Co-3Deator: A Team-First Collaborative 3D Design Ideation Tool

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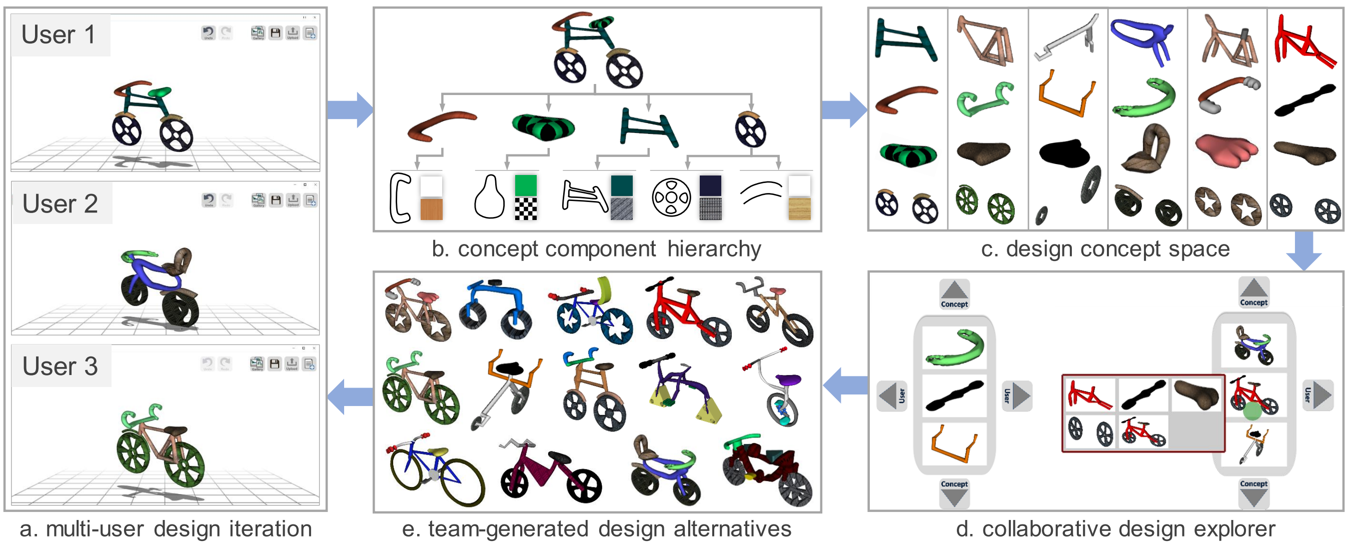

Figure 1. General overview of Co-3Deator design workflow and features: (a) Designs individually constructed by 3 users in a team, (b) Example of representing a design as a concept component hierarchy, (c) Design concept space with multiple concept component hierarchies, (d) Collaborative design explorer for navigating concept space and sharing design data, (e) Design concepts generated by a team using Co-3Deator.

ABSTRACT
We present CO-3DEATOR, a sketch-based collaborative 3D modeling system based on the notion of "team-first" ideation tools, where the needs and processes of the entire design team come before that of an individual designer. Co-3Deator includes two specific team-first features: a *concept component hierarchy* which provides a design representation suitable for multi-level sharing and reusing of design information, and a *collaborative design explorer* for storing, viewing, and accessing hierarchical design data during collaborative design activities. We conduct two controlled user studies, one with individual designers to elicit the form and functionality of the collaborative design explorer, and the other with design teams to evaluate the utility of the concept component hierarchy and design explorer towards collaborative design ideation. Our results support our rationale for both of the proposed team-first collaboration mechanisms and suggest further ways to streamline collaborative design.

ACM Classification Keywords
H.5.3 Information Interfaces and Presentation: Group & Organization Interfaces—*Computer-supported Cooperative Work*

Author Keywords
Collaborative design; creative ideation; early-stage design; 3D modeling

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INTRODUCTION
Collaboration is now widely accepted to be a vital part of early-stage design ideation, and many tools such as TeamStorm [11], skWiki [38], and GroupMind [28] have been proposed to scaffold this activity. The core tenet of collaborative ideation is—the more design alternatives one generates, the more high-quality/novel designs one ends up with [22]. However, to

our knowledge, in all currently available collaborative design tools, sharing a design—such as a sketch, prototype, or 3D model—to brainstorm a wide variety of design alternatives with your team is an explicit and often heavy-weight operation. The reason for this is that all current design tools are first and foremost just that: *design tools*, where the focus is on content creation for individual designers rather than collaborative creativity across the entire team. In other words, we can characterize all current tools as *"designer first"* ideation tools.

In this paper, we propose the notion of *"team first"* ideation tools, and further introduce a specific team-first ideation tool called CO-3DEATOR for creating, sharing, and assembling 3D objects via pen-and-touch sketch-based 3D modeling. Similar to the *"mobile first"* paradigm of responsive web design [35], the goal of team-first ideation tool design is to let the team's design process—rather than that of the individual—guide the analysis and design of the tool. As a case in point, our Co-3Deator is designed from the ground up based on the notions of a *Concept Component Hierarchy* and *Collaborative Design Explorer*. The concept component hierarchy serves as the data representation for any content creation—such as the sketch-based 3D modeling support in Co-3Deator—and automatically detects, segments, and organizes each part of a design artifact as the user is creating it. These parts are automatically shared with all collaborators through the design explorer, such that each member of the team can browse, adopt, and assemble them with other parts into new designs. Thus, the concept component hierarchy and design explorer in Co-3Deator make the adopting and remixing of parts a natural operation leading to an effortless creation of several different design alternatives by any team member.

We motivate our novel team-first design philosophy for ideation tools based on industry's exploding need for fostering effective yet inexpensive creative processes during product innovation and development [9]. Scaffolding such creativity requires robust design teams where different designers contribute unique perspectives, re-interpret each others' ideas, and collectively uncover a larger design solution space [32]. Enabling collaboration is thus a core principle for digital creativity support tools [29], and our team-first philosophy takes this idea to its logical conclusion. Our inspiration for the specific techniques in this paper stem from the fact that early-stage design is generally characterized by iterative sequences of both convergence and divergence [38], where new designs are created and then discarded or refined, respectively. Thus, the rationale for the team-first collaboration mechanisms in Co-3Deator is that these iterations can be significantly accelerated if the component parts of a design created by one designer can be automatically identified, segmented, and shared to other team members, during the collective creative process.

