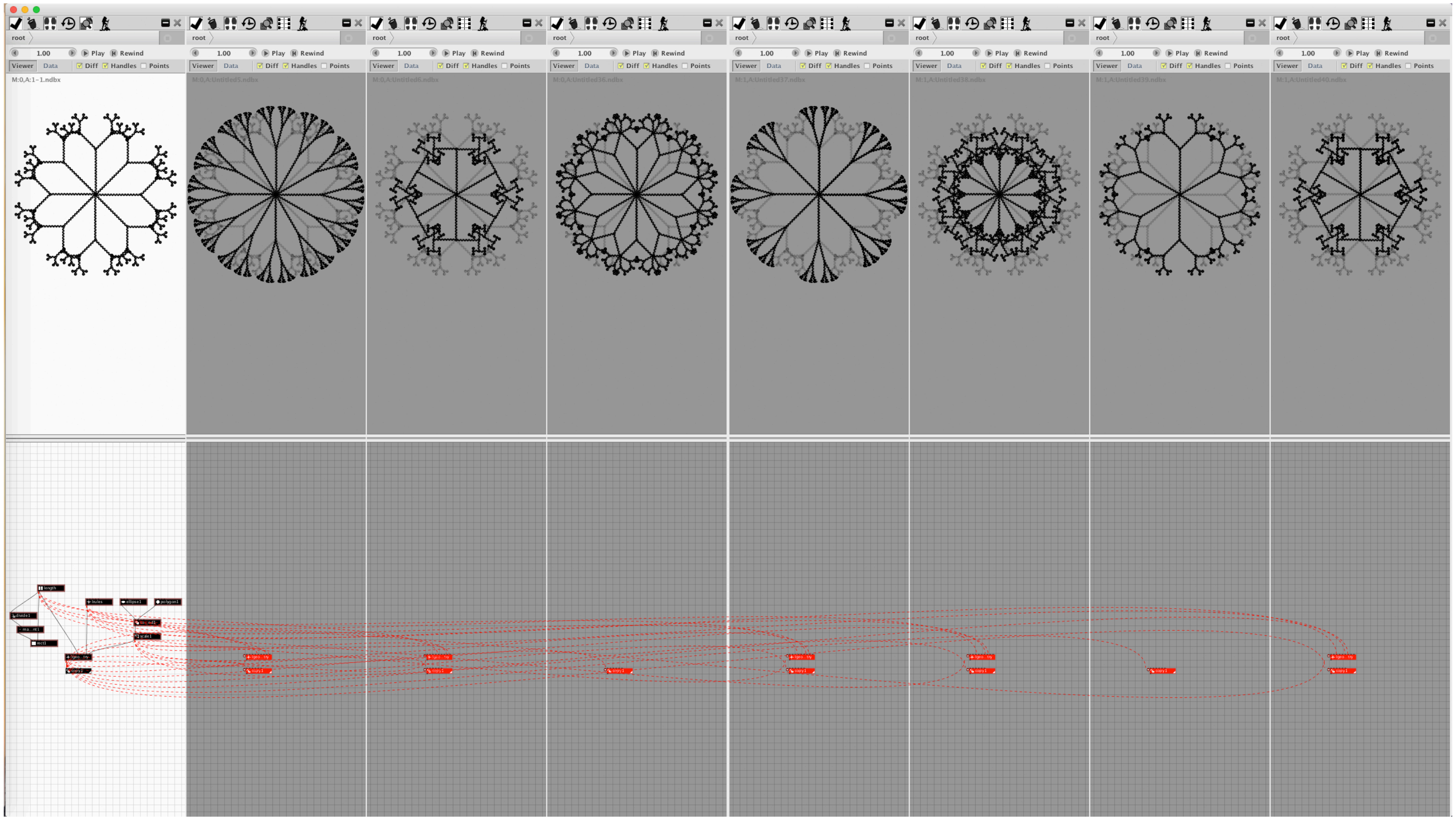
