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COLLABORATIVE SKETCHING WITH skWiki: A CASE STUDY

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ABSTRACT

Sketching for conceptual design has traditionally been performed on paper. Recent computational tools for conceptual design have leveraged the availability of hand-held computing devices and web-based collaborative platforms. Further, digital sketching interfaces have the added advantages of storage, duplication, and sharing on the web. We have developed skWiki, a tool that enables collaborative sketching on digital tablets using a web-based framework. We evaluate skWiki in two contexts, (a) as a collaborative ideation tool, and (b) as a design research tool. For this evaluation, we perform a longitudinal study of an undergraduate design team that used skWiki over the course of the concept generation and development phase of their course project. Our analysis of the team's sketching activity indicated instances of lateral and vertical transformation between participants, indicating collaborative exploration of the breadth and depth of the design space. Using skWiki for this evaluation also demonstrated it to be an effective research tool to investigate such collaborative design processes.

1 INTRODUCTION

Product design and development are now global ventures not only in the industry, but also in academia, with distributed teams of designers and engineers enrolled in globally distributed capstone classes [1, 2]. Such collaborative environments have resulted in methodological as well as technological developments to aid design teams. Today, design tools have become more sophisticated, enabling concurrent, collaborative design for both collocated and distributed teams. Underneath the sophisticated tools available today, the early conceptual design process largely remains the same: collecting scraps of inspiration, doodling, rearranging, and iterating. Sketching has universally been acknowledged as "the archetypal activity of design" [3, p. 97], and while it is prevalent throughout the design process, it is more dominant in the early conceptual design stages. Sketching is not just a method for documentation and communication, it is also a tool for thinking: the act of sketching provides a memory extension, as well as a baseline for abstraction to the designer [4].

While computer support tools for design have made inroads into most design stages, from requirements gathering to detailed design, the (paper) design notebook remains the primary tool of the designer for sketching, recording observations, and making notes. This is partly due to training of the user—most people have sketched on paper since childhood—and the casualness of the medium—a notebook is easily carried around, and can store sketches as well as photos or clippings pasted to it [3]. Hong et al. [5] observe that "Where paper notebooks are used by designers to capture work for personal reference, an electronic version has the potential of being accessed by team members across space and time". Moreover, digital support for sketching has the

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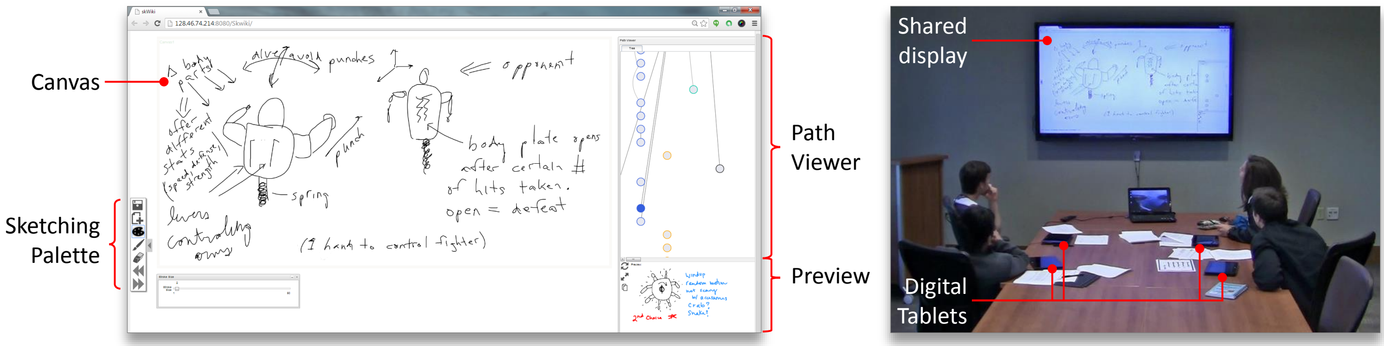

FIGURE 1. The experimental setup and apparatus are shown in the photograph on the right, with a screenshot of the skWiki interface on the left. skWiki runs in an ordinary web browser, and is thus platform-independent. The team is shown using skWiki on Microsoft Surface Pro devices, while a laptop running skWiki serves as a shared display for discussing ideas. A video demonstration of the system can be found here.

potential to aid design collaboration, including duplication, modification, and archival of concepts. The value of digitizing the design notebook was recognized early on [6], but it was not until the rise of direct-touch smartphones and tablets that the digital design notebook became a realizable vision.

Dorta [7] argues that computer support tools for ideation should "augment instead of imitate": to use the computational and interactive power to augment traditional design methods and tools, rather than imitate them. Collaboration adds a level of complexity to concept generation and progressive development: an effective communication and iteration mechanism is necessary to effectively utilize ideas generated by individual team members. Digital support for sketching should thus augment the intuitiveness of sketching on paper with the capabilities of storage and communication offered by computers.