To showcase the team-first design approach, we conducted a user study with four teams of experienced designers. Results from the studies were very promising and clearly highlighted the benefits of the concept component hierarchy and collaborative design explorer in team-based design processes.

BACKGROUND

"All design is redesign" is a common axiom among designers and design researchers [8], referring to the analogous and iterative aspects of design. There is a parallel between this view of design and the notion of creativity as a novel combination of existing ideas. Boden [2] identifies three approaches to creativity, (a) combination: creating new ideas by combining existing ones, (b) exploration: systematic search within a defined conceptual space, and (c) transformation: iteratively modifying parts of a defined solution. Our work is based on Boden's interpretation of creativity, and motivated by three assumptions about design ideation: (a) creativity is often a combination or reinterpretation of existing ideas or artifacts, (b) such novel combinations and reinterpretations are better performed by teams, and (c) there is a need for 3D design tools and processes—that support quick realization and exchange of ideas—which can be leveraged to support novel combinations and reinterpretations. In this section, we explore existing research that support our assumptions and motivate our work.

Creative Ideation in Conceptual Product Design

Traditional creativity tests such as Guilford's Alternative Uses Test, based on his Structure of Intellect [10], and the Torrance Test of Creative Thinking [33] focus on the idea of creativity as "flexible thinking". Flexible or divergent thinking refers to the act of creating new ideas by reusing or reinterpreting existing ideas and artifacts, an example of Boden's approach of *combination* [2]. Brainstorming is perhaps one of the most widely used creative ideation processes, and it promotes creativity by focusing on the divergent aspect of ideation, with the prompt "generate as many ideas as you can", while deferring judgment on the ideas [20]. Studies have shown that there is a positive correlation between the number of ideas generated and the greater incidence of creative ideas [22]. Research has also shown that in a design process, ideas that have a stronger connection to other ideas generated earlier, tend to be more creative [34]. That is to say, creative ideas are formed when the designer first generates a large number of ideas, and then iterates over these ideas to change, modify, and refine them.

Widely used techniques to aid generation of more ideas and promote divergent thinking include SCAMPER [16], Method 6-3-5 [23], C-Sketch [26], and the Gallery method [21]. All of the above methods use the notion of modifying, reinterpreting, and combining existing ideas to form new ones, which can be seen as examples of Boden's *combination* and *exploration* approaches. A systematic technique to explore a large number of solutions to address complex problems was introduced by Fritz Zwicky [39]. His solution, now commonly used in product design as the *Morphological Matrix* involves identifying the main *functions* that need to be performed to address a design problem, generating a number of possible solutions for each function, and coming up with meaningful combinations of such solutions [19]. In essence, a *Morphological Matrix* provides a means for navigating through a finite space of design concepts at varying levels of functional or structural details. In Co-3Deator, we explore how to visually represent such a design space in a 3D design ideation tool, such that design teams can efficiently explore new ideas by combining and reinterpreting existing designs.

Collaborative Design Tools

Today, most practical design work involves collaboration between people with diverse, often complementary expertise [3]. In fact, with the exception of SCAMPER, all the divergent thinking techniques listed above *require* the involvement of a team. A study performed using the 6-3-5 method has shown that the group's involvement increases the originality of the final ideas even when the initial, individually generated ideas are not very original [1].

Digital tools for collaboration were traditionally designed to support the later stages of design. Recently, there has been considerable interest in computational support for collaborative ideation. These include tools for collocated collaboration, such as the i-LAND environment [31], the immersive Hybrid Ideation Space [6] and an integration of paper and digital media in the form of IdeaVis [7]. Other tools such as TEAMSTORM [11] and GAMBIT [24] support sketch-based collaborative ideation on mobile devices. skWiki [38], a more recent framework supporting sketch-based collaborative ideation, is designed with the creative process of modification, reuse, and reinterpretation in mind. It thus supports branching, the creation of alternatives from a source sketch, and merging, the combination of existing sketches to form a new idea.

Design Representations for Collaborative Work

While our approach draws inspiration form the creative process presented in skWiki, we emphasize use of 3D models to represent design ideas. This is because, in addition to enabling greater visual clarity of design ideas, 3D models can be inherently represented as a hierarchical structure that allows for systematic deconstruction of a design concept into sub-assemblies, parts, and shapes [13]. We find that such modularity of 3D designs naturally lends itself to collaborative morphological operations, where design components are shared, combined, and reused at varying levels of details. On the other hand, sketch, text, and 2D image based representations are not as amenable to such operations, as they require explicit segmentation and sophisticated algorithms for extracting hierarchical components [17]. Thus, in Co-3Deator we seek to support team-first based collaborative design ideation by leveraging the inherent structural and functional hierarchy of 3D design models.

Sketch-based 3D Design Modeling

Given its focus on early-stage design ideation, the ability to quickly externalize ideas is an essential aspect of Co-3Deator. We find that most conventional modeling tools utilize highly detail-oriented or parametric workflows that can prevent capturing of fleeting ideas and stifle creativity during early-stage design [30]. Thus, we seek a low-fidelity 3D modeling workflow that allows users to quickly express ideas in 3D form, with minimal effort and without the need for details (e.g. dimensions or spatial constraints).

Recent advances in sketch-based 3D modeling techniques utilize our natural ability to sketch with a pen for generating 3D designs [18]. Such techniques allow users to construct 3D shapes by simply sketching their 2D outlines, while the back-end system infers the intended 3D geometry [12, 25]. Given their ease of use and efficiency, sketch-based 3D modeling tools are highly amenable towards early-stage design ideation. In Co-3Deator, we present a 3D modeling tool—driven by a similar sketch-based approach—which not only supports design creation but also light-weight storage and transfer of design data. Further, this tool allows for seamless integration of our team-first features within the modeling workspace, and helps maintain consistency of interactions during both modeling and collaborative operations.

Combinatorial 3D Design

In computer graphics, several works have explored the notion of decomposing 3D designs into useful parts, and recombining them to create new designs. Such works mainly focus on automating the 3D design synthesis process [14, 37] or enabling creativity by exploring a pre-defined and immutable design spaces [4, 36, 27]. In Co-3Deator, we focus on a team-centric approach, where real time collaborations between team members foster both creation and exploration of a design concept space. Here, in addition to combinatorial creativity, we also emphasize construction of new design content, along with re-definition and re-interpretation of existing ideas.