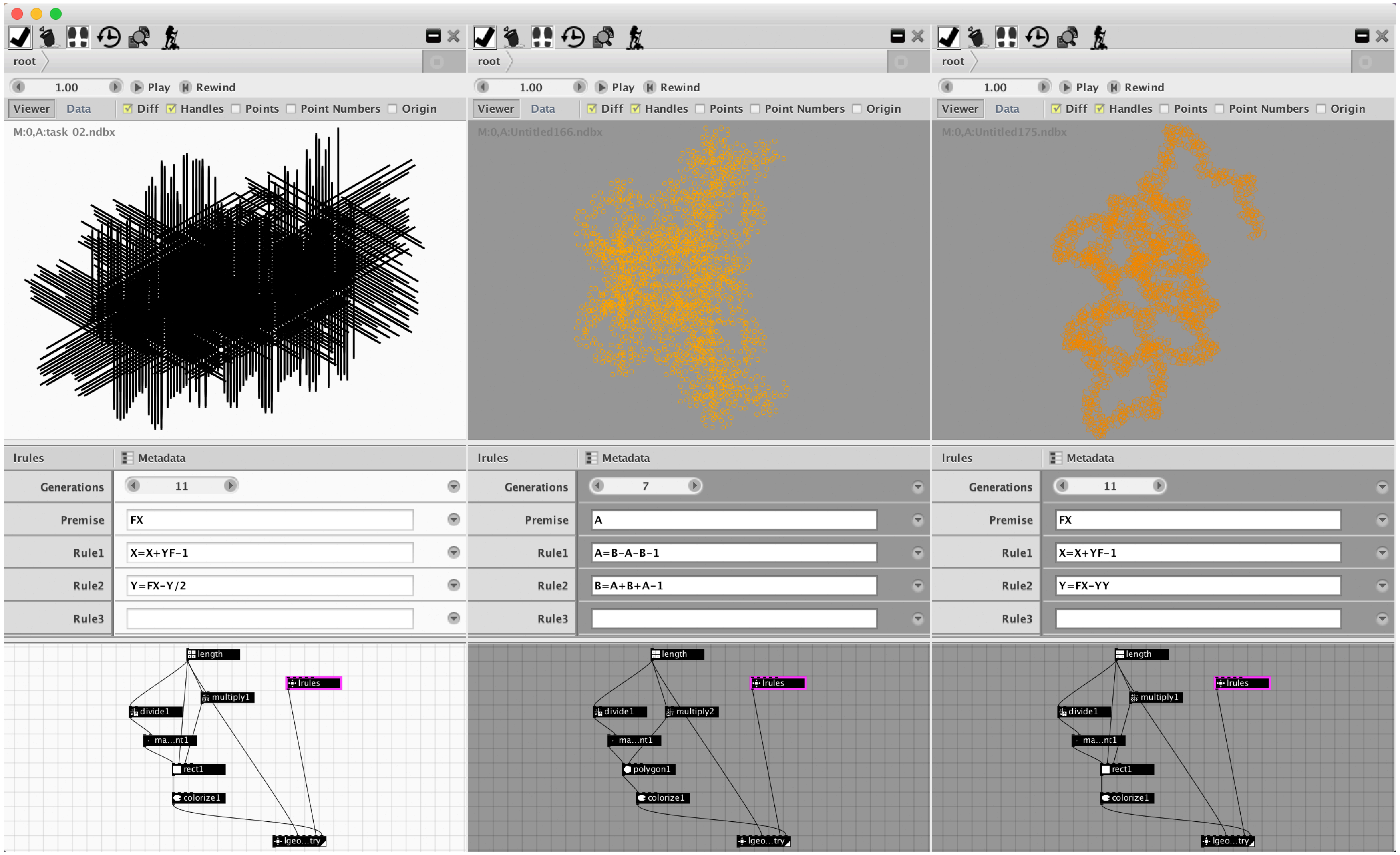