With this in mind, we developed skWiki [8] a web-based application framework for collaborative creativity that would couple the "natural" interactions afforded by hand-held personal computing devices, with the collaborative power of a web-based platform. skWiki allows users to sketch their ideas, add text annotations and images, and share them with collaborators (Figure 1). The system also features a representation of a team's collaboration: a "path viewer" (Figure 2) that graphically and transparently represents all team activity, tracking all edits, modifications, and duplications of sketches. Our aim in this paper is to answer the following research questions:

Q1 How does the availability of "shared design notebooks" aid the concept generation and development process? In other words, does skWiki aid lateral and vertical transformations [9] of ideas between designers in a team?
Q2 As a research tool, what insights does the path viewer representation offer about the design process itself?

To answer these questions, we performed a longitudinal study with skWiki in a classroom design scenario, where the system was used by a team in an undergraduate toy design course, over a period of 19 days. Note that the study was meant to examine how digital creativity platforms affect the design process, and not directly compare the performance of skWiki with that of a traditional ideation process using pen-paper as a medium. Such a comparison is premature as sketching performance on direct-touch tablets is yet to meet that of paper [10], and comparing design processes between the two media would require conflating the effects of sketching performance as well.

2 BACKGROUND

In this section, we look at different approaches to collaborative ideation, and related work in developing computer support.

Brainstorming [11] is perhaps the most popular and extensively studied collaborative ideation technique. Other methods for group ideation include the Method 635 [12] and brain writing [13]. Designers use a combination of sketches and actions to communicate with each other [14]. Thus, graphical methods such as the Gallery method [15], brainsketching [16], and the more recent C-sketch [17] have also gained popularity. Each of these methods has its own strengths, and group ideation sessions often use a combination of these methods, or switch from one to another as the situation demands.

Evaluations of such idea generation techniques have yielded mixed results: studies on brainstorming have shown that a higher number of ideas would lead to a higher quality of ideas, while others have observed that brainstorming groups end up with ideas that are lower in quantity and quality compared to individuals brainstorming alone [1].

Collaborative design is progressive: it is as much about developing designs and alternatives as it is about expanding the problem space using concept generation methods. Blair and Hölttä-Otto [18] studied progressive idea generation methods such as 6-3-5 brainwriting with respect to how much the group contributes to an initial idea. They report that while the contribution to highly original initial ideas is not high, the group significantly increases the originality of previously unoriginal ideas.

Requirements of computer support tools for supporting conceptual design have been articulated by many. These include enabling easy entry of geometric, numeric, and text data, capturing ambiguity of early concepts with imprecise dimensions, allowing separate representations for conceptual (sketchy) and detailed (CAD) designs, allowing selective development of details, and enabling easy reviewing of alternatives [19]. On a more abstract level, Gorti and Sriram [20] suggest a framework that allows users to consider functional as well as structural alternatives, and allows the capture of functional intent behind the design. Yang [21] reviewed concept generation and sketching among student designers, reporting that the quality of the design outcome is positively correlated with the number of dimensioned sketches in the design notebook, and makes an argument for electronic design notebooks aiding collaborative conceptual design. Wang et al. [22] review collaborative conceptual design tools, and report that most tools support the later part of conceptual design. They identify key challenges in the field, including but not limited to web-based collaborative conceptual design, tools for managing conflict resolution, knowledge management in collaborative environments, distributed design project management, and intelligent web-based interfaces. They observe that there were few tools that support early stages of conceptual design such as branstorming and sketching.

Since then, numerous tools for brainstorming and sketching have been developed. Dorta [7] developed a Hybrid Ideation Space (HIS) which uses a spherical mirror model to provide an immersive virtual reality environment that incorporates a digital sketching interface as well as a 3D scanner for 2D and 3D exploration and manipulation of ideas. Clayphan et al. [23] devised a tabletop interface called "Firestorm" for text-based brainstorming, with a view to faster idea generation, high visibility of ideas, and easy selection and arrangement of ideas. Participants use keyboards to generate brief descriptions of ideas, without figures, and collaboratively use a tabletop interface for arranging and selecting ideas, which are color-coded to each participant. Support for multi-user sketching support was pioneered by the i-LAND environment [24] that uses personal sketching interfaces as well as collaborative display walls. TEAMSTORM [25] and GAMBIT [26] allow sketching on mobile devices, coupled with a large display for sharing and manipulating sketches. IdeaVis [27] recognizes the designer's preference for sketching on paper, and uses cameras and projectors to integrate paper into a collaborative environment that uses hybrid media. Most of these systems require the use of an environment specifically designed for the purpose, and thus pose challenges in the context of design teams, especially student design teams, that are unstructured and mobile. Finger et al.'s Kiva Web [28], a system for group collaboration, circumvents this limitation by requiring web-enabled computers and a projector, available in most generic meeting rooms.