OVERVIEW: CONCEPT COMPONENT HIERARCHY

The concept component hierarchy is a core aspect of our team-first approach, and serves as a data representation for hierarchically creating, organizing, storing, and accessing design concepts. Co-3Deator enforces this hierarchy at all stages of the design workflow. Here, designs are inherently constructed in a hierarchical manner (Figure 1 (b)), where 2D sketches form individual 3D shapes, shapes are grouped into functional parts, and parts collectively define a design concept. By associating shapes to parts (through tagging), this hierarchy not only captures the geometric structure, but also functional and semantic concepts at different levels of a design. Further, it also provides the primary basis for collaborative design via sharing and reuse of multi-level design data.

As shown in Figure 1 (c), a design concept space comprises multiple concept component hierarchies generated by a design team. In Co-3Deator, we utilize the collaborative design explorer (Figure 1 (d)) as a medium to visually represent, interactively navigate, and further explore this space.

CO-3DEATOR

The Co-3Deator interface enables both 3D content creation and collaborative work. For flexibility and intuitiveness, it is best used on a digital tablet supporting pen-and-touch inputs, but is also compatible within ordinary PCs. It consists of two components—a *3D Design Workspace*, and a *Collaborative Design Explorer*—both catering to the team-first approach.

3D Design Workspace

The 3D design workspace enables both construction of new designs and collaborative design work. By allowing users to model a full design within this workspace, it prevents shifting of focus across different views, and also allows creation of new shapes in context of a progressing design [15]. Figure 2 illustrates the general design workflow with different creative activities that can be performed in the 3D workspace.

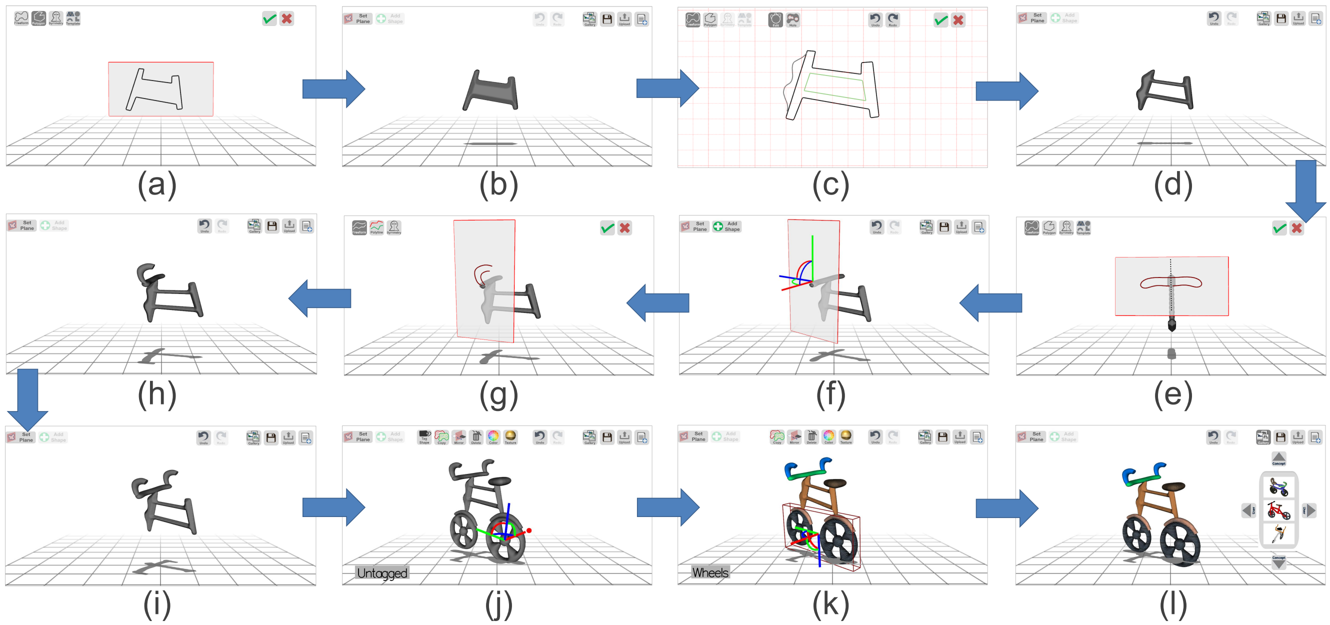

Figure 2. General 3D design workflow in Co-3deator with a bicycle design example: (a-b) Using a tapered blobby shape to define the bike frame, (c-d) Adding a hole and modifying the shape (with overdrawing) on the bike frame, (e) Setting a sketch plane at the tip of the frame and defining the handlebar with a rounded blobby shape, (f) The 3D manipulation widget on the sketch plane allows users to adjust its placement, (g-h) Defining a handle grip using tubular shapes, (i) Mirroring the handle grip about the frame, (j) Completing the design by adding seat and wheels - the rear wheel shapes are copied and scaled, (k) The shapes are colored/textured and tagged to appropriate parts- each part can be selected and manipulated as a single entity, (l) The design explorer can be accessed within the 3D workspace.

New Shape Creation

Users can create 3D shapes by drawing their 2D outlines on a sketch plane. This plane is defined either at a central workspace location (Figure 2 (a)) or over a progressing design (Figure 2 (e-g)), and freely manipulated with a 3D widget.

We utilize tubular shapes (sweeps in CAD) and blobby shapes (inflated meshes)—demonstrated in several sketch-based design tools [12, 25]—as the basis for constructing 3D designs. Such shapes have been shown to allow sufficient complexity and diversity within designs, and can be constructed using simple 2D sketch inputs.
Blobby Shapes are created by drawing a closed "profile curve" on the sketch plane, and inflating its interior region outwards from the plane. Users can choose from four different inflation functions—rounded, flat, tapered, and linear (Figure 3).
Tubular Shapes are defined using two "rail curves", between which a sweep geometry with circular cross sections is fitted. We can use freeform or polyline sketch inputs, to draw the profile and rail curves. The raw sketch data is automatically smoothened using a single exponential function and uniformly resampled to avoid geometric artifacts.