Figure B-6. Design 3: difference visualization view (with subtractive encoding).



M:0,A:task 02.ndbx

Generations	11
Premise	FX
Rule1	X=X+YF-1
Rule2	Y=FX-Y/2
Rule3	

M:0,A:Untitled166.ndbx

Generations	7
Premise	A
Rule1	A=B-A-B-1
Rule2	B=A+B+A-1
Rule3	

M:0,A:Untitled175.ndbx

Generations	11
Premise	FX
Rule1	X=X+YF-1
Rule2	Y=FX-YY
Rule3	

Figure B-7. Design 4: unenhanced view.

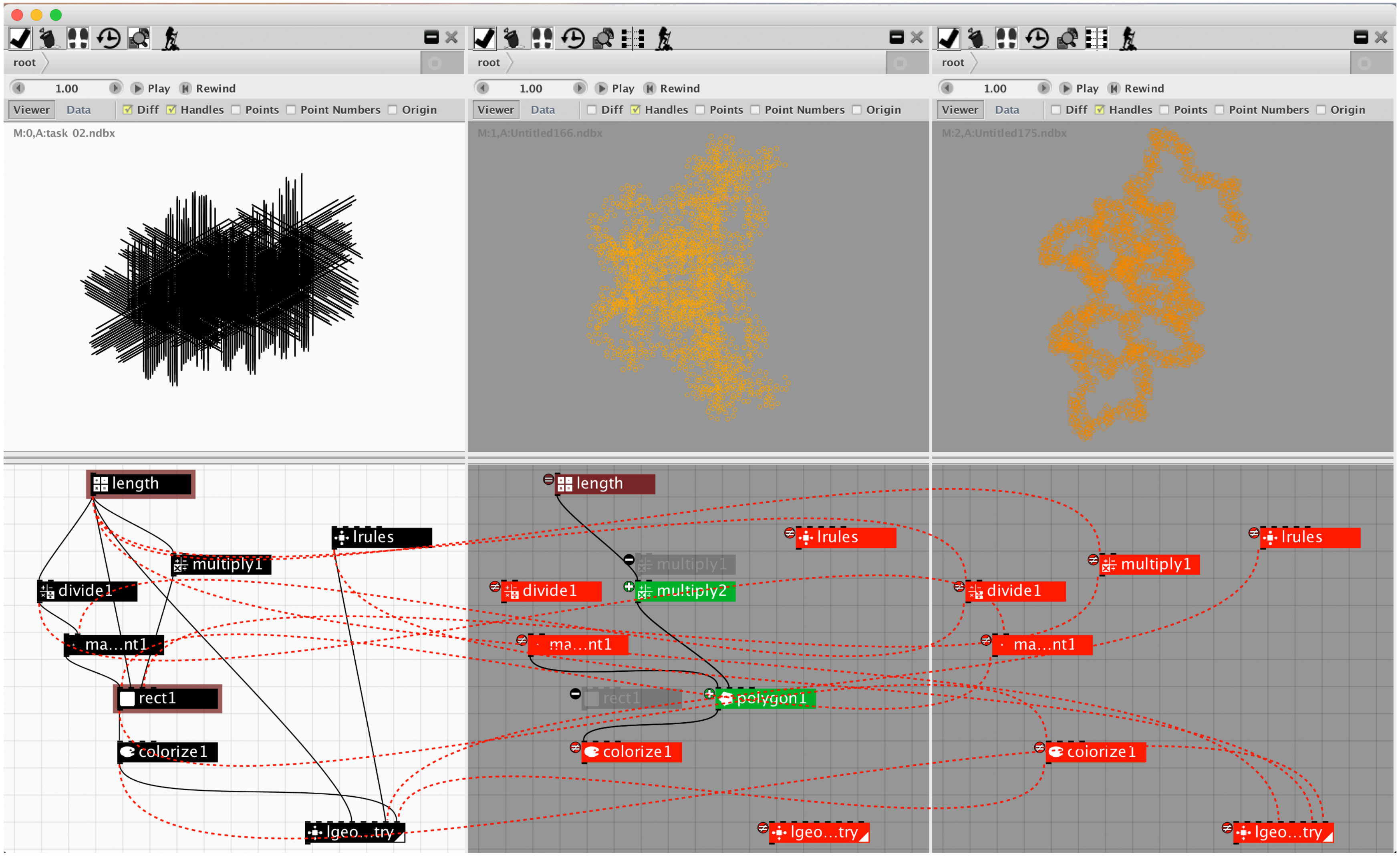

root
1.00
Play
Rewind
Viewer
Data
Diff
Handles
Points
Point Numbers
Origin
M:0,A:task 02.ndbx
M:1,A:Untitled166.ndbx
M:2,A:Untitled175.ndbx
length
lrules
multiply1
multiply2
divide1
ma…nt1
rect1
polygon1
colorize1
lgeo…try

Figure B-8. Design 4: difference visualization view (with subtractive encoding).