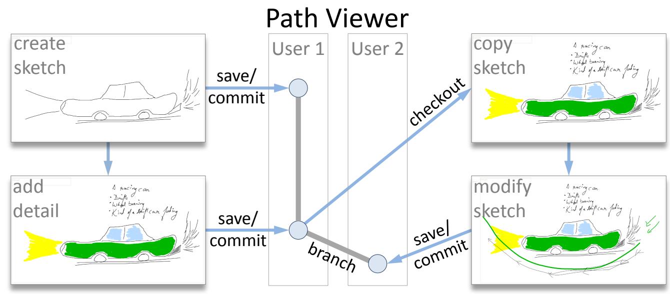

FIGURE 2. A basic representation of what the path viewer depicts. A sketch created by user 1, once saved or committed, is represented on the path viewer as a node (shown in light blue). Every time the user makes any modifications and commits the sketch, that particular version is added to the path viewer as another node. Any of these versions can be checked out by User 2 and modified. Upon committing, User 2's version appears under his ID on the path viewer, with a link to the original checked out version, called a "branch". Branching can thus be seen as checkout + modify + commit.

skWiki combines the usability of mobile devices for sketching with the added advantage of easy setup and use. Collaboration occurs over the web, requiring only a digital tablet with a stylus and an internet connection. A large display can be set up using a laptop connected to a projector or a large screen. While the large display helps collocated teams discuss their ideas, it is in no way required.

3 SKETCHES AS IDEA TRANSFORMATIONS

Ferguson [29] identifies three kinds of sketches that designers make: the *thinking sketch*, for nonverbal articulation of their ideas, the *prescriptive sketch*, for detailing an idea to a draftsman or a CAD modeler, and the *talking sketch*, as a means of collaboration and communication with other designers. Of these, the thinking sketch and the talking sketch have a fluidity and ambiguity to them that renders them mutable—an important attribute for divergent thinking. They are thus of particular importance to those studying the conceptual design process.

A categorization of design problem-solving and related aspects is famously detailed by Goel [9]. Specifically with respect to sketching, Goel identifies two main kinds of transformations:

- A **Lateral Transformation** involves a change or movement from one idea to another idea that is related to, but distinct from, the original. Lateral transformations are essential for divergent thinking: generating ideas, exploring alternatives, and expanding the problem space.
- A **Vertical Transformation** involves detailing an existing idea by adding annotations, dimensions, or features. Vertical transformations can be seen as a form of convergent thinking, to help refine an idea and develop its details.

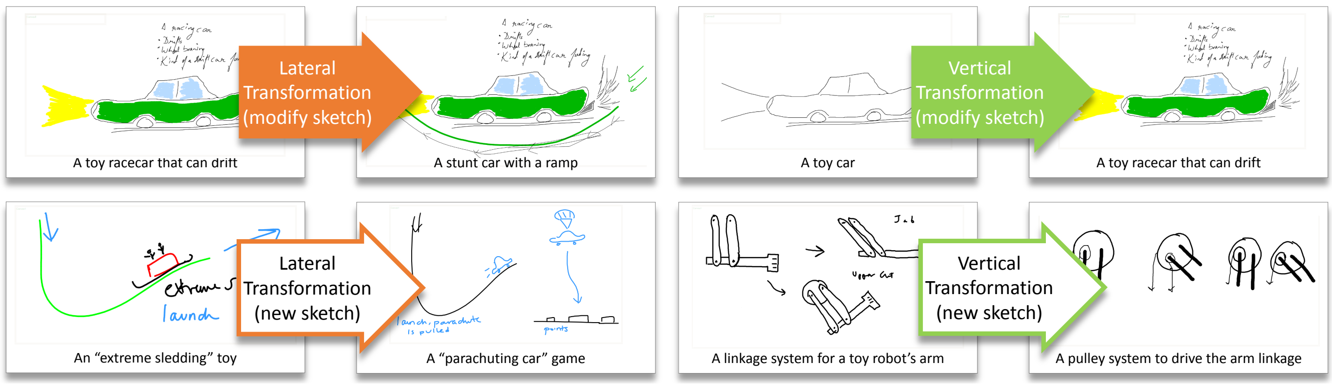

FIGURE 3. Lateral and vertical transformations observed in the study. Lateral transformations can occur through modification of an existing sketch, or through the creation of a new sketch inspired from an existing sketch, to create a new idea. Vertical transformations can occur through adding details such as dimensions, annotations, or features to an existing sketch, or through a new sketch showing a different detail, to develop an existing idea.