Editing and Modifying Shapes

The edit mode (Figure 2 (c)) is invoked by selecting a shape with a double tap gesture. Here, the workspace switches to a purely 2D sketch mode with the shape's underlying curves displayed in a front facing view. In this view, the curves are magnified to enable operations requiring finer control and precision. Users can perform two types of edit operations.
Overdrawing: As shown in Figure 4, sketching directly over a region on a curve allows us to make changes to a shape and

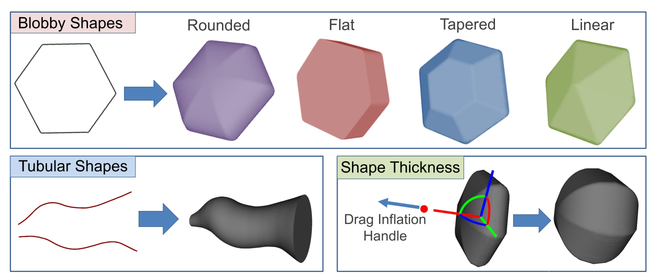

Figure 3. (top) Generating four types of blobby shapes from a profile curve; (bottom left) Generating a tubular shape from two rail curves; (bottom right) Increasing thickness or inflation magnitude of a blobby shape using the 3D manipulation widget.

also add details. For tubular shapes, overdrawing can also be used to extend or truncate the rail curves.
Holes: Drawing closed curves within the profile of a *blobby shape* indicates a hole through its 3D geometry.

Shape Selection & Manipulation

When a shape is selected with a single tap gesture, a 3D manipulation widget gets anchored to it (Figure 2 (j)). By dragging an axis or arc in the widget, users can translate or rotate the shape and explore different configurations. For *blobby shapes*, the widget also consists of a spherical handle at the tip of its normal axis (Figure 3 (bottom-right)). Dragging this handle changes the shape's inflation magnitude.

Additional Operations

We provide *Delete*, *Copy* and *Mirror* operations for removal, replication, and regular or symmetric arrangement of iden-

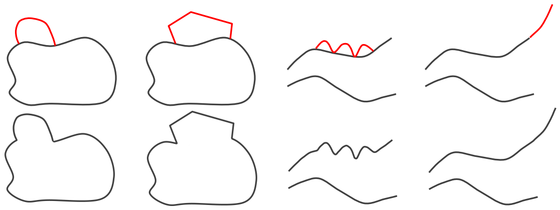

Figure 4. Overdrawing to modify profile and rail curves: (top row) overdrawn curves are shown in red, (bottom row) result of integrating overdrawn curves with profile and rail curves.

tical shapes. Here, shapes can be copied to a user selected location or mirrored across the sketch plane of another shape. Additionally, the *Undo-Redo* commands allow users to retrace modeling operations upto the last 100 steps.

Color and Texture Application

Color and textures allow users to enhance the appearance of designs and also uniquely characterize shapes with specific material properties. Here, we use the default Windows color dialog box, and provide a texture library of commonly used materials (e.g. metals, wood, plastics, leather, rubber etc.)

Tag Shapes to Specific Parts

Before a design activity, Co-3Deator requires design teams to identify high-level functional parts pertaining to the current product context, and label them with distinct names (e.g. wheels, seat etc.). Each shape within a design is thus tagged to a specific part after its creation, using the tagging menu. This ensures functional and semantic modularity of design models during collaborative work. The aforementioned operations (e.g. copy, mirror, manipulate etc.) can also be concurrently applied to multiple shapes forming a given part.

Collaborative Design Explorer

The design explorer is the central medium supporting all team-first design activities. It visually represents the design concept space developed by the design team, and enables storing, browsing, sharing, and accessing of design ideas.

Elicitation of the Design Explorer

Before implementing the design explorer, we sought to understand how designers perceive a design concept space with multiple concept component hierarchies, and how they would like to see it represented within a 3D ideation tool. For this, we conducted an elicitation study with 9 engineering and 3 industrial design graduate students, with expertise in product design and 3D modeling. Our goal was to use the insights from this study to infer guidelines for the design explorer.

Each study session was carried out with a single participant, and involved an interview style discussion. The participants were first presented with the following scenario.

> *Assume there is a 3D design ideation tool that allows users to construct design concepts in a hierarchical manner, i.e. parts and shapes of designs are naturally segmentable from the design. This tool is used by a design team to collectively generate multiple design concepts. These concepts along with their components form an abstract space called the design concept space.*

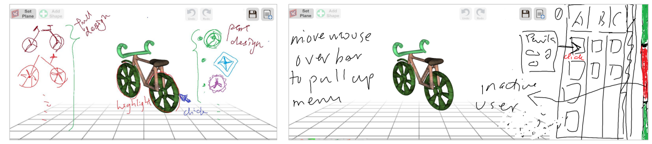

Figure 5. Two examples of sketches created by elicitation study participants to illustrate the design explorer's appearance and functionality.

Based on this scenario, the ensuing interview questions focused on three underlying topics.

- *How would the participants like to have the design concept space represented within the 3D design workspace?*
- *What kinds of interactive mechanisms would they like to see for navigating the design concept space to view, share, and access design information?*
- *What kinds of capabilities would they like their concept space representation to provide for supporting collaborative design ideation?*

In addition to verbally expressing their ideas, participants were also encouraged to sketch what they thought the design explorer should look and function like. We provided them with a screenshot image of a minimal 3D workspace of Co-3Deator, over which they could draw and comment. Figure 5 shows two examples of how participants sketched their ideas.

From the information provided by the designers, we abstracted the following attributes that the design explorer should have to support efficient navigation of the design concept space and fluid sharing of design ideas across team members.

G1 **Concurrent visibility of explorer in 3D workspace.** Being able to observe and reflect on others' ideas during a design activity not only inspires creativity but also helps identify new possibilities in one's own design.

G2 **Hierarchical navigation of the concept space.** This allows users to quickly browse through multiple design concepts in their entirety, and only take a detailed look at interesting or relevant designs.

G3 **Chronological arrangement of design ideas.** The newest designs in the concept space typically represent the most recently developed ideas or those that have been polished through iterations. Displaying them first provides a quick overview of the current state of the concept space and also prevents dwelling over defunct designs.