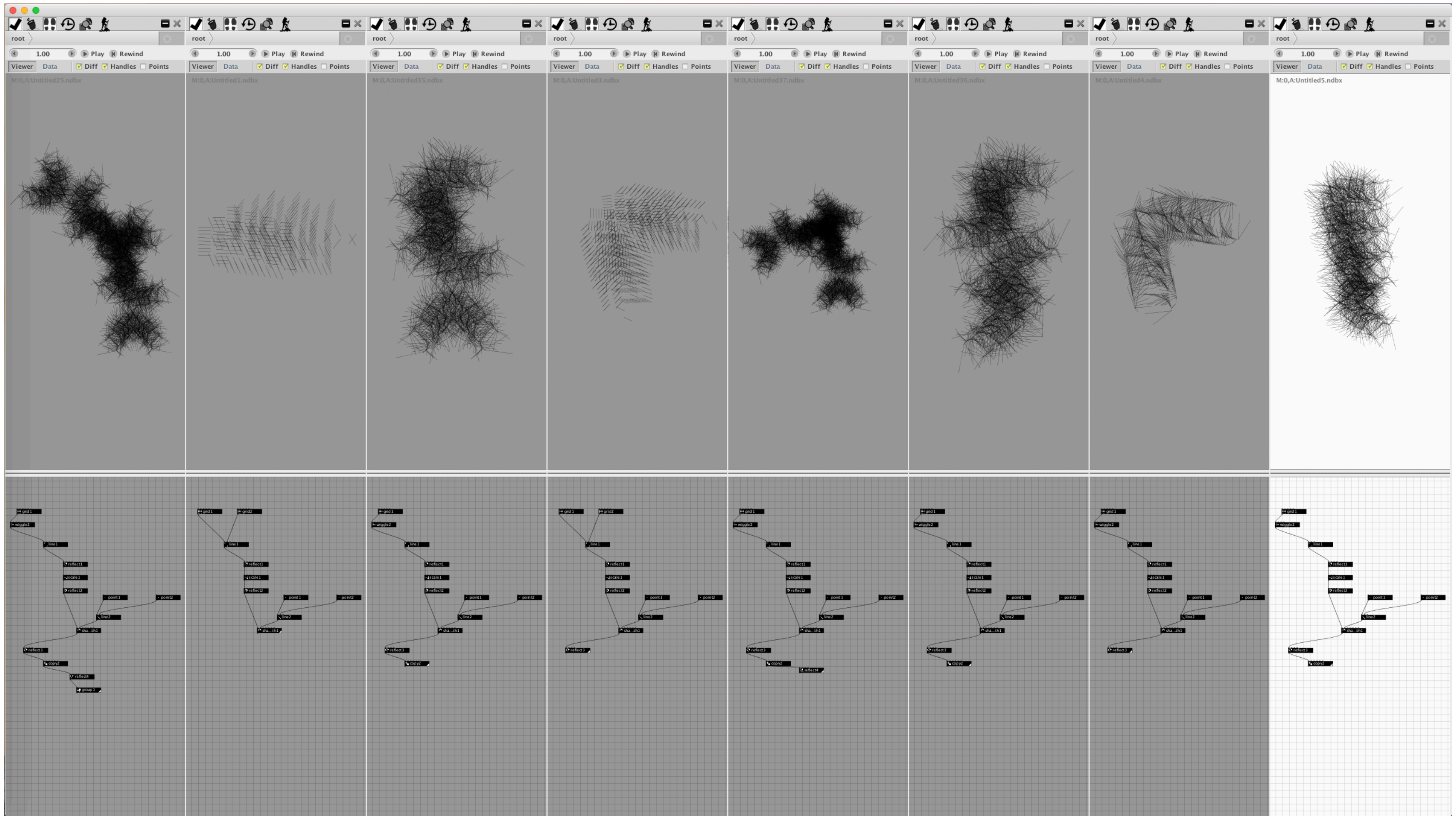


Figure B-9. Design 5: unenhanced view.