Lateral and vertical transformations are thus signs of divergent and convergent thinking, which in turn enhance the creativity and quality of the final design [3].

Each of these transformations can take two forms (see Figure 3). A lateral transformation can be performed by either (a) referring to, or being inspired by an existing sketch, and creating a new version that denotes a design alternative, or (b) modifying an existing sketch to create an alternative. Similarly, a vertical transformation can be performed by either (a) creating a different view of the object denoted in the original sketch to show more detail, or (b) embellishing the existing sketch with dimensions, annotations, and additional features to provide detail.

In both transformations, option (b) while more convenient than (a), would result in the original idea being lost to some degree. A collaborative design setting increases the potential for lateral and vertical transformations, but the sketching medium—traditionally pen/ pencil and paper—inhibits most instances of modification, especially when it comes to others' sketches.

Among collaborative, graphical ideation techniques, the C-sketch method [17] prescribes the use of modification to effect lateral and vertical transformation, while the gallery method [15] prescribes the use of creation (of a new sketch) to do the same. The C-sketch method reduces the inhibition against modification by incorporating it into its prescriptive method, but suffers from the loss of earlier ideas in the bargain. The gallery sketch, while less prescriptive, is time-consuming and suffers from the limitation of the (paper) medium on which it is often performed.

Digital tools for collaborative sketching have the potential to enable lateral and vertical transformations both by creation and modification. Such a system would need to make sketches persistent, by preserving older versions, and shareable, through duplication. skWiki, our framework for collaborative sketching, is designed with this requirement in mind. In the following sections, we describe the sharing model of skWiki and its rationale.

4 COLLABORATIVE SKETCHING REQUIREMENTS

The paper-pen paradigm enjoys its position as the medium of choice among designers owing to its flexibility and ease of use. However, digital media is gaining ground through its advantages of better storage and sharing models, with its interfaces rapidly evolving to bridge the gap between the two. In this section, we define a sharing model on a digital platform in terms of four aspects required for designers, and explain the skWiki interface on the basis of these aspects.

A1 **Storage and retrieval:** This aspect represents the variety of sharing operations possible using a digital platform. The fundamental operations of storage and retrieval include:
Save: Saving a new concept (or sketch) to a storage space. This may happen onto a private space (handheld device) or a shared space (network/ cloud storage).
Modify: The modify operation extends the *save* operation, and involves updating (edit + rewrite) a saved sketch on the storage space.
Branch: A branch operation occurs when a saved sketch (representing one or more concepts) is modified and stored as a new sketch in the storage space, commonly seen in code versioning systems.
Merge: In most concept design processes, coming up with one or more final ideas (convergence) is as important as the divergent processes. Also, concepts can span over multiple sketches and thus requiring a merge operation that can merge the sketches together into one.
Some of these operations are possible with pen and paper. However, they require a lot of manual effort and use of scanners or copy machines, and lack the level of ease and control possible in digital platforms.

A2 **Atomicity of the data:** In our context, atomicity refers to the smallest identifiable entity in the data that can stored through one transaction with the storage space. While an image can be stored on a file system, structured data in the form of text or vector representations are more atomic, and can be stored on a database. This allows for higher retrieval speeds and richer, more controllable encoding of the data. For sketches, this translates to the capture and storage of its history, at the level of individual strokes.

A3 **Collaboration representation:** Visual representations of authoring and collaboration can provide necessary situation awareness to the user. A graphical representation of user activity and of user contribution to a shared repository helps provide an overview of both user activity and data (in this case, sketch) evolution.

A4 **Capture of user intent:** This includes capturing user comments and explanations of the concept for the understanding of other users and/ or administrators. Types of capture may include video, audio, and textual methods.

4.1 skWiki: An Overview

skWiki stands for "sketch wiki", and is a web-based system for managing concepts that are generated in the form of different media types such as text and sketches. It captures individual user operations such as the creation of sketch strokes or text input, and stores the operations rather than graphical entities on a database. This allows for a higher level of atomicity (A2) in the collected data, and enables flexible storage and retrieval of sketches (A1). By combining these two aspects, skWiki enables history support for stored media, allowing save, branch, and merge operations. These operations are implicit, with the user performing normal file-like operations such as save/ commit, checkout, and edit.

The collaboration representations (A3) in skWiki include a path viewer and a thumbnail viewer. The path viewer is a node-link diagram representing the saved ideas as nodes, and connections between them such as branch and merge as links. The path viewer provides the ability to examine and use data (in this case, sketches) created by other users, modify them, and save them as new versions. Capture of user intent (A4) in skWiki happens through the implicit way of annotating the sketch. Figure 2 shows the user-level operations using skWiki, and its representation on the path viewer.

skWiki was built as a web application using the Google Web Toolkit[1] and runs in a web browser, requiring no additional software installation. Data in skWiki are stored as sets of operations. For example, a sketch is treated as a set of strokes, and adding a stroke becomes an atomic operation for the sketch. The operation sequence is stored in a database and it allows version management of the ideas generated, thus reducing the stored data. A detailed description of skWiki is provided by Zhao et al. [8].