G4 **Classify designs by team members.** To ensure that each member gets credit for his contributions and to track the history of a design's evolution, each concept should be identifiable to its author.

G5 **Filter design space by specific component.** This allows users to filter the content of the explorer, relevant to a specific design component or a modeling activity, and also efficiently search for ideas within that context.

Design Explorer Features

Based on the guidelines inferred from the study, we implemented the design explorer as shown in Figure 6. We place alphanumeric labels for each guideline (e.g. G1, G2) in the

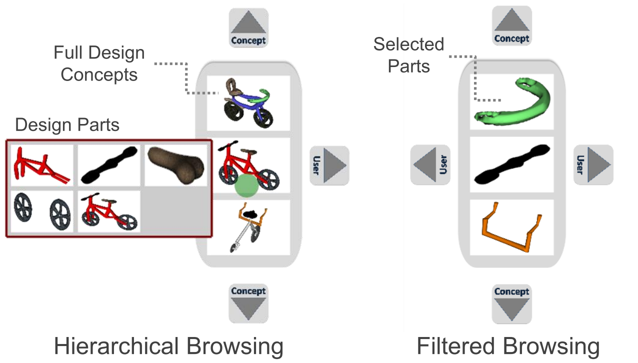

Figure 6. Dual Modes for Concept Space Navigation: (left) Hierarchical view with full design concepts and exploded view of a selected concept, (right) Filtered view with a specific part (handlebar) displayed

text to help readers understand how they are addressed. The design explorer comprises the following features.

List View of Design Concepts: The design explorer is essentially a single column menu with thumbnails of design concepts as menu items. It displays the most recent designs from a particular team member, and can be vertically scrolled to view his/her previous concepts (**G3**). It can also be laterally scrolled to view designs across other team members. We use this organization as it enables grouping of designs by their creator (**G4**), and allows team members to track where a shared design came from. Further, a single column view helps avoid clutter in the 3D workspace, while allowing designers to navigate the concept space during a modeling activity (**G1**).

Dual Mode for Concept Space Navigation: We provide two modes for browsing through concepts in the design explorer.

- *Hierarchical Browsing:* Here, the explorer by default shows thumbnails of the full design concepts. When a given concept thumbnail is selected, a secondary menu pops up with thumbnails showing a close up view of the concept's individual parts, separate from the design (**G2**).
- *Filtered Browsing:* This mode can be used when a design model is active within the 3D workspace. By selecting a specific part or shape on the model, users can filter the explorer such that only the corresponding parts from the concept space are displayed. Here, the selection in the modeling space serves as a query input for filtering the explorer content (**G5**).

Sharing and Importing Designs

During a design activity, users can choose to share their designs and ideas only when they feel ready. This helps avoid evaluation apprehension [5], and provides team members with freedom for independent thinking. Each design is initially stored locally within individual tablets. Users can upload their design(s) at any point to make them accessible in the explorer.

Users can import designs from the explorer into their personal workspace. Here also, the hierarchical and filtered browsing modes can be leveraged to import either the entire concept or just a specific component. Design data can be imported from the explorer in two ways.

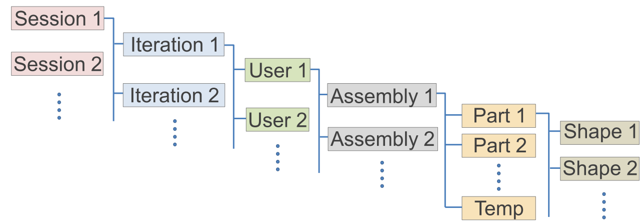

Figure 7. Folder structure used in cloud-based repository for storing and sharing 3D designs in design explorer.

Insert: This operation makes a copy of a full design model or a single part and places it in the workspace at a location specified by the user.

Replace: A given part in the workspace can be substituted with a corresponding part from another design in the explorer. This operation first deletes the original part from the workspace, generates a copy of the new part, and places it at the same location in the design. Here, the system finds an optimal orientation and scale for the new part by matching its minimum bounding box with that of the previous part. Similarly, a full design model can also be replaced with another concept model.

System Implementation

Setup and Hardware: Co-3deator was implemented using OpenGL and written in C++. To run this application, we used Microsoft Surface Pro 3 tablets (Windows 8, Intel Core i5, 4 GB RAM), which came equipped with digital pens.

Design Data Format: To store 3D shapes, we defined a lightweight text file format containing 3D vertices of the underlying curves and other data (e.g. texture file, scale, inflation magnitude etc.). Whenever a design is imported or loaded into the workspace, the file data is read by the system and corresponding shapes regenerated. The shapes in a design model are stored in a folder with a distinct ID, and grouped within subfolders pertaining to a specific part (Figure 7). A temporary folder is also used for retaining untagged shapes.

Design Data Storage: In our setup, the unshared designs for each team member are stored locally in their tablets. The shared designs however are kept in a cloud based (Dropbox) repository, which is shared across all tablets. As shown in Figure 7, the design data in the shared repository are organized within a four-layer folder structure, each layer denoting a design's session, iteration, user, and assembly ID. During execution, Co-3Deator employs a listener function to scan this repository at regular intervals of 2 seconds, check for changes in the design data, and update the explorer accordingly. Screenshot images of the design concepts and its parts are also stored within the respective folders. These images are captured when a design is saved and used as the explorer's thumbnails.

USER STUDY

To evaluate Co-3Deator, we conducted a qualitative user study with four design teams, each in a co-located setting. This study mainly explored how design teams use the system towards early stage design ideation, the resulting creative outcomes, and the system usability.