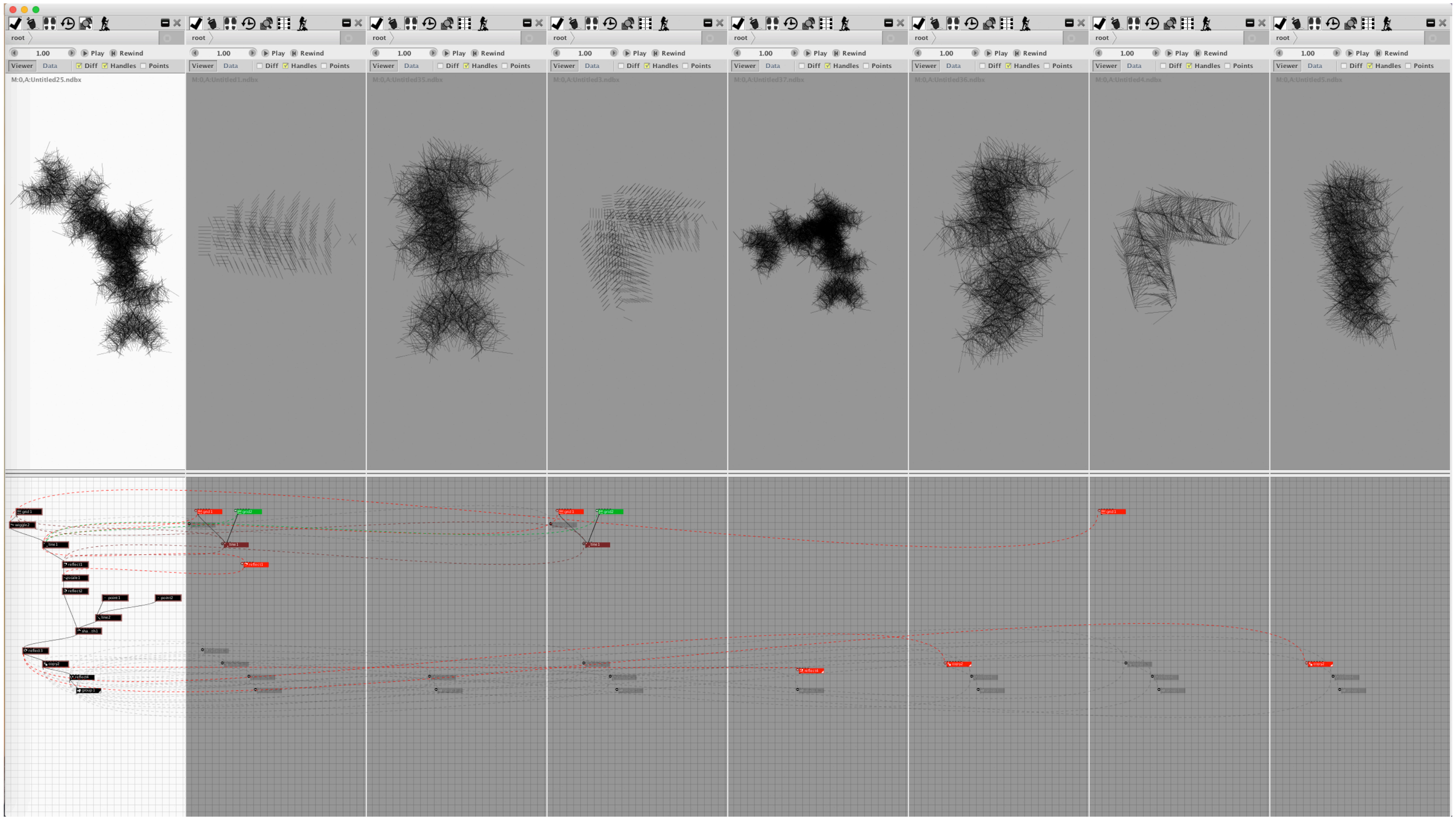


Figure B-10. Design 5: difference visualization view (with subtractive encoding).