A pilot study with skWiki was performed based on the C-sketch method [17]. This is a prescriptive ideation method that incorporates the 6-3-5 brainwriting method into a sketch propagation process, with each participant creating a sketch, and passing it on to the next participant, who adds on to or modifies the sketch to develop the idea further. We compared this process with a "looser" version of C-sketch, made possible with skWiki, where participants could choose a sketch from any of the earlier created sketches. We observed that more participants tended to choose earlier, undeveloped ideas to work on as they showed more potential for development. skWiki thus increased the potential number of lateral and vertical transformations possible from a pool of sketches, and delayed the onset of saturation. The details of this pilot study are also available in Zhao et al. [8].

5 CASE STUDY

We performed a longitudinal study, conducted over a period of 19 days, to observe how a student design team uses skWiki. To do this, we embedded the study in a design project of an undergraduate toy design course.

5.1 Participants

We recruited one team of 4 participants (3 male, 1 female), of ages 21-22 from an undergraduate senior elective course on toy design. All four were undergraduate students of Mechanical Engineering. Since the timing of the study was chosen to coincide with the concept generation stage for the course project, the participants had been trained in the fundamentals of freehand sketching as detailed in Taborda et al. [30], understanding play value [31], as well as ideation techniques such as brainstorming and SCAMPER techniques [32]. While there was no monetary remuneration, participants were granted personal use of the tablet computers used for the duration of the study, as an incentive.

5.2 Experimental Setup

Each participant was given a Microsoft Surface Pro equipped with its dedicated stylus, the Surface Pen. skWiki was run on the Google Chrome browser in all the devices. In addition, a laptop, also running skWiki on the Chrome browser, was connected to a large display for participants to view and discuss each other's sketches whenever required. The experimental setup is shown in Figure 1. Note that in the normal working of the course, the participants are required to work with their teams in a large classroom with sheets of paper and a cork board for each team to pin up their ideas.

5.3 Process Followed

The course structure requires students to spend the most part of a laboratory session in concept generation using the above techniques, after which they continue working on the concepts outside class hours. They submit their final concept 18 days from the in-class concept generation session, and start work on detailed design using a CAD application. We designed our study to follow the same process. The study began from this concept

[1] http://www.gwtproject.org/

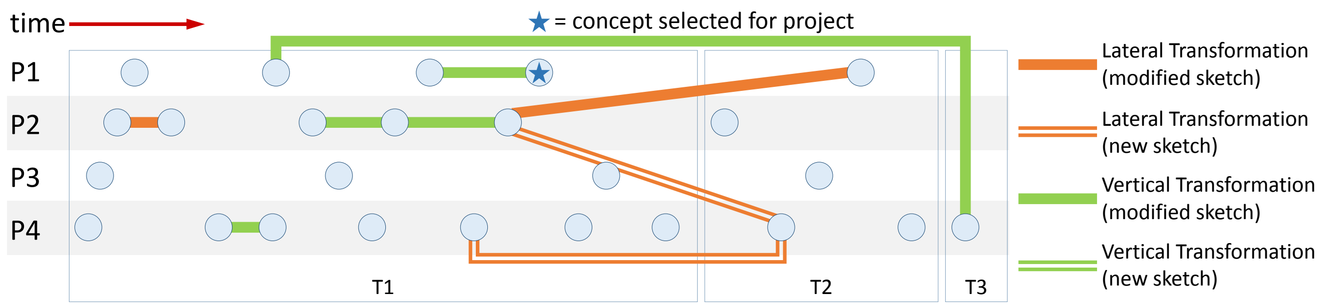

FIGURE 4. Lateral and vertical transformations observed in the in-class concept generation session with skWiki. P1–P4 are members of the design team, and their sketches are denoted by the blue nodes, arranged in the order of creation from left to right. Lateral transformations by branching, lateral transformations by visual reference, and vertical transformations (see Figure 3) that occur during this session are shown.

generation session, and ended when the students moved on to detailed design and started generating CAD models.

The longitudinal study was split into two main stages:

1. **Concept generation session:** This was the part of the study when participants were more closely monitored. An observer was present at all times in the same room as the participants, monitoring them through the given tasks, and helping the team with any problems they faced with skWiki. Participants were video recorded with their consent.
2. **Concept development:** During this stage, participants were required to use the system whenever they worked on the design. Their activity was not physically monitored, with server logs later used to study the team activity on skWiki.