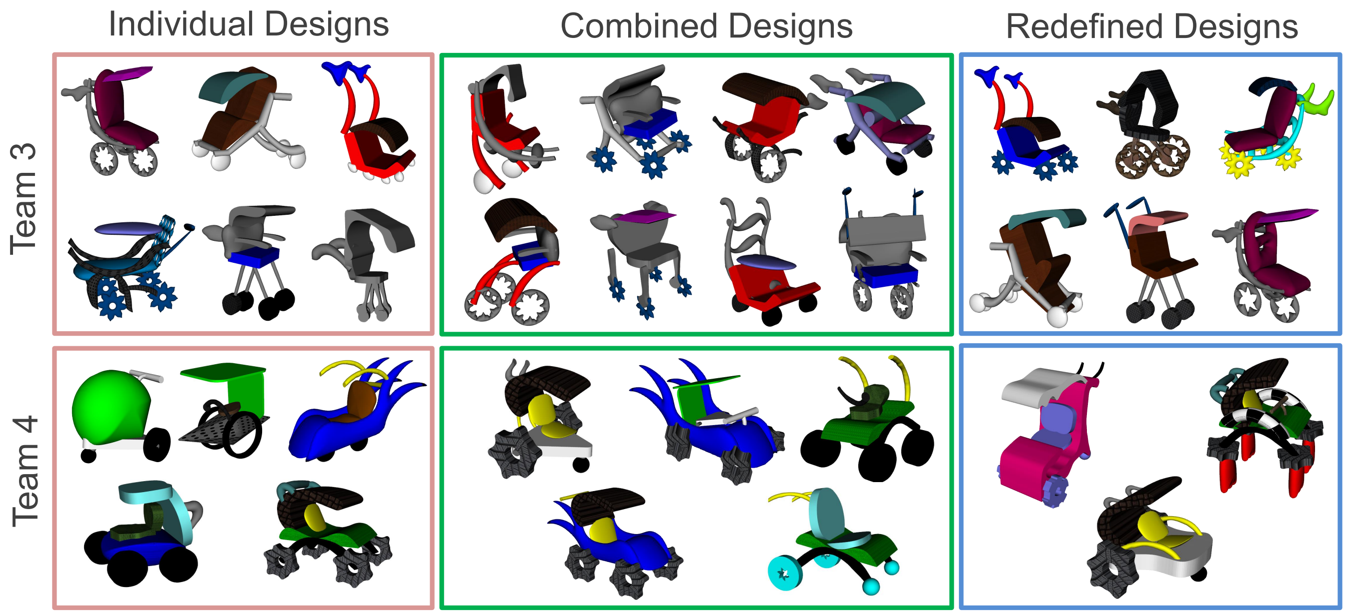

Figure 8. Design concept spaces developed by Teams 3 (most productive) and 4 (least productive) during user study.

Method

Participants

We recruited 4 design teams, each comprising 3 randomly assigned members. All participants (9 male and 3 female; aged 22 to 31) were graduate students in Mechanical Engineering and had experience in product design, 3D modeling, and design teamwork.

Procedure

Each session lasted 2 hours and was conducted in a small conference room. The participants were seated at a table facing others, and had access to individual tablets with Co-3Deator installed. The room was also equipped with a large monitor, for displaying the design concept space generated by the team. At the beginning of each session, the moderator gave a 25-minute step-by-step demo of the system (shown in the large display), which the participants followed on their tablets. To prevent creative fixation, we only showed how to use Co-3Deator, not what kinds of things can be achieved with it. After the training, participants proceeded to the study tasks. Upon completing a session, they filled out a post-study questionnaire to document their experiences.

Tasks

Each session was treated as a single design activity, where teams developed and expanded a design concept space using Co-3Deator. To contextualize the activity, we posed a specific design problem while allowing for sufficient creative freedom.

> *Your design team has to come up with new and interesting ideas for a stroller—fit for kids between 6-24 months of age. This stroller will be primarily marketed in locations with prolonged winters and considerable snowfall.*

Before coming up with ideas, each team first discussed the design problem to identify functional parts they would use within their designs. This mainly focused on what the parts would do (e.g. something to push the stroller) rather than how they would look. The design activity was divided into three tasks, inspired by Boden's approach towards creativity [2] and ideation techniques discussed in the background section.

1. **Create:** Each team member used the 3D modeling features of Co-3Deator to generate as many design concepts as they could on their own within a 25-minute time limit. Verbal communication was not allowed to encourage independent thinking during the early stages of the activity and to ensure original contributions from each member.

2. **Combine:** The goal in this task was to expand the concept space through quick combination of parts—from designs created in the previous task—within a 20-minute time limit. To emphasize combinatorial creativity, the only shape modifications we allowed was scaling (to adjust proportionality) and color/texture (appearance) changes on the parts. Here, participants were allowed to communicate with teammates or ask questions about their designs.

3. **Redefine:** This was a freeform activity, where participants could take an existing design and redefine it into a new concept, however they found it fit. To prevent continuing work on one's own designs, participants could only redefine their teammate's designs. This task was also 20 minutes long, and allowed verbal communications.

Data Collection

We captured a log of system events from each tablet to help us observe user activities during the design tasks. We also video recorded each session for post-study analysis of group discussions. Finally, participants filled out a post-study questionnaire—comprising Likert-scale ratings and subjective written comments—to record their experiences.

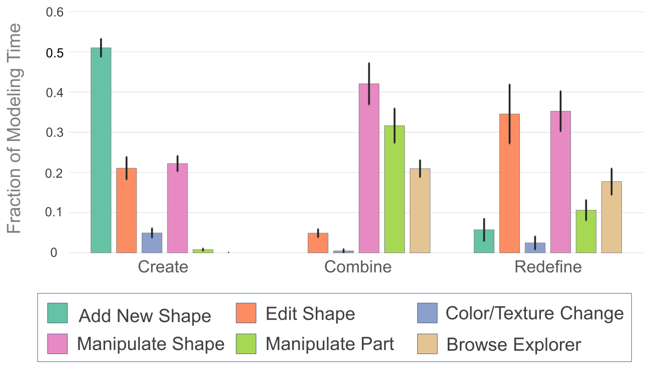

Figure 9. General trends in how users allocated their time towards different activities during the three tasks. Each bar represents a fraction of the total modeling time.

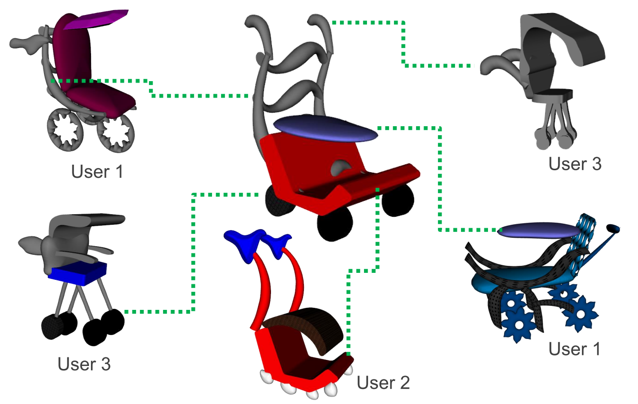

Figure 10. Example of a new design concept generated by combining parts from existing designs, constructed by different team members.