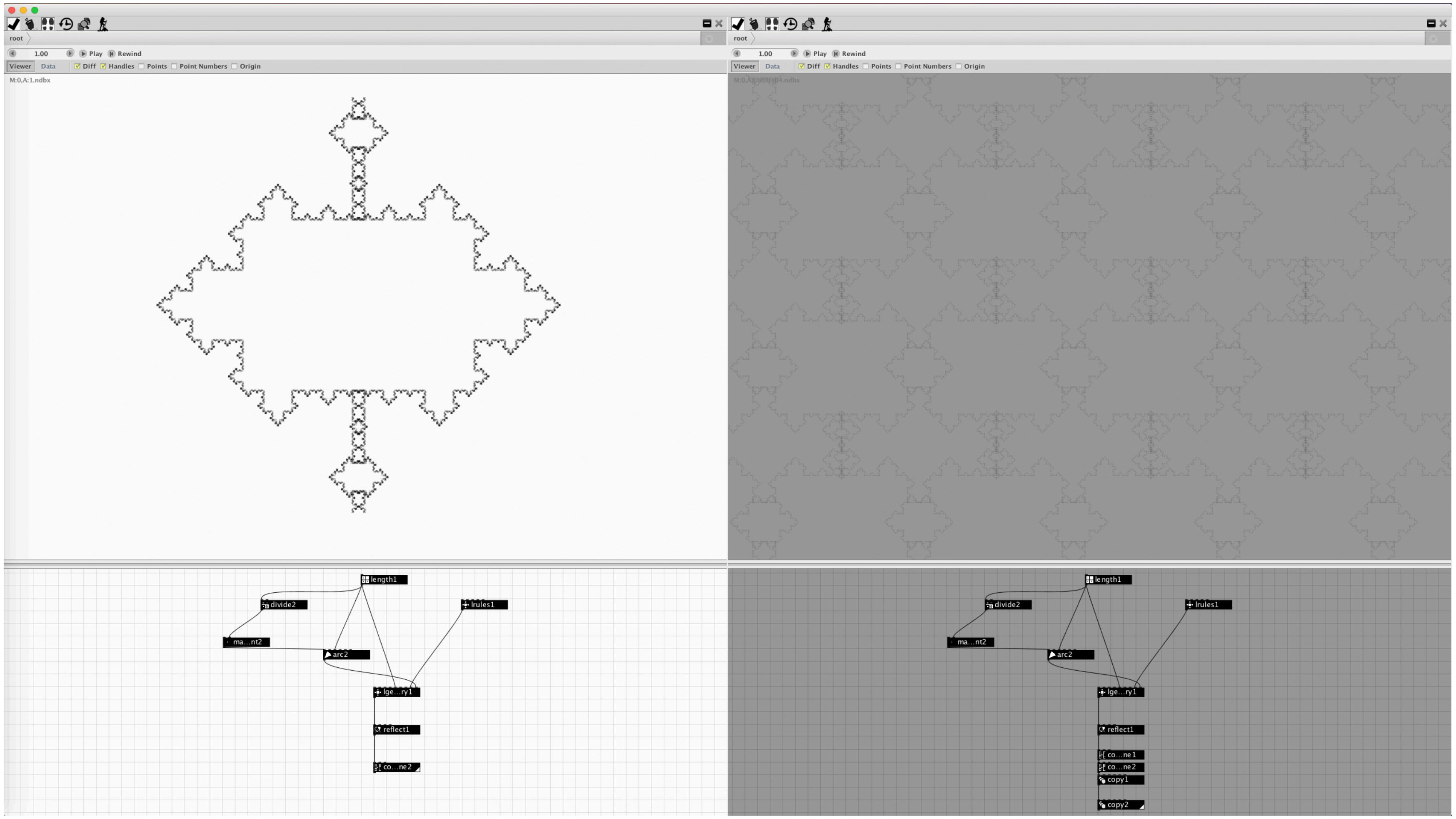


Figure B-11. Design 6: unenhanced view.