At the end of stage 1, participants filled out a survey, reporting on their demographics and an immediate feedback of the process they followed and their experience with skWiki. At the end of stage 2, we conducted a short interview with the team, where they provided further feedback of their use with the system.

5.4 Tasks

The team was given a user interface guide, to show them the different features and operations possible with skWiki. The process of sketching, adding more canvases, and using the path viewer was explained, and the team was asked to practice creating and saving sketches, as well as branching and merging operations. The team was allowed to practice using the interface until they were comfortable with it.

They were then asked to generate concepts for their project, an action toy. The overall concept design process was split into three tasks, with five-minute breaks after each task:

Task 1 (25 minutes): The team was asked to generate ideas for the toy based on the requirements given. Participants were instructed to sketch out no more than one idea per layout. However, they could create multiple sketches of the *same idea* on one layout. Participants were also asked to add brief descriptions and annotations wherever possible, and use the shared display whenever necessary to explain your ideas to the team.

Task 2 (25 minutes): Participants were asked to discuss all generated ideas and select the most promising ideas. They were to extend these ideas, combine them with others, and generate new concepts, either by creating new sketches or by branching out from existing sketches using the path viewer.

Task 3 (15 minutes): The team was finally asked to discuss and select a final idea and refine it.

At the end of the in-class session, the team was asked to continue using skWiki on the tablets, to elaborate the final concept and develop it over the following 18 days, at which point they would move to detailed design using a CAD application.

5.5 Analysis

We used skWiki's interface to obtain all versions of the participants' sketches. We also used skWiki's path viewer to determine instances of branching, sketch development, and merging, as well as a rough overview of the sequence in which sketches were generated. The team activity on skWiki was matched up to the video recordings determine which sketches were created during each of the three tasks. We classified all sketching activity into the following categories:

- S1 The creation of a new sketch from scratch, representing a new idea, with no reference to pre-existing ideas.
- S2 The creation of a new sketch, representing a new idea that is inspired from or based on an earlier sketch, created by the same or by a different participant.
- S3 The creation of a new sketch, showing additional detail of an existing idea.
- S4 The modification of an existing sketch to create a new idea that is distinct from the original idea, but uses elements from the sketch.
- S5 The modification of an existing sketch to add further detail to the existing idea, through dimensions, annotations, or additional features.

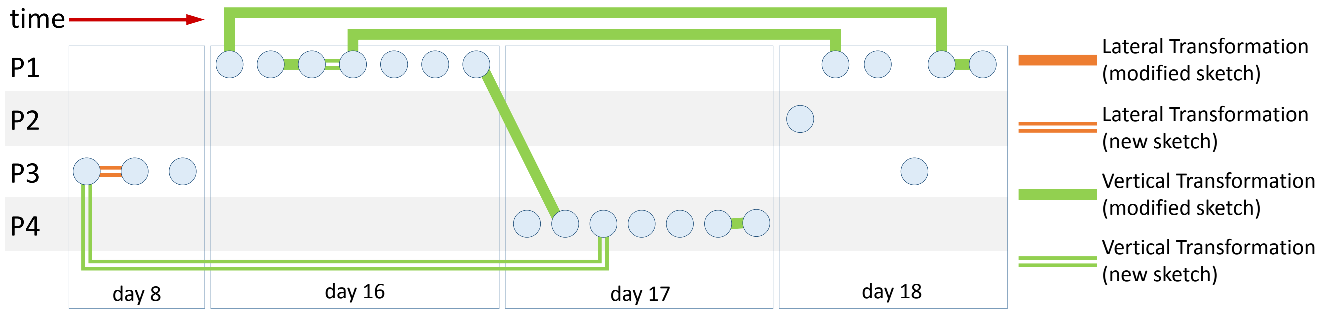

FIGURE 5. Lateral and vertical transformations observed in the out-of-class concept development session with skWiki. P1–P4 refer to the same participants as in Figure 4. Since this phase involves concept development, one would expect addition of detail to the selected concept, which translates to a higher number of vertical transformations as compared to the concept generation phase.

In the path viewer, sketches of types S1, S4, and S5 were immediately visible: S1 appeared as a new node, while S4 and S5 were visible as either branches or successive commits with significant changes. Studying the actual sketches further helped determine if they were of type S4 or S5. S1 and S3 were less straightforward: apart from studying the content of the sketch, noting the sequence in which the sketches were created was necessary to determine if a sketch belonged in either category. For the in-class concept generation session, viewing the video of the team discussion further helped categorize these sketches. The sequence of sketches by each participant, along with the identified source for inspiration or modification are shown in Figure 4 for the in-class concept generation session, and in Figure 5 for the out-of-class concept development sessions.