Results

To illustrate our observations and insights from the study, we will frequently refer to Figures 8 and 9. Due to space constraints, we only show concept spaces generated by Teams 3 and 4 in Figure 8. These were the most and the least productive teams, respectively, in terms of number of concepts generated. In Figure 9, we show how users allocated their time towards different modeling activities during the three tasks. Each bar in this chart represents the average time spent on an activity, expressed as a fraction of the total modeling time.

Individual Creative Expressiveness

As shown in the first column of Figure 8, each participant could independently express a variety of ideas within the design context. We observed creative diversity not just across design teams and team members, but also within ideas generated by an individual. On average, constructing a design model took about 12 minutes and 14 seconds (std. dev. = 3 min). Here, 9 user created 2 or more designs and the remaining 3 created only one. In addition to creating and editing individual shapes (Figure 9 - Create) we found the frequency of shape manipulations to also be significant. This could be attributed to users moving shapes around to explore different design configurations and forms.

Combinatorial Creativity

In the Combine task (Figure 8, second column), each team was able to at least double the size of their concept space, and produce designs different from their sources. The few designs that look redundant are because they share a common central shape (e.g. blue race car like stroller in Team 4 combined designs). Figure 10 shows one example of how parts or shapes from completely different designs can be arranged to produce an entirely new concept.

Most users generated 2-3 new concepts in an average time of 5 min and 54 sec (std. dev = 2 min and 20 sec). The user activity log (Figure 9 - Combine) showed that participants spent a considerable amount of time manipulating shapes around such that the parts would better conform to the new design.

We observed users apply two main approaches in this task. The more pragmatic approach entailed importing a central part (e.g. the seat or frame) which showed potential, and adding other parts that fit well with it. One participant stated *"I selected the main part, in this case the frame, and then the rest of them were assembled on top, similar to how we assemble a product in real life."* The other—more adventurous—approach involved browsing through the explorer and importing all parts that *"stood out"* or *"looked cool"*. Various configurations would then be tested, to prune out those that didn't work, ultimately converging to a satisfactory solution.

Design Redefinition

In the Redefine task, users employed four approaches to create new concepts from existing ones (examples in Figure 11):

- *Completing:* Given the time limits in the study, some designs could not be completed. In such cases, we found other team members naturally inclined to use this task as an opportunity to bring such designs to a closure. As one user indicated: *"I looked for something that was not good looking or something that had scope of improvement."*
- *Extending:* Users commonly sought ways to augment a design either to improve its functionality or add additional capability. The example in Figure 11 shows a case where wheel treads are added for better traction, side armrests for safety, and elevated handlebars for ergonomic pushing: *"[using the explorer] it was easy to judge what was earlier missed in every design, and what could work better."*
- *Branching:* Users often created design variations by simply changing color, texture, and style of one or more parts.
- *Reinterpretation:* To save time, some users borrowed one or more shapes from a specific part and reinterpreted them with an entirely new meaning or function. In an extreme case, shown in Figure 11(d), one user reinterpreted the wheels as jet boosters (the red shapes represent propulsion flames), to enable the stroller hover in midair.

On average users spent about 8 minutes (std. dev. = 4 min, 40 sec) on each design. 7 of them were able to come up with two or more designs and the remaining 5 only one. The high variation in both the completion times and productivity, could be attributed to the open-endedness of this task. For example,

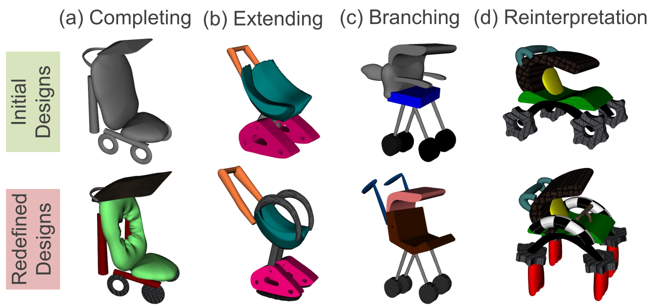

Figure 11. Four distinct ways in which users redefined existing designs in the explorer to generate new concepts.

while branching a design generally takes less time, completing and extending designs are more involved.

Final Concept Selection

To close the activity, each team reflected on the overall concept space and collectively selected a final concept (Figure 12). Interestingly, all of these final concepts were produced during the Combine and/or Redefine phases, and had undergone at least one iteration beyond their conception. This is consistent with the notion that creative ideas are generally connected to ideas from prior iterations [34]. We also found Teams 1, 2, and 3 to further refine their final concepts to better meet the functional needs of the design problem. Here, one member volunteered to serve as a "designated modeler", incorporating changes to the final design based on discussions and suggestions from other teammates. The teams also requested to show the shared workspace on the common display for everyone to view and comment upon.

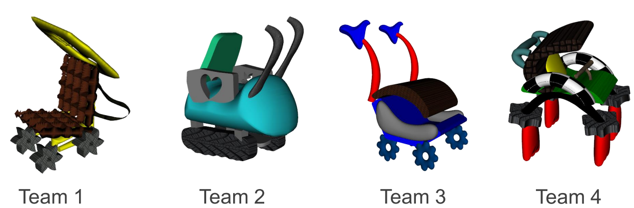

Figure 12. Final concepts collectively selected and finalized by each design team at the end of the activity.

Design Explorer Browsing Behavior

During the study, we observed participants using both the hierarchical and filtered modes for navigating the design concept space. The choice for when to use a specific mode was largely based on the level of design detail being sought and the stage of a design activity. For example, the hierarchical mode was mainly used to inspire new design ideas, particularly when starting out from a blank slate. As seen in the Combine task, this mode allowed users to observe multiple designs in parallel in order to come up with novel combinations: *"If I was combining different shapes, then I would prefer to look at all of my options together."* The ability to view each part in their original context also helped users better understand how to employ them in a new design: *"It gives me insight about the part before actually using it."*

The filtered mode, on the other hand, was mainly used to search for specific parts or shapes for a design already under progress: *"as you progress through the design when specific things are required the filtered view is better."* Here, it served as a means for substituting parts or shapes in the design, either to refine its form or generate its variants. Users found this mode to be an efficient way to quickly search and identify a relevant part (or shape) without going through multiple levels of menus: *"I could see all the options available for the exact part that I needed."*

System Usability

To help evaluate system usability, each participant filled out a post-study questionnaire, comprising 5-point Likert scale questions. These question covered the primary features of the interface, and their concise version are shown in Figure 13, next to corresponding results. We also encouraged participants to provide comments to support each rating.