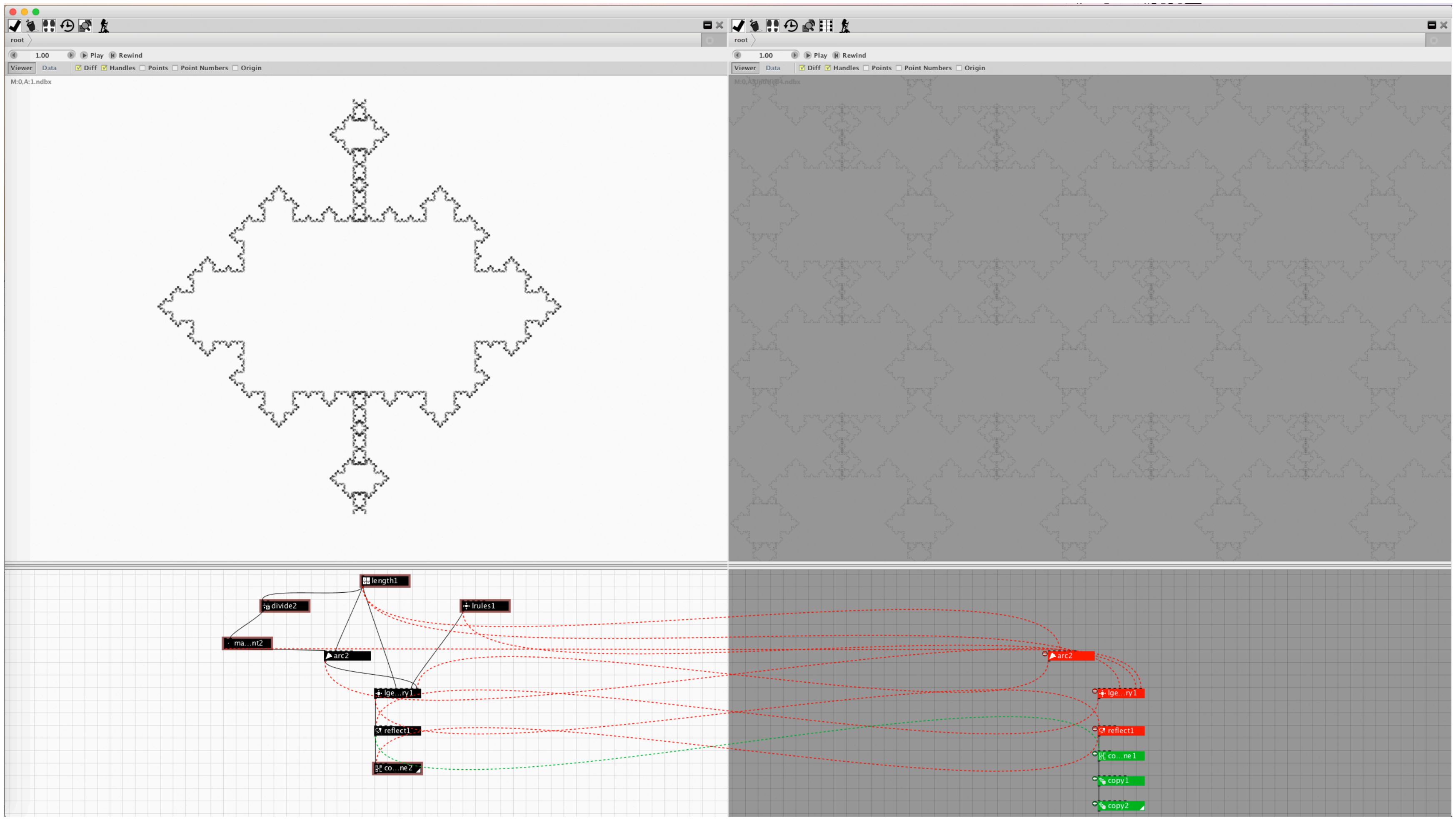


Figure B-12. Design 6: difference visualization view (with subtractive encoding).