Point of no Undo: Irreversible Interactions as a Design Strategy

Beat Rossmy
beat.rossmy@ifi.lmu.de
LMU Munich
Munich, Germany

Nađa Terzimehić
nadja.terzimehic@ifi.lmu.de
LMU Munich
Munich, Germany

Tanja Döring
tanja.doering@uni-bremen.de
University of Bremen
Bremen, Germany

Daniel Buschek
daniel.buschek@uni-bayreuth.de
University of Bayreuth
Bayreuth, Germany

Alexander Wiethoff
alexander.wiethoff@ifi.lmu.de
LMU Munich
Munich, Germany

Figure 1: Irreversibility is an inherent feature of the physical world, but is disregarded in current HCI research. We rediscover and appropriate this alleged deficiency and amplify it as an inherent material property in the design of interactive systems.

ABSTRACT

Despite irreversibility being omnipresent in the lifeworld, research on interactions making use of irreversibility in computing systems is still in the early stages. User freedom – provided by the undo functionality – is considered to be a pillar of "usable" computer systems, overcoming irreversibility. Within this paper, we set up a thought experiment, challenging the "undo feature" and instead take advantage of irreversibility in the interaction with physical computing systems (tangibles, robots, etc). First, we present three material speculations, each inherently utilizing irreversibility. Second, we elaborate on the concept of irreversible interactions by contextualizing our work with critical HCI discourses and deducing three design strategies. Finally, we discuss irreversibility as a design element for self-reflection, meaningful acting, and a sustainable relationship with technology. While previously individual aspects of irreversibility have been explored, we contribute a comprehensive discussion of irreversible interactions in HCI presenting artifacts, a conceptualization, design strategies, and application purposes.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

KEYWORDS

Speculative Design, Design Strategies, Irreversibility, Causality, Tangible User Interfaces, Reality-Based Interaction, Robotic Interfaces

ACM Reference Format:
Beat Rossmy, Nađa Terzimehić, Tanja Döring, Daniel Buschek, and Alexander Wiethoff. 2023. Point of no Undo: Irreversible Interactions as a Design Strategy. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3544548.3581433

1 INTRODUCTION

One of the fundamental HCI heuristics [105] postulates that *user freedom* – mostly embodied through the *undo* feature – has to be implemented to enable efficient and smooth interaction with computing systems. In other words, in the digital realms, we can revoke and reverse almost all our (inter)actions. In many cases, the reversal happens with a simple click on a button and without visible consequences on the system or the human – as long as action and effect stay within the system, not affecting other humans[1].

The resulting ubiquity of reversibility stands in contrast to the causality of interaction we experience in the physical world. Yet, causality – and therefore irreversibility – is a fundamental keystone in learning about the inmost mechanisms of the world [54] and thus deeply rooted in the way we conceptualize interactions and materials in the physical realms. If a glass gets broken, we learn that it remains broken.

As much as irreversibility is central to our everyday lives, HCI interfaces often try to avoid or mask irreversibility in their design to enable efficient and smooth interaction with computing systems [12]. Yet, more recent efforts such as slow technology [56]

[1]In the following, we will refer to the **human in interaction** as **actant** to differentiate from study (participant) and usability (user) contexts.

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04…$15.00
https://doi.org/10.1145/3544548.3581433

or technology for critical reflection [7] stress the importance of designing not only for efficiency and productivity enhancement, but also for qualities such as mindfulness, rest and sustainability, in order for technology to blend into user's everyday lives. While irreversible processes and practices have been implicitly used in HCI interfaces [72] and research practices [102] before by the means of undesigning [110], unmaking [128], ephemeral interfaces [39], etc., irreversibility itself has not explicitly been conceptualized and reviewed as a design factor – which is the main goal of our paper.

Without any ambition for the iconoclasm of the essential achievement behind the undo functionality, we initiate a thought experiment in this paper and want to explore the advantages and implications that irreversibility offers in the design of HCI systems with the following two questions:

> *How can irreversibility, as a design strategy in HCI, be conceptualized?*
>
> *What are the advantages and implications of using irreversibility as design strategy in interactive technologies?*

Thus, we line up with speculative [6] and critical design [8] practices. As such, we understand practices which are interested in designing for a critical reflection on the societal and technological status quo, rather than focusing on the "utility-oriented, feature-laden, and productivity-enhancing development of digital technologies" [59]. We therefore explore the *undesign* [110] of reversibility, sharing our observations, insights, and learnings, while not questioning the usability of either reversible or irreversible interactions.

In order to inform the design of irreversible interactions, we contribute a comprehensive conceptualization and discussion of irreversible interactions as a topic in HCI. Our contribution is thus fourfold:

(1) We provide insights from our material speculations [138] and compare our observations with exemplar projects, which fit our understanding of irreversible interactions.
(2) We present an initial conceptualization of the properties and factors that shape the qualities of irreversible interactions.
(3) We contextualize related work with our speculations and our conceptualization, and deduce *altering*, *creating*, and *destructing* as design strategies for irreversible interactions.
(4) We discuss application purposes, focusing on reflection and mindful acting, meaningful thresholds, and embedded narrative. We end our discussion with the influence of irreversibility on power and empowerment in human-computer-interaction.

2 MOTIVATION & BACKGROUND

Irreversibility is an inherent characteristic of our physical world. The second law of thermodynamics teaches us that a process is irreversible if it can not return to its initial state by following the reverse order of actions. In other words, there is a $X \rightarrow Y$, but no $Y \rightarrow X$ [26, 27]. The concept of irreversibility, due to its omnipresence and emergence in different facets, is deeply rooted in human thinking patterns. This is reflected, for example, in proverbs which touch on the theme of irreversible spoken words ("A spoken word cannot be taken back.") or done deeds and scarce resources ("You can't eat your cake and have it"). While in the physical realm causality and irreversibility are axiomatic properties that can only be approached with deliberation and sharpened awareness in interaction, computer scientists recognized early on that this can be transcended in the digital.

In what follows, we (1) explain how irreversibility in the digital realm has been partially overcome by the undo feature, (2) touch upon how computer interfaces in the physical realm deliberately use materials' inherent limitations to create specific experiences and interaction flows, (3) explain how positive user experience not necessarily has to rely on pleasant experiences and interactions, and (4) how HCI research uses and investigates irreversibility in the topics of unmaking, uncrafting, and undesigning.

2.1 Undo: Overcoming Irreversibility in the Digital Realm

To overcome irreversibility in the digital realm, especially in the context of human involvement – with its inherent fallibility – the simple reversal of one or more actions in a computer system is one of Shneiderman's golden interface design postulates [126].

The idea of undo as an essential system's feature is older than 30 years, with many researchers to date investigating what undo is and what it should do (e.g., [5, 133, 140]). Abowd & Dix [1] discuss the difference between these two questions on undo. What undo *is* presents the system's perspective on undo. As such, undo is a function, an interface element, a feature that the system offers to the user in order to easily revert actions. What undo *does* eludes an user's intention to reverse to a previous state, not necessarily using the undo feature. Having a dedicated undo that enables the reversal is highly suggestive, but not necessary to carry out the undo intention.

As Nielsen[2] writes in the context of his third postulate on user control and freedom: "Users often perform actions by mistake. They need a clearly marked 'emergency exit' to leave the unwanted action without having to go through an extended process." The main purpose of undo is to recover from erroneous or mistaken actions through forward and backward error recovery [1]. In backward recovery, users "retrace their steps and reverse the effects of past actions" [1], whereas in forward recovery they "determine a new course of action which will take them forward from their current situation toward their original goal" [1].