We immediately see that sketches of type S2 and S4 fall under lateral transformations, while sketches of type S3 and S5 fall under vertical transformations.

In-Class Concept Generation: Concept generation is essentially a process of exploring and expanding the problem space. We thus expected to see more sketches of types S1, S2, and S4 in this session, with a higher concentration of new ideas from scratch (S1) during task 1, and more lateral transformations, such as new ideas inspired by existing ones (S2) or modifications of existing ideas (S4), during task 2. This was indeed the case, as we can see in Figure 4. While vertical transformations (S3 and S5) are rarer in such situations, it is not unexpected to see them.

From the point of view of skWiki, the inter-participant transformations were of particular interest: evidence of branching and/or merging of ideas using skWiki, or sketches of types (S4 and S5). This occurred twice in this session. The first occurrence was between P2 and P1 as a lateral transformation: P1's idea of a toy sports car that "drifts" was transformed by P2 into a toy stunt car with a take-off ramp. The second transformation occurred between P1 and P4 as a vertical transformation: P1's idea of a mechanical spider was detailed by P4 through the addition of annotations detailing it as a wind-up, non-scary spider capable of making "random motions". Note that while the instructions of Task 3 were to select a concept and develop it further, it was not a mandatory requirement, and so the team merely short-listed promising concepts. The other lateral transformation seen was by participant 4, who used the preview and checkout options in the path viewer to draw inspiration from existing ideas and create a new sketch (type S2). There were no sketches of type S4—vertical transformations created by drawing a new sketch detailing an existing idea—which is normal for a concept generation stage. The final concept selected by the team, a robot sparring game proposed by P1, is represented by the node with a star in Figure 4 and its sketch is shown in Figure 1.

Out-of-Class Concept Development: The team was given possession of the tablets and styli for the next 18 days to develop the selected concept. We thus expected to see more vertical transformations of types S3 and S5, and these are indeed evident in Figure 5. While individual or team sessions during this stage were not monitored physically, monitoring the server activity helped determine that there were 3 sessions of individual participants developing concepts, with no-one else being online at the time, and one group session with all participants online at the same time. Our final interview with the participants revealed that they were also collocated during this session.

All the work done during this stage was in developing the selected concept. Technically, this meant that *every single node* in Figure 5 was a vertical transformation of the selected concept. This is not explicitly shown in the figure, so as to emphasize the transformations that occur within these sketches. Note that all instances of skWiki's branching and continuous commits here take the form of vertical transformations, with only one inter-participant transformation between P1 and P4, where P4 adds further detail to annotations created by P1 on a mechanism description. Another interesting observation here is the emergence of participant profiles, notably that of P1 and P4: P1 commits fewer sketches in the concept generation session, but after his concept is chosen for the project, there is a marked increase in

TABLE 1. Sketches of type S1 – S5 by each participant (P1 – P4).

		Number of Sketches				
		S1	S2	S3	S4	S5
Concept Gen.	P1	3	0	0	1	1
	P2	3	0	0	1	2
	P3	4	0	0	0	0
	P4	7	1	0	0	2
Concept Dev.	P1	6	0	1	0	4
	P2	1	0	0	0	0
	P3	3	1	0	0	0
	P4	4	0	1	0	2

the number of commits he makes. P4's commits remain high in both sessions. Table 1 shows the number of sketches under each category (S1–S5) by each participant for the concept generation and concept development sessions.

5.6 Team Feedback

Feedback from the team was positive overall: 3 out of 4 participants found skWiki to be an effective and fun way to collaborate. The fourth participant reported server lag as the main reason why he did not find the system effective. All team members reported that they felt less burdened due to skWiki, as they did not need to carry their sketches around, and that even without the tablets, they could open a browser on any computer and access skWiki to look up their sketches. They also liked the idea that saved sketches become immediately accessible to the entire team, and they no longer needed to be collocated.

With respect to the sketching experience, responses were mixed, with two participants finding the tablet hard to sketch on, while the other two found it easier to adapt to. All team members used the stylus to annotate the sketches, in spite of a keyboard being available, and the team was unanimous in their dislike of the application's relative insensitivity to handwriting. They suggested the embedding of audio files to sketches so they could speak out details while annotating key points, which would make communicating easier in a distributed collaboration setting. They also reported feeling impatient when waiting for a teammate to finish a sketch and share it, before they could view and discuss it; they desired a model that would update in real time. Finally, the team mentioned that they would like a "shared whiteboard" emulation, where multiple people could sketch on the same space simultaneously, which would improve their collaboration.

6 DISCUSSION

In this case study, we attempted to answer our research questions of how skWiki functions as a tool for collaboration, and whether it aids the expansion of the design space and the development of design solutions. We observed the different transformations at different stages of concept design, and found how it fits in Goel's categories of transformations.

Our second research question concerned the effectiveness of skWiki as a research tool. We found that skWiki enabled us to see the progression of ideas and the collaboration between team members, as well as distinguish between different the different forms of lateral and vertical transformations described in section 3. We will discuss both these answers in detail.

6.1 skWiki as a Collaboration Tool

Recall that skWiki was designed with the four aspects of storage and retrieval (A1), data atomicity (A2), collaboration representation (A3), and capture of user intent (A4). Aspects A1 and A2 in a sketch translates to history support, similar to feature-level history support for a CAD model. Just as a CAD model is more than just a boundary representation of a geometric entity, a sketch is more than just a collection of marks on paper. A CAD model represents a sequence of logical operations that captures user intent. Playing back this history allows both understanding of how the model was designed, and opportunity to modify the model from an earlier version of it. Similarly, skWiki's data representation allows an understanding of the designer's thought process, especially for early conceptual sketches. Additionally, it allows for a semantic grouping of chronological operations on a particular sketch. A sketch can thus be "rolled back" to an earlier version, and can be modified to take the idea in a different direction, thus increasing the potential for both lateral and vertical transformations. This potential is increased by the path viewer, through which a designer has access to every version of every sketch created by their teammates.

Designers have been described as "both doodlers, by virtue of their sketches, as well as hunters and gatherers... made evident by the types of paraphernalia that they collect for inspiration and reference" [3, p.186]. Designers take inspiration from the world around them, from analogies in nature to in mechanisms and products in different domains. The design notebook is the main implement of such a hunter-gatherer. In today's networked world, skWiki, running on a digital design notebook such as the tablet used in this study, becomes a powerful tool for accumulating and sharing new ideas through images, text, and sketches.

Further, the path viewer provides a representation of collaboration (aspect A3), or an overview of the team's activity. Group awareness has been a key research area in computer-supported collaborative work (CSCW), and skWiki's path viewer provides a non-intrusive, effective way for each team member to view their team's ideas as well as progress. By assigning roles in skWiki, this awareness can be tweaked to either a WYSIWYS (what you see is what I see) or a WYSINWIS (what you see is not what I see) system, based on the demands of any given project [33].

6.2 skWiki as a Research Tool

In this study, we were able to identify the sequence of the sketches and classify the different transformations that occurred, chiefly by playing back the sequence of activities and observing the connections between sketches and participants using the path viewer. The path viewer explicitly indicates the connections between sketches through its branching and continuous commit connections, and implicitly indicates the less tangible connections by allowing the researcher to view the sequence of sketches and compare the contents to determine possible origins of an idea. Additionally, through skWiki's aspects of storage and retrieval (A1), coupled with its data atomicity (A2), and capture of user intent (A4), a researcher can look deeper into the process of sketching to understand the designer's thought process

Schmidt [34] discusses research questions for CSCW to focus on, such as identifying the signals and cues an actor relies on when observing team activity, and the aspects of group awareness that are monitored actively in order to make sense of the surrounding (team) activity. skWiki thus doubles as a powerful research tool, allowing the researcher to collect data unobtrusively, and observe forms of collaboration between any combinations of synchronous, asynchronous, collocated or distributed teams.

7 CONCLUSIONS AND FUTURE WORK

We presented a case study of skWiki, a web-based sketching system for collaborative conceptual design. We embedded our study in a design project in an undergraduate toy design course. Operations performed by the team were classified into five categories of sketches, namely sketch creation from scratch, sketch creation as a modification of an existing idea, sketch creation to detail an existing idea, sketch modification to modify an existing idea, and sketch modification to detail an existing idea. We used Goel's categories of lateral and vertical transformation as a theoretical basis to understand these operations, and showed how skWiki increased the potential of such transformations, in turn increasing the potential for creative collaboration. We further illustrated the use of skWiki as a research tool for observing team collaboration, and for understanding explicit and implicit transfer of ideas between team members.

We obtained positive feedback from the team for skWiki being an effective and fun tool for collaboration. Suggestions from the team for further improvement included a more heterogeneous communication medium such as audio and video, in addition to text and sketches, and for a "digital whiteboard" allowing multiple designers to work simultaneously on a sketch. This is in line with findings by Purcell et al. [14], who showed that designers communicate by means of sketches, speech and actions, seamlessly switching between media to communicate with other designers. This form of "talking sketches" [29] can be enabled for distributed, or even asynchronous teams by incorporating such multimedia options for communication, akin to tagging sketches with gestures and speech.

We plan to extend such longitudinal studies to larger, more diverse teams over longer periods of time to obtain insights into scalability and adaptability. Our future development of skWiki will incorporate a more diverse set of tools for both creation and communication of ideas, improving the usability of the system, to create a powerful collaborative design notebook.

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