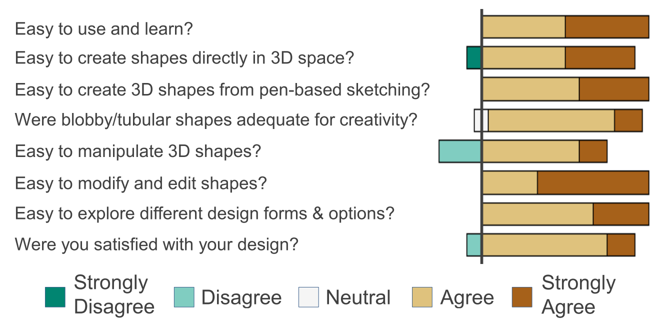

Figure 13. 5-point Likert scale feedback on system usability. Bars (brown) to the right of the central line indicate positive responses, while those (green) on the left indicate negative responses.

In Figure 13, we can see that users responded favorably towards the overall system, the modeling workflow, and its specific features. We found that all users could learn and independently use the system with only 25 minutes of training. Most users found direct creation of shapes in 3D to be *"simpler and faster, instead of sketching in 2D and then extruding [as in conventional modelers]"*, and that *"it is easy to see how everything [or shapes] lines up and scales"*. Despite their simplicity, blobby and tubular shapes enable users to express a variety of design forms. However, some users indicated that *shelling*, *extruded cuts*, *non-orthogonal holes*, and *revolves* could further enhance expressiveness. All users were able to easily modify shapes in the edit mode. Figure 9 shows that shape editing was frequently used during the initial creation and redefinition stages, and mainly utilized for adapting existing shapes into new contexts or borrowing them as seed geometry for new shapes.

While the 3D widget provides greater controllability than multi-touch gestures, few users found its shape manipulations to be tedious, as it only allows 1 DOF control at a time. Several users thus indicated that enabling spatial constraints between shapes could *"help adjust the parts much faster"*.

DISCUSSION AND IMPLICATIONS

The results of our user study clearly show that the Combine and Redefine operations allowed design teams to efficiently come up with divergent concepts from prior iterations. This is largely attributable to the *concept component hierarchy*, which provides users with the freedom to selectively choose what level of design information to work with from a given concept. Combinatorial operations are an obvious way to generate new concepts by integrating parts from separate designs. However, simply putting parts together does not lead to an aesthetic or structurally sound design. Instead, the ability to isolate, manipulate, and reconfigure individual shapes and parts in Co-3Deator is what allows users to adapt it to a new design context. Similarly, during design redefinition, the *concept component hierarchy* gives users the flexibility to alter a design at multiple levels of detail. As a result, they were able to produce divergent concepts ranging from stylistic alterations to complete structural or functional reformulations.

While Co-3Deator serves as a team-first ideation tool, by necessity it also consists of designer-first elements. This is because to support any collaborative design process, there needs to be available a preliminary design concept space with seed ideas. Thus, in our team-first workflow, individual design creation is mainly used for initializing the concept space. The main strength of our approach however lies in its support towards collaborative creativity. Here, the combinatorial and redefinition operations across the concept component hierarchies allow design teams to rapidly expand upon an initial concept space. Such productivity cannot be achieved with a designer-first approach alone.

Several users in our study indicated that the ability to view different concepts in the design explorer—while working on their own designs—helped inspire new ideas not just for their current work, but also for those during future iterations. As two participants indicated: *"Looking at the designs made me realize how I could improve my own ideas and keep adding ideas for new designs"*; *"It helped me diversify my ideas and bring out some other factors I did not think of."* This is consistent with the notion of "working with multiple design ideas in parallel to foster the creative process" [11]. However, our design explorer takes this a step further by allowing users to work with multiple designs not just at a global concept level, but also at individual part and shape levels. As a result, the ability to hierarchically navigate the concept space or filter design information allows users to search for creative inspiration within focused contexts, while uncovering solutions or ideas at different levels of detail.

While our user study mainly focused on validating the creative mechanisms resulting from the team-first design approach, we find a scope for an extended study that deeply explores each mechanism in greater detail, and the system's usability within long term and multi-disciplinary design scenarios. Further, given the interesting results observed, we see value in a study that seeks to understanding collaborative creativity resulting from design concept re-interpretations. For example, it would be interesting to observe the creative outcomes if we allowed design teams to concurrently work with multiple product contexts. Here, how would the designers share and reinterpret ideas across different contexts? Or, how would this influence the collaborative ideation process and output?

In Co-3Deator, the 3D workspace mainly serves as a personal space for individual users to create and explore designs on their own. However, an interesting observation we made was that during a convergent process like final concept selection, design team members were naturally inclined to improvise a shared workspace, where the modeling activity reflected the ongoing discussions and mutual decisions. Thus, we find a strong prospect for exploring collaborative 3D design tools, where multiple designers can concurrently create, modify, and exchange 3D content and ideas in a shared workspace. Given the 3-dimensionality of the designs, such a system poses several interesting questions: (a) what will the system and its modeling interactions look like, (b) what types of design representations foster creative collaborations in such interfaces, and (c) how can we leverage proxemics to optimize social interactions and make the system non-intrusive?

CONCLUSION

We have presented Co-3Deator, a 3D design ideation tool for creating, sharing, combining, reusing, and redefining early stage designs based on the notion of "team-first" ideation. Team-first represents a class of ideation tools, whose design and operation emphasizes collaborative design processes and mechanisms. In Co-3Deator, such mechanisms were characterized by the *concept component hierarchy* and *collaborative design explorer* for representing, storing, browsing, and accessing design data, while allowing design team members to collectively explore and navigate a design concept space. To this end, the concept component hierarchy and design explorer together support creative design ideation via combinatorial design compositions and multi-level design redefinitions. Finally, we have validated the utility of these contributions through a qualitative user study with four design teams.

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