Another perspective on undo is to conceptualize it as an enabler of "redo". According to a system's reachability property [86], undo allows reaching some of the system's previous states. As consequence, undo and redo together form a "causal dependence" [86] – in order for a redo to exist, there must have been a previous undo. Antonymous to undo, redo is the bearer of achieving alternative future system states. Undo and redo can help "relief anxiety"[126], and as such, engage the user in interaction surpassing error recovery (e.g., [2]), e.g., in "exploring unfamiliar options" [126].

[2]www.nngroup.com/articles/ten-usability-heuristics

2.2 Materials and Intentional Design Limitations in HCI

Opposite to the digital realm, irreversibility is implicitly contained in matter, with irreversible processes creating new materials or lasting changes. Referencing our surrounding physical world and its concepts can be beneficial for the user experience [87] and overall intelligibility of new technologies, as users' prior knowledge and real world experiences are taken into account [66]. For example, Reality-Based Interactions (RBI) focus on the people's skill and awareness to bodily act in their physical and social surrounding. More recently, materials and material sciences [113] have continued to become a focus of HCI research [53], as digital content is increasingly integrated into users' daily lives and environments [64] – with such properties of materials as permanent and non-permanent material changes being investigated. The manipulation of the surrounding matter and the resulting experience [49] is a central design approach since it puts the material qualities in relation with the people's prior knowledge. The manipulation of objects based on their materiality [122], such as squeezing or crumpling, can be mapped to understandable actions such as distorting sound [134] or as a representative action for emotions such as anger [130]. Ephemeral user interfaces [39], with soap bubbles [131] or ice [25] as materials, embody the concept of *transiency*, by the impermanence of the materials. Edible interfaces [71, 89] elude *finality* in that the material is scarce. Thus, a causality is established that is understandable and clearly conveys the impact of actions [32, 33].

Using such materials comes implicitly with constraints, which can be conceptualized as external restrictions. However, intentional design limitations – which are self-imposed restrictions –, such as the refusal of capabilities of software and instead revert to restrictions known from the physical world as practiced by artists [79], embracing the imperfection of the human nature by taking advantage of faulty memories [103] or using *ephemerality* (opposed to the permanence of the digital), are increasingly gaining momentum in HCI. A variety of design limitations aim at deliberately decelerating the human-computer interaction. Design frictions [91] intentionally break the interaction flow to create awareness and thus prevent errors and potentially harmful actions. Similarly, reflective design [124] and slow technology [56] seek to promote contemplation and thoughtfulness of both one's own and others' (inter)actions, with the goal of changing or accepting one's behavior [29]. In addition, interfaces can even strive to reverse user's expectations on their functional premises to encourage critical thinking and action [8]. Counterfunctional interfaces limit a system's expected functionality, but at the same time seek to encourage the invention of new ways of interaction [111]. Most extremely, and with the same goal as previous designs, there have been recent calls to "undesign" technology [110], ranging from inhibition to complete erasure of parts of technological functionality.

2.3 Undesirable and Uncomfortable Interactions

These approaches to redesign technology fundamentally challenge what is considered a pragmatic, functional, or positive user experience [58]. While desirable experiences aim to engage consumers in an interaction, undesirable, unpleasant, and uncomfortable [11] actions and feedback can create comparably powerful experiences, even if this seems contradictory at first. To do so, HCI research explored various types of stimuli and sensations such as claustrophobic situations [21] or sensory perceptions such as pain [77] and uncomfortable emotions [84]. Contrary to the assumption that such feedback would discourage users, the use of pain to create attraction has a tradition dating back to the 19th century carnival [109]. Since pain and fear release similar hormones as positive situations would, the experience of such stimuli provide their own aesthetics and appeal [67]. Beside explicit feedback, interactions can also be designed to be implicitly uncomfortable. "Brute Force Interactions" as known from martial arts, inflict pain and fear. Thus games, which require intense physical actions [96] such as hits and punches [97], can "facilitate emotionally rich reactions that result in unique experiences" [95] even if this experience is partly uncomfortable.

2.4 Unmaking, Uncrafting, and Undesigning

While we refer to the central concept of this paper as irreversible interactions, works that address irreversibility implicitly in their designs, design practice, and design theory have a tradition in the HCI community.

The topic of unmaking [121] is concerned with the usage and outlasting of technology after its production and its intended use [80]. Here, decay, destruction, and deconstruction are aspects to be taken into account. Not only can objects be designed to be part of a zero-waste cycle by using only reusable materials [17], but they can evolve in meaningful patterns when exposed to external influences and interactions, and even transform into other objects offering new functionalities [128]. Thus, the unmaking of interactive artifacts is not simply an implicit phenomenon in the causal world, but an explicit design decision. Therefore, deconstruction, recycling, reuse, and modification of technologies [65] are inherent capabilities to enable sustainable technologies, such as in the case of separating materials in recycling smart textiles [139]. In the context of unmaking, irreversibility is the underlying concept which is broken down into a design vocabulary of object transformations. While unmaking is concerned with these transformations and how they can be used in the design of technologies, the focus is not on the interactions (as in interacting with an interface) that use this vocabulary, but on the material changes inflicted. In the case of irreversible interactions, we are particularly interested in how interactions that lead to these changes can be used in interactive systems.

While unmaking explores the vocabulary of deconstruction, uncrafting is concerned with the process of deconstruction [100], decomposition [82], and de-synthesis [83] as the "thoughtful, reflective process of disassembling" [102]. It is seen as a process through which knowledge is created based on the experience during the act of deconstruction [83], disassembly [101] or observations made during stages of decay and decomposition. Here the focus is entirely on the process itself and not on the outcome of the deconstruction or disassembly. Even if irreversible interactions are used in such workshops [99] and design sprints as a method to investigate technologies, these interactions are not part of the regular use of the deconstructed systems or technologies. Uncrafting proposes the generation of knowledge as a result of deconstruction, while irreversible interactions focus on the incorporation of irreversibility in the interaction design of new technologies.

Whereas the topics of breakage, aftercare, and repair are concerned with irreversibility due to the causality of the underlying processes, unmaking and uncrafting are, as stated above, not about functional interactions at their core. Instead, they focus on knowledge creation and on the aftermath of technology. However, we are interested in the utilization of irreversibility in the moment of a functional interaction, which means creating an effect or reaching a system state by executing irreversible means. This intent is more closely related to projects known from the undesign movement [110] in which technological functionalities are renegotiated unconditionally as demonstrated by, e.g., the *Obscura 1C* [112] camera. The *Obscura 1C* is a digital camera with its components enclosed within a continuous concrete body. As a result, the immediate accessibility of the taken photos, is "undesigned" or removed from the system. The camera must be broken open to gain access to the photos. A normally reversible action, removing the SD card, becomes an action with irreversible consequences for the entire system, which is unusable once the photos have been accessed. This fundamentally changes the use of and relation with the technology.

While this specific example illustrates an irreversible interaction in the authors' sense, conversely not all undesign projects implement irreversibility. The focus of this paper is on interactions that are a functional part of an HCI system by design and are irreversible by their nature.

2.5 Summary and Objectives

As described before, irreversibility is a fundamental and ubiquitous principle of the physical world, which is comprehensible for the human being acting in it. In contrast, in the virtual realm, undo functionality was introduced to overcome limitations imposed by non-reversibility – now established as an enabler of interaction and exploration. With the emergence of interactive technology embedded in and interwoven with the physical world, both principles are competing with each other. In our work, we explore the potential of irreversible interactions in tangible artifacts as a dedicated system's function. Hence, we rediscover and appropriate this alleged deficiency and instead amplify it as an inherent material quality and property.

In doing so, we add to the body of research on design limitations by examining and conceptualizing deliberate constraints on system functionalities that are irreversible in both the system domain and the physical domain. In what follows, we present three material speculations that make use of irreversibility at the core of their functionality and interaction with the human.

3 MATERIAL SPECULATIONS

We present three material speculations drawn from the authors' recent research[3]. We use the term material speculations as defined by Wakkary et al. [138] who define it as "the manifestation of a counterfactual in a material artifact[, which] occupies the boundary between actual and possible worlds [and] when encountered, generates possible world accounts to reason on its existence". These projects were not originally envisioned as a contiguous series of investigations, but grew out of an interest in creating HCI systems that effect behavior change through implicit interaction rather than explicit prompts using irreversibility to create "discursive interventions" [138]. Methodologically, these projects followed the experience prototyping workflow [22], beginning with an investigation of the design, technology, and context of use, followed by exploration and evaluation of the derived designs. We consider these projects to be exploratory, in that interest grew out of a desire to actually use and experience these ideas, and speculative, in that design decisions were not informed by expert input, but rather on the underlying hypothesis and objective of using and exploring irreversibility in interaction design.

Thus, we contemplate these projects to rather present "artifacts intended to be carefully crafted questions" [142] than to be formally informed design prototypes. In doing so, the artifact is the materialization of the question through which we can create an encounter and observe and reflect on its effect on the actant. While the first question focuses on the conceptualization of irreversibility in the design of HCI systems, the second question is about the advantages, implications, and consequences for the humans in interaction. Although these projects are situated in interchangeable contexts, they share the same core principle: irreversibility in their interaction. Our goal was to explore how irreversibility shapes actants' thoughts and actions, aiming at identifying factors that influence their interaction with the system one way or another. However, we do not lay focus on empirically testing nor comparing the speculations but instead aim to identify indications and pointers to spark an in-depth discussion and to create access to the topic through the experiences and observations recorded throughout the experiments. Further, this research through design approach enabled – through the materialization – a core knowledge production to derive the conceptualization described in section 4.

For each speculation we provide an overview of the design aims and report on observations that, although difficult to quantify, we believe highlight the essential features of irreversible interactions.

3.1 Four on the Floor – Irreversibility in Production

Modern musicians are used to music production software that includes usability principles such as undo functionality to increase productivity and effectiveness by lowering the risk of potential harmful interactions. Contrary to this, former practices such as playing and improvising live music require foresight and the consideration of the musical context in advance to successfully perform music. In that sense, music production on the computer entails an exploratory process that is much more about user freedom through trial and error and its retrospective analysis. On the other hand, playing live music requires a commitment to performed interactions, which builds primarily on prospective thinking and audiation [51].

The aim of this speculation was to explore how a production task and the related user experience change when

[3] All participants of the system evaluations agreed that their data may be used for scientific publication in anonymized form and were compensated fairly. All participants' quotes have been translated into English.

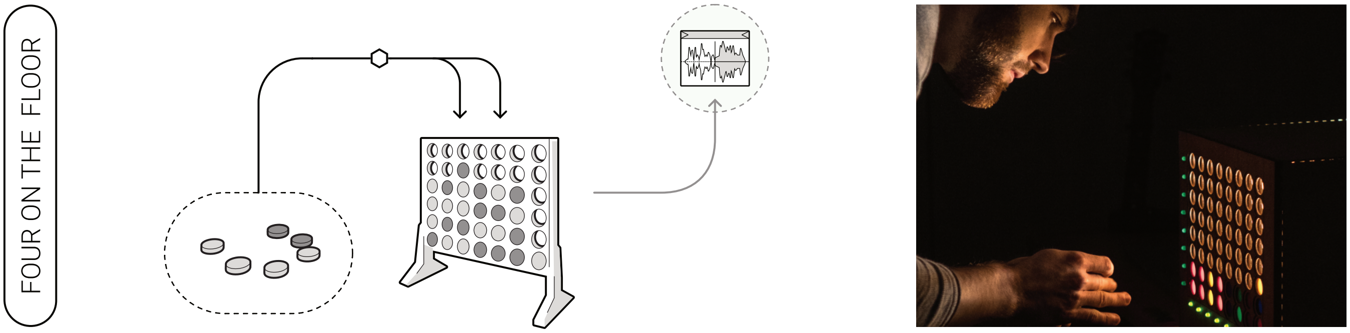

Figure 2: Typically, music software tries to optimize users' efficiency. If the expected user freedom is altered, the irreversibility of users' actions is enforced. Consequently, users have to change their usage patterns from trial-and-error exploration towards prospective thinking and mindful acting.

the familiar reversibility is transformed into an irreversible interaction with a computing system.

3.1.1 Artifact Design. We designed the experience prototype *4 on the Floor* (cf. Fig. 2) to create a musical production interface which incorporates irreversibility in its workflow. Our design goal was to naturally include the irreversible interaction by building on a familiar interaction concept that includes irreversibility per se. Since step sequencers and midi loops already look like chess boards or other games, we looked for a game during which players accept that their actions can not be modified. Thus, we picked the *4 in a row* game and transferred the idea to a musical sequencer (see Fig. 2). By dropping colored discs in an eight by eight vertically suspended grid, actants build musical melodies and rhythms. The colors represent pitch or samples and the columns along the x-axis represent time increments. By throwing chips into the grid, a sequence of notes is created and stacking chips forms chords or layers sounds. This sequence is constantly repeated in a loop, as known from step sequencers. Via a webcam-based image processing approach, the chips were tracked in real time, converted into midi triggers, and then sent to a digital audio workstations for sound generation.

3.1.2 Observations. We confronted 20 participants (self-identified as: 11 ♀ and 9 ♂; average age: 24.2 years) in a laboratory AB testing setup with our artifact. Participants were recruited from the personal circle of the study conductor and from the university email list for study recruitment. We informed the participants about the interface's mechanisms and interaction principles, after which they used the interface in two configurations in a counterbalanced order. The first configuration (A) used the irreversible interaction, whereas the second configuration (B) allowed removing individual chips at all times. After experiencing the artifact during three trials each (about 30 minutes), a semi-structured interview was conducted that addressed the observed behavior patterns during the previous interaction and the participants' thoughts on the different concepts. The statements and comments were then clustered and coded by the project researchers using an inductive approach following the principles of thematic analysis [15, 16] to identify patterns, topics, and themes in the participants' thoughts, comments, and in their observed behavior. Our approach followed three iterative phases, as found in other HCI research [48, 119]: (1) collection of the qualitative data, (2) topic extraction, (3) theme development and review.

When asked about the benefits of the irreversible interaction, participants commented along the following four themes. They stated that they appreciated the *creative aspects* (*n*=6), since the irreversible interaction required them to adapt dynamically to new situations, thus encouraging them "to make something new and good from the previously laid." (ID20). As a result they got "other ideas to change" (ID6) the musical sequences and patterns. This theme is analogous to art practice and performance in which often "mistakes represent an opportunity not a deficiency" [4]. Further, they experienced the interaction as a *thoughtful process* (*n*=6) that triggered a "purposeful execution" (ID16), "anticipatory thinking" (ID17), and required them "to mentally go through the steps before laying the stones" (ID5). Nevertheless, they experienced the interaction as a *challenge* (*n*=4), since the task was "more demanding" (ID10) due to the irreversibility and required to "apply the acquired knowledge without just messing around" (ID13). They further emphasized the *playful qualities* (*n*=3) and suggested application scenarios in educational contexts, such as kindergarten or music school classes.

Only two participants completely rejected the concept, with one reporting *frustration* due to the inability to change already entered notes (ID19). A closer investigation showed that participants in favor of the irreversible process were divided into two different mindsets. Eight participants exclusively pointed towards playful or creative aspects, whereas six participants enjoyed the interface due to its challenging and thoughtful character. Further, one participant stated that "... every step had to be carefully considered and it was necessary to reflect if the previous decisions were working towards the planned results. Mistakes triggered creative reactions which was overall a lot of fun" (ID1).

Observations in the irreversible case revealed some participants to occasionally pause the interaction and take a step back, in order to get a holistic overview. Consequently, this action created a moment of rest to think about and plan upcoming interactions.

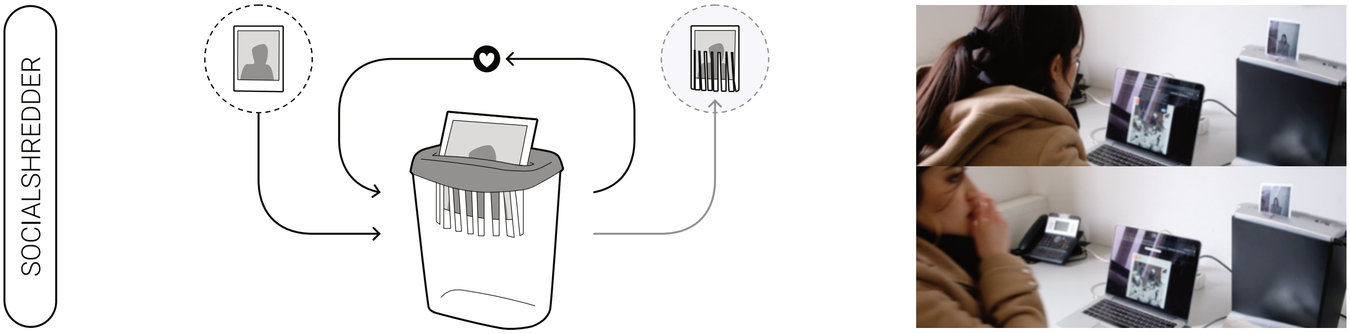

Figure 3: The provision of data on the internet is often not fully reversible. Despite this, users often do not adapt their usage behavior. By illustrating the irreversibility of their given data via the incremental alteration of a personal photograph, the participants adapted their behavior during our exploration and provided less likes.

3.2 SocialShredder – Irreversibility in Providing Personal Data

When interacting on social media, whether by uploading, commenting or liking content, users are often aware that they provide personal data to the platform. Yet, they still do not have privacy concerns regarding such services – this phenomenon is called the "information privacy paradox" [75, 106]. Our hypothesis is that few know that each interaction with social media is more or less irreversible, even though it seems reversible. If a user likes and later dislikes an image, the like may be deleted from the web interface – yet, the like-dislike interaction depicts a valuable information for companies. Further, effective data removal from trained machine learning models is not trivial [50], if not impossible. Nonetheless, only few users actually change their interaction patterns on such platforms due to this knowledge.

The aim of the speculation in the context of providing personal data was to explore whether an actant's behavior changes if the irreversible nature of their interaction (with social media) is materially emphasized.

3.2.1 Artifact Design. We designed the experience prototype *SocialShredder* (cf. Fig. 3) that irreversibly alters a personal item – a Polaroid picture of the participant – whenever they like images on a mock-up social media platform. This visualizes and emphasizes the fact that the provided personal data is permanently lost and cannot be reclaimed in its entirety. Thus, we strive to achieve the following: first, interrupt the participants and shift their focus away from the virtual realm to disturb the automatized behavior pattern [68] and second, communicate via an incremental and irreversible alteration of the physical image that some of the participants' personal data has been irrevocably lost. This cause-and-effect relation is easy to conceptualize and strikingly illustrates that, once an image is liked and thus altered to ultimately destruction, it cannot be restored by disliking the content. Even if this happens, the Polaroid will stay irreversibly destroyed. We opted to use a personal image because we wanted to have a feedback method that reflected the contextual characteristics of acting in social media, thus emphasizing the connection between the participant, the object of interaction, and the information generated as a result of that interaction. To disintegrate the image, we considered several options, but decided to use an electric shredder in order to be able to digitally control the gradual destruction of the image, rather than other possibilities such as burning or altering the photos. The shredder also symbolizes a transfer of the information to another sphere, as the image is physically removed from the direct access of the participants. Via USB, the shredding action was triggered whenever a *like* was given on the mock-up platform.

3.2.2 Observations. To explore the effects of the irreversible feedback on participants' behavior, we let 16 participants (self-identified as: 9 ♀ and 7 ♂; average age: 27 years) experience the speculative artifact. The participants were recruited from the personal circle of the study conductor and from the university email list for study recruitment[4]. They had to interact in a laboratory setting with the image feed of the mock-up social media platform where they could like the posts. The exploration incorporated two counterbalanced conditions: (A) with irreversible feedback, i.e., Polaroid shredding, and (B) without any feedback. The Polaroid pictures of the participants were taken in the beginning of the experiment and placed in the shredder's opening without informing participants about the functionality of the device. They were instructed to act on the mock-up platform as they normally would on their preferred services, liking as many pictures as they wanted. The participants were not informed of the destruction beforehand, as the goal was to observe their situational adaptation as an immediate response to the confrontation. Using this exploratory approach, we asked participants to describe their impressions and thoughts after their experiences in semi-structured interviews and to rate some aspects of their experience. The statements and comments were then clustered and coded by the project researchers using an inductive approach to identify patterns, topics, and themes in the participants' thoughts, comments, and in their observed behavior (cf. as described in 3.1.2).

Our observations show that the participants provided less likes for images in the condition with irreversible feedback provided (Median of likes. A: 2.5; B: 27.5). Further, participants reported (1) longer contemplation on whether they should give a specific like (n=15) and (2) a heightened awareness of their likes being irreversible

[4]As is usual for studies within the scope of smaller research projects and university theses.

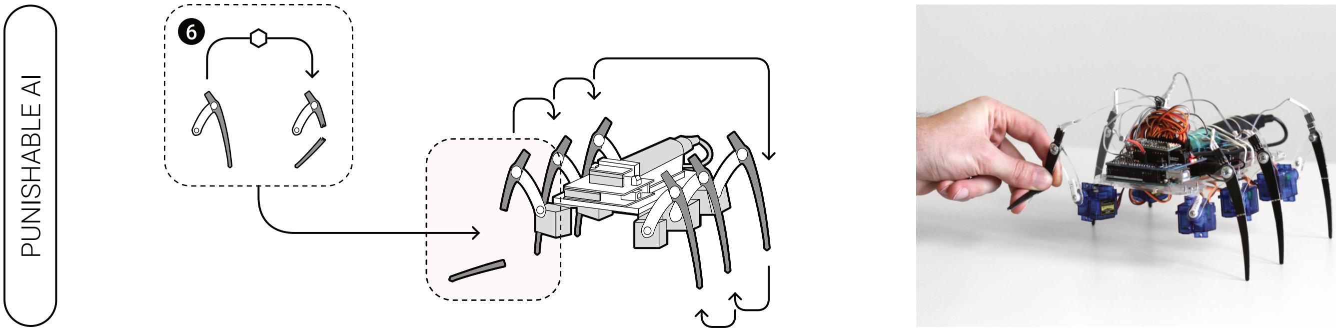

Figure 4: Irreversibility emphasizes the effect on the system to which the feedback is directed. This is not due to the effect on the system, but to the actant's perception and interpretation. Breaking the robot's leg to inform the system must be consciously thought through. The finiteness of the system and the feedback conflicts with the need to preserve the system's functionality.

information (*n*=8). Participant ID1 stated: "When I realized that my photo was being destroyed with every like, I realized that with each like, a piece of my personal information was being given up". When reflecting on the experience with the irreversible condition, participants stated that they were influenced (*n*=10) by the destruction of the picture – they felt bewildered and confused by the feedback. The majority (*n*=11) reported that they did not experience amusement as a result of the irreversible interaction. During the interviews, we found that participants responded differently to the irreversible feedback. Some completely stopped the interaction after they realized that pushing the like button results in the Polaroid being cut. As the statement of ID5 suggests, "I only gave one like, since I found it unpleasant and terrible to destroy an image of myself", responding also to the socio-emotional meaning of the personal image. While some participants were likewise immediately attached to the Polaroid, others did not have a "major emotional attachment to the picture because it was taken just before the study" (ID3), so the destruction was less momentous. Therefore, the personal motif was not necessarily a reason to restrain from the interaction. Yet, it did change how they were considering more "carefully before [they] liked a picture and hoped that not too many good pictures would follow" (ID11) before giving likes. On the contrary, four participants continued giving likes, even after the image was completely shredded. As participant ID10 mentioned, the unusual quality of the interaction was somehow fascinating and motivated a further exploration of the interaction with all its consequences – "You rarely experience that kind of user interaction and that's why I found it fun and interesting at the same time and I enjoyed that." (ID10).

Our observations confirmed, that the shredding moved participants' attention away from the screen. While this was partly due to external stimuli, such as the loud shredding action (which attracted the attention based on basic human reflexes), participants as well followed along with the incremental shredding. One actor (ID5) even went one step further and attempted to remove the image from the shredder to prevent further destruction after the initial feedback was received. Finally, some participants asked for their individual Polaroids even when completely shredded since they "wanted to keep it because of the story" (ID15) as a memory or souvenir.

3.3 Punishable AI – Irreversibility in Interaction with Intelligent Systems

As intelligent systems continue to enter the everyday live, new design challenges are emerging. Whereas natural concepts and RBI principles are used in designing the interaction, not all usability principles are still applicable [3, 41]. Since providing feedback and fine-tuning such systems can be challenging, anthropomorphic design strategies, such as praise and scold [18], are considered to enable the interaction for non-expert users. To accept such interactions, users need to believe in the effect of the method. This requires their belief that (1) the machine is sufficiently intelligent to understand the meaning of and (2) is affected by the interaction.

The aim of the speculation in the context of intelligent systems was to explore how actants perceive the impact of incremental destructive feedback when applied with irreversible consequences.

3.3.1 Artifact Design. We implemented a walking robot – personified as an insect – to investigate whether the human perception of the consequences to a system of providing feedback (influencing the robot) changes when performed as an irreversible interaction. Here, the robot should be trained to walk a straight line. When it gets off track, the robot gets "notified". Feedback to the robot is provided first by scolding, second by a negative stimulus (bright flashlight), and last by gradually breaking the robot's legs (see Fig. 4). The breaking interaction was limited by design and could only be repeated once per leg. Implicitly, the finite character of the interaction communicates a strong impact of the interaction to the system, compared to the non-destructive modi. Several design aspects aimed to implicate the irreversible interaction, such as the fragile, long, and thin legs as well as the predetermined perforation which both indicate the breakability. Through the PCB legs, the state of the legs (interrupted traces) and touches of the participants (capacitive areas) could be sensed. While all feedback mechanisms were in fact carried out during the interaction, the learning of the system was not implemented, since we were interested in the experience during the application of the feedback and not in the feasibility of the machine learning aspects.

3.3.2 Observations. 20 participants (self-identified as: 9 ♀ and 11 ♂; average age: 26 years) participated in an exploration of the material speculation. The participants were recruited from the personal circle of the study conductor and from the university email list for study recruitment. They executed the three feedback methods (scolding, negative stimulus, breaking the leg), which represented a stringent escalation during the training. The detailed results have been published in [119]. For that reason, we will highlight only results of interest with respect to irreversibility. As a new perspective, we add informal observations that emerged from an internal colloquium, during which we presented to and discussed the prototype with professors and senior researchers from the HCI and computer science context. The discussions were conducted in the form of non-directive interviews. This was due to the general structure and nature of the event. Nevertheless, the perspective of the computer science experts triggered interesting discussions that revealed many aspects and controversies about the use of irreversible interactions.

The observation and analysis revealed that the irreversibility clearly affected the participants, as they hesitated to execute the breaking action and stated to rather avoid destructive feedback. During execution, some participants responded strongly to the implemented reactions of the robot. When the robot started trembling upon touch, to depict resistance, they sighed and there were short exclamations like "Oh no ..." when they broke the leg. Due to the PCB's flexibility, a certain force must be applied before the leg snaps. Thus, participants slowly built up the tensions until they reached the breaking point, which created a moment of anticipation. Additionally, eye contact with the instructor was sought as if they were looking for confirmation of their actions. The subsequent interviews revealed both an economic and an emotional argument against the irreversible interaction. Some participants felt empathy for the robot and thus, the interaction was perceived as cruel and discomfortable, affecting their own emotions. As a consequence, participants felt "sorry for the robot" (ID3) and pointed towards the robot's aliveness as one contributing factor for such responses, "Well, if it was just a piece of metal, I would just have broken off a bit. But he kind of made facial expressions" (ID36).

During the demonstration in the colloquium, we primarily observed two behavior patterns. First, we discussed with advocates of the economic reasoning. They saw the irreversibility in conflict with maintaining the robot's functionality. In an extreme case, one participant categorically refused to carry out this action, as he principally objects senseless destruction. Second, many experts perceived the idea as a curious provocation, contradicting established design principles. In that spirit, they rather executed the interaction for entertainment reasons. Yet, they re-visited the demonstration, at times more than once, to further engage in discussions. We interpret this as an indication for a triggered reflection process.

3.4 Summary

Within all presented speculations, participants demonstrated a clear understanding of the cause-effect relationship, that is omnipresent in the irreversible interactions – either by the finite nature of the interacting object, in conjunction with the irreversible change or by the limited access to an interaction-relevant resource. This can be explained by the basic human understanding of the physical world [66], on the basis of which the consequences of (inter)actions are extrapolated and anticipated. Thus, the participants knew that a chip thrown into the *4 on the Floor* matrix, could not be removed. Similarly, they knew when a second like is given, the image would be further altered by the *SocialShredder*. Finally, they knew that when most legs of the *Punishable AI* robot were broken, it would be unable to walk.

Whereas the causality, and the aforementioned RBI perspective, can explain participants' understanding of irreversibility and its effect on a system, we have reason to believe that these perspectives are not fully adequate to explain why participants are affected – to the observed extent – when confronted with an irreversible interaction.

For example, we observed that irreversibility stimulated participants to contemplate their actions (*4 on the Floor*), reminded them of action implications (*SocialShredder*), or made participants reconsider the sense of an action (e.g., breaking a leg) due to the irreversible alteration of an interactive object (*Punishable AI*).

As consequence, we want to highlight three key observations beyond the simple restrictive nature of irreversibility.

- **O1** Participants *consciously* interrupted their interaction flow when confronted with an irreversible action.
- **O2** Participants *showed interest* in the objects they irreversibly altered.
- **O3** Participants' reasoning against the application of irreversible interactions went *beyond purely rational* considerations.

We used convenience sampling for recruiting our participants, which can potentially introduce problems regarding personal bias. However, our key observations and findings are not based on any explicit rating of the material speculations, which are more likely to be influenced by personal relationships. Rather, our findings build upon implicit behavioral patterns that are resistant to conscious influence.

Looking into the observations, we recognize that various factors shape the effect on the actant. For example, **O2** is based on the object itself, whereas **O3** poses questions about the reasoning process, among others, the personal or social context. This led us to conceptualize irreversibility, in order to appeal to the question "what factors of irreversibility contribute to the observed influence on the actant's behavior?". In what follows, we suggest factors of irreversibility that differentiate an irreversible interaction from other interaction principles, as part of HCI.

4 CONCEPTUALIZING IRREVERSIBILITY

To understand the influence of irreversible (inter)actions on the experience, we consider the influencing factors that are either *unique* to, *influenced* by or *emphasized* by irreversibility. By doing so, we focus on the gap between objective measures – the artifact and interaction design – and the subjective experience. In the context of irreversibility, the identified factors contribute to the experience as a distortion and thus influence any intended effect. Understanding the factors and their relationship, helps to better understand the experience of an irreversible interaction.

We deduced the following factors by comparing our speculative artifacts and exemplar HCI projects that, in our opinion, similarly include irreversibility in their designs. As result, we identified shared properties that we consider to be influential in the conceptualization of irreversible interactions and their effect on the actant. These properties (see Fig. 5) contain factors that belong to (1) the artifact, its materiality and object character, (2) the context which is established by the individual and external measures, and (3) the actants' involvement in the irreversible (inter)action itself.

4.1 Artifact-Related Factors

Both our speculations and the exemplar projects, make use of diverse materials and objects. Two main factors, the artifacts' *value* and *symbolism*, can be considered as explicit design decisions.

4.1.1 Value. Irreversibility in our context directly involves the interactive artifact with its entire materiality, sometimes with permanent consequences that diminish its value. The artifact's value can depict two different things. First, the *objective value*, i.e., an economical value based on supply and demand or on a societal agreement. This differs a Fabergé egg from a hen's egg, or an ordinary piece of paper from a money bill. Second, the *subjective value* which is either based on the individual's subjective perception, emotional attachment and past experiences, as well as on cultural considerations such as moral and ethical principles.

Objective Value - In the case of *Punishable AI*, the robot, as a technological device, gets attributed a relatively high objective value. This value influences the economical considerations when interacting and consciously breaking the robot apart. The objective value, attributed to complex devices, depicts a threshold which has to be actively crossed when applying the irreversible interaction.

Differently, *Destructive Games* by Eickhoff et al. [44] uses the objective value of money to increase the interaction stakes. Here, two players are cutting apart a money bill in a laser-cutter during the game play. Replacing money with paper would lower the stakes, the implied risk, and thus the commitment which positively affects the excitement. In both cases, a typically thoughtless interaction becomes a conscious choice due to the artifacts' objective value.

Without value the same action becomes trivial such as breaking a toothpick or tearing apart a napkin. In this way, incense chips are used in interfaces for spiritual interactions [137]. Here, the irreversible material change determines the time-span of the experience, acting as replaceable resource and therefore neither creates a threshold nor a high stake interaction.

Subjective Value - In contrast, the portraits used in the *SocialShredder* experiment or the handcrafted items in *Scotty* by Mueller et al. [98] hold a greater subjective than objective value. In both cases, a unique item gets destroyed during the interaction. In the case of *Scotty*, this object is later recreated via a 3D printer when sent to a friend. The destruction of the original has a great importance, as the uniqueness and thus the subjective value is preserved. In the same way, the Polaroid used in the *SocialShredder* bears an individual subjective value for every single actant, based on its uniqueness (non-digital) and the personal motif, which even can outlast the object's destruction (**O2**). This perception of subjective value is as well used in the music-box prototype *MuRedder* [73], which builds on the subjective experience of music. In *MuRedder*, simple paper tokens, representing songs, are shredded to be played back. Whereas, the token only bears a low objective value, actants were consciously planning the time and place of listening the music piece to be able to actively listen and value their favorite music.

In addition to the personal attachment towards cherished objects, subjective values can also reflect societal norms and principles. As reflected in the statements of some *Punishable AI* participants, they revealed strong principles they applied to reflect on the destructive interaction (**O3**). This is comparable to Bartneck et al.'s [9] assumption that the perceived intelligence of a robot influences the willingness to destroy it, such as there is a lower social acceptance regarding the killing of intelligent animals (cf. mosquito vs. primate). Such considerations can include (a) ethical principles, (b) moral norms (e.g. the value of life, which is often used as a constitutional principle [10]), or (c) societal standards.

4.1.2 Symbolism & Subtext. The reference made in the design of an interactive artifact can create a decodable subtext based on, e.g., the collective memory [55] of a society. When we compare *4 on the Floor* and *Punishable AI*, we see that the design informing objects influence the perception of the irreversible interaction. There is a playful reference in the *4 on the Floor* project to stimulate a free, uncomplicated, and exploratory interaction. Whereas, the zoomorphic design as a symbolic representation of a living organism, stimulates the need to preserve and maintain the artifact. Further, breaking a leg creates a different subtext than smashing a robot with a hammer in pieces [9]. One could argue that the destruction itself is already connoted negatively and primarily defines the subtext, however many everyday activities create joyful experiences through destruction. Unwrapping a present by ripping the paper wrap apart in sheer anticipation creates a different emotion than receiving the present without surprise and symbolic stimulation. Just like the incremental destruction of a flower when playing "He/She loves me ... he/she loves me not ..." can create amorous excitement, since the actions cannot be reversed and the outcome cannot be predicted. Further, many people enjoy popping bubbles of a bubble-wrap, which can even have a calming and stress-releasing effect on the performer [36]. So part of the experience is based on the choice of object and material, what associations they trigger, and what interactions with such an artifact are perceived as natural and fitting.

4.2 Actant-Dependent Context

Values, symbolism and subtext depend to a great degree on the interpreting person and their societal context [14]. Contemplating the design process as the creation of meaning is not possible without considering the individual using the artifact, thus creating an own context in which design and interaction are interpreted. The context created is partly personal as well as socio-cultural. When an individual is confronted with an irreversible interaction, which is generically about permanent change or a transformation, we can objectively describe the change such as "ice transforms into water" but the perception of *melting ice cubes*, *a melting ice sculpture* or *the melting of the polar caps* depends on the context that first is established by the individual or the belonging society.

Remains - If we take a look at the *Punishable AI* and the *SocialShredder* projects, the state in which the artifact remains after

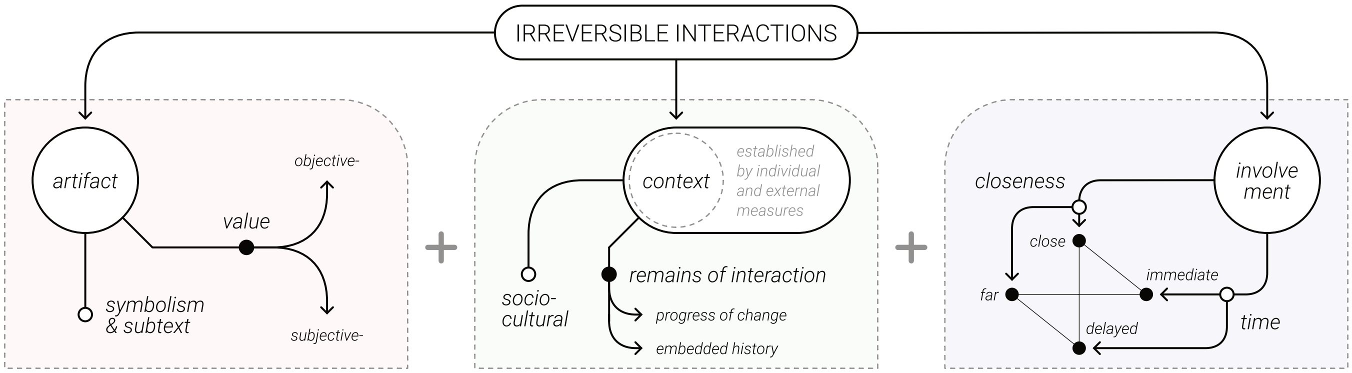

Figure 5: We found three main properties influencing the experience during the irreversible interaction. These are artifact, context, and involvement related.

the interaction has – via the irreversible alteration – some visible history embedded. We can see how many legs already have been broken or how much of the picture has already been shredded. Comparable to research on using wear marks in digital files as consequence of reading and editing the files, with the goal of communicating over time and distance [61] or on traces of use in HCI to embed information [117, 118] and affordances [62] into interactive artifacts, irreversible interaction artifacts implicitly do the same. For example, the project *PlantDisplay* [76] communicates actant's social interaction with others via the adapted watering and consequently encodes the actants' interaction in the health of the plant.

In fact, permanent changes that tell a story are incorporated in many cultural practices. For example, everyday scars allow people to get in touch with others, by comparing them, telling stories based on them, and via these empathetically relate to others. In that sense *SocialShredder* participants developed an interest in the remains of their Polaroid pictures since they embed a story to be told (**O2**).

Socio-cultural Context - To fully understand the meaning of an irreversible interaction, one has to consider the socio-cultural context, e.g., cultural practice or history. Take, for example, human scars. While in many western societies facial scars are today seen as an imperfection, in the cultural practice of scarification [47] scars are perceived with a spiritual or tribal meaning. The same goes for the so called "Schmiss"[19] (facial dueling scar) which, in the early 20th century, Germans perceived as a badge of honor, but bewildered foreigners.

In HCI, the projects *InScene* [70] and *SenseCenser* [137] both make use of the irreversible act of burning incense chips during the usage of their interfaces. Burning incense is common in the spiritual context, which is shaping the perception of this action. Yet, burning other materials or in another context creates a different meaning and experience. Whereas burning incense creates a fragrant smoke, which is connoted to be relaxing, meditative, and used consciously, lighting up a gas stove will be perceived as functional, as it is pragmatically used in the everyday processing of food.

On the contrary, burning books (even if seemingly equivalent to the burning of other matter) is perceived as a much "heavier" act. This is due to the history of censorship, in which burning books symbolized burning *knowledge* – contrary to the books' intended function to collect, contain, and preserve information. Yet, this historical link was established only recently. Beforehand, in ancient cultures, there was a predominant "intimate connection between destruction, burning and purification" [60].

4.3 Actant's Involvement

The last factor, is the interface's way to involve the actant in the irreversible process. We identified that actants take roles, based on their involvement in the interaction, which, in turn, shapes their experience. Illustrated by the art installation *Helena & El Pescador* [42] – in which visitors were confronted with a set of blenders, each containing one living goldfish – the visitors either were *actors*, actively blending the fish, *spectators*, waiting on the sideline for someone to blend, or *moralizers*, who went by and built their opinion[5]. Either way we actively participate, but the way we participate shapes the experience. With this example in mind, we identify two dimensions of the involvement. First, how *"close"* our action is coupled to its consequence – is there a proxy between the interacting artifact and the actant? Second, how much *"time"* separates the consequence from the cause of the interaction – is there a delay or is the consequence immediate? The non-existence of a proxy and of a delay contribute to what we call a stronger involvement since the "distance" between the actant and the system is reduced. In other words, there is a direct cause-effect relationship visible. While both dimensions are continuous, out of simplicity we consider four different *closeness-time* combinations of actants' involvement: (1) close & immediate, (2) far & immediate, (3) close & delayed, and (4) far & delayed.

Close & Immediate - The closest way we can apply an interaction is probably by doing it with bare hands, directly on the artifact, in real time. In that sense, *Punishable AI*, *To kill a mockingbird robot*[9], or *Obscura 1C* [112] directly involve the actant without a separating proxy. The actant thus becomes the active performer, breaking the interactive device and in this role takes full responsibility and perceives the full agency regarding the interaction.

[5]https://artelectronicmedia.com/en/artwork/helena-by-marco-evaristti/

Far & Immediate - When adding proxies between the action and the effect the irreversible interaction has, the distance between cause and effect is enlarged – the involvement is reduced. Examples for this are *SocialShredder*, *DESU 100* [115], *Destructive Games* [44], or *Scotty* [98]. Here, a button press evokes the irreversible alteration – instead of a direct destruction. This indirect relation reduces the involvement and can change the perception from being the actor towards being in a spectator role.

Far & Delayed - Increasing the time between the cause and the effect of an interaction will let the actant perceive less responsibility for the action, taking a rather spectator role. In *PlantDisplay* [76], the actant's social contacts lead to watering the plant, thus happening in a different context. In that sense, the plant is a visualization of the actant's behavior only indirectly affected by it. Furthermore, the delay occurring between the plant being not watered and the plant drying out increases the distance between cause and effect.

Close & Delayed - We could not identify related work that presents an actant involvement, which uses a direct cause in conjunction with a delayed effect. An hypothetical example from human-robot interaction can illustrate such a scenario. If we were to physically interact with a robot by, e.g., punching it, we might get confronted with the consequences later in form of an, e.g., "bruise" which develops over time. As an example from the arts, chain reaction installations such as *The way things go* [43] by Fischli and Weiss use small actions with irreversible consequences. The result is delayed and the actant's role changes from active to being a spectator. Chemical processes that cure materials such as resins or photographic emulsions also feature close interactions with delayed consequences.

4.4 Summary

We outlined various influencing factors on the actant experience when performing irreversible interactions. These factors include, the artifact's value and symbolism, actant's personal and socio-cultural context, and actant's involvement in the irreversible change. As designers we can deliberately use and functionalize them to influence the user experience as shown in the observations **O1-O3**.

Accordingly, we can fine-tune these factors in an artifact's design and the associated irreversible interaction. Measures designers can take include the adaption of the objects objective or subjective value, the contradiction or capitalization of the socio-cultural interaction context, or the purposeful degree of actant involvement.

While the factors present a convenient way to shape irreversible interactions one way or another, the final experience is a result of the complex interplay of all introduced factors. As stated by McCarthy and Wright "any pragmatically useful analysis of artifacts is inseparable from an analysis of the values and experiences of those who use them or feel their effects", thus it is important that these factors are not considered isolated from each other since they form a "complex web of meaning relations" which amplifies itself so that it emerges to something larger than the sum of its parts [90]. This essentially reflects the understanding of interactive systems in terms of Actor-network Theory (ANT), which includes "non-material entities, such as policies, laws or societal norms" [45] and acknowledges their influence in the network of actants.

5 DESIGN STRATEGIES

Reflecting upon our material speculations (cf. Fig. 6), we have used irreversibility in three ways: (1) in *alteration*, (2) in *creation*, and (3) in *destruction* of a physical computing system. On a more general note, these approaches differ in the motivation and extent of use of irreversibility. More specifically, they encapsulate distinct characteristics of the aforementioned conceptualization. We shaped the general and specific focus through our designs, with each speculation embodying one way of approaching irreversibility in design. Following, we present these approaches as derived design strategies, suggesting how irreversibility might be incorporated into system design.

Alteration lies at the core of every irreversible interaction, as per definition, it is matter that changes without the possibility of revoking to its initial state. As such, alteration represents a middle ground between the extremes of *creation* and *destruction* towards which an irreversible interaction may gradually move. The direction of the movement depends on the value and functionality of the object, that is, the material under change. In case *added value* is being *produced*, or *existing value* is being *transformed*, the process becomes a process of creation. Otherwise, if *existing value* is being nulled, it turns into destruction.

In our speculations, we observed that the design strategies provoke more reflective and thoughtful engagement (**O1**) – regardless of the included factors. In the *SocialShredder* project, the actant's own image is altered with each like on a social media platform. Although finally cut in pieces, the image still preserved its subjective value of a photograph that captures a moment in space and time. In other words, the actant might still recompose the shredded remains (**O2**), distinguishing this process from destruction. By visualizing their interaction, actants felt provoked to more deeply think of the consequences of a superficially harmless interaction. Furthermore, the number of shreds could provide narrative on how many likes have been given, with additional information potentially enriching the narrative. For example, information on when the shred happened, with varying periods between, might point to actant's hesitation to act towards the end. In *SocialShredder*, the actant indirectly (i.e., far) and gradually decreased the photographs value. The effect of shredding was increasingly visible by the end, moving the tipping point rather far – in space and time – from the actant.

The tipping point presents, on the continuum of actant's engagement in irreversible interaction (i.e., the lower curve in Figure 6), a certain threshold at which the value substantially changes, either decreases to void, transforms or even exceeds its initial value. At these points, the heightened awareness about the interaction turns into more profound, even existential, considerations (**O3**). The greater the value changes in both directions, the higher the thoughtfulness of acting.

In **creation**, the actant's imagination is challenged towards the end result by continual re-examination of the steps and workarounds that lead to a potentially surprising result. Although reversibility and undo are said to promote creativity and exploration, we observed in *4 on the Floor* that actants were, by trial-and-error, rather handling towards a premeditated goal. Actants created the music piece again only by proxy (i.e, by throwing chips into the

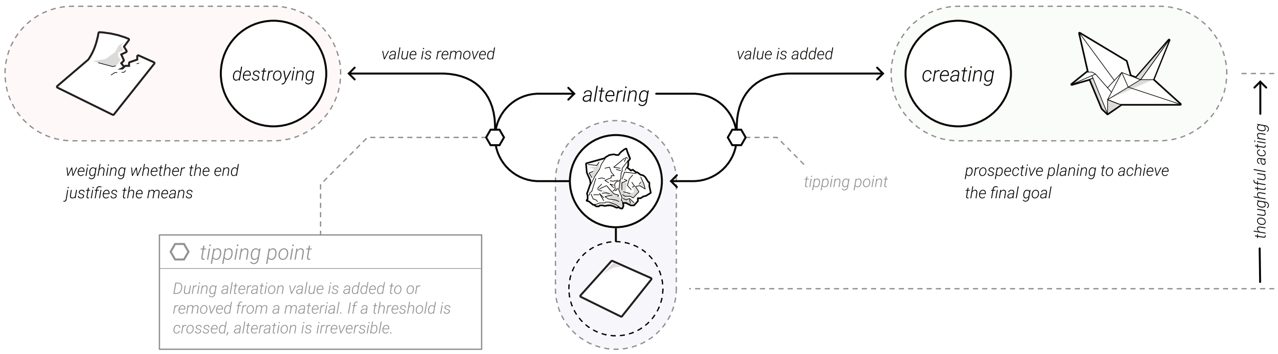

Figure 6: Altering a material can either end in creation or destruction, depending on whether value is added or nulled. Illustrated using paper, a sheet can be torn in destruction, crumpled in alteration, and folded into an origami creation. In destruction, the paper looses its functionality and value. In crumpling and folding, the creases are permanent, but the paper remains functional. Additionally, value is gained in creation. Along that continuum, if a certain threshold is crossed, alteration irreversibly tips. The carefulness of alteration will in this case highly depend on the value of the used material – it is not the same for a blank piece or a 100€ bill.

raster), the change implied was delayed (offset between playback position and position of change). Each step within the irreversibility condition required brain work and imagination, as the output of the step had to be played in mind upfront. If we think of current, everyday digital technologies that can keep us entertained wherever and whenever, we have deprived ourselves of the right to be bored, thus often abolishing spontaneous moments of imagination, contemplation, and reflection. If we are unable to stop (mindlessly) using technology, can we restore creativity by implementing irreversibility within our interaction with such everyday technology?

In **destruction**, the end result is clear – to diminish the value of an object – but the reflection is rather contained in the reexamination of the meaning and sense of the act of destruction itself. In other words, with each step, actants actively weigh whether the end result justifies the means (**O1**). The threshold marks the point at which there is no going back – at which the value is irreparably lost. In *Punishable AI*, actants could directly break the robot's legs with immediate effect – the tipping point is passed when the robot could no longer move and thus lost its functionality.

While we identified three design strategies, we do not claim completeness. These strategies can motivate and guide the design of interfaces that use irreversible interactions to create embodied and experiential interactions. Additionally, the strategies and their properties are not exclusive. For example, there is a thin line between alteration and destruction in the *SocialShredder*. It even makes sense to combine the strategies. For example, in WabiSabi [136] an object is first destroyed, but then its remains are carefully being glued together with gold. This in turn, adds value to the initial object.

6 DISCUSSION

While at first glance our design approach seems fundamentally contrary to decades of HCI research [105], we found that the intentional appropriation of irreversibility can stimulate actant behavior which joins in with current research trends. This accentuates the interest in designing HCI systems in a way to address qualities that focus more on actants' well-being [58, 129], system sustainability [37, 127] or meaning [92, 93] than to create systems, which are only about accuracy, speed or usability. In that sense, our discussion breaks down to three application purposes – on the actant and the interacting system respectively – for employing irreversibility in design. We discuss these application purposes against current HCI research.

6.1 Stimulate Reflection and "Mindful" Acting

Our observations on our designs, together with studying exemplar HCI projects, showed irreversibility to break actants' mindless *interaction flow* [28, 31, 38]. In turn, actants reflect on the implications of their actions and thus on the actions themselves. This is consistent with theories on interaction design that conceptualize risk as intertwined with attention and engagement. Thus risks becomes a "positive aspect of embodied practice" [57], where risk is understood as the consideration of choosing and performing an "action which cannot be undone while the consequences of the action are not fully knowable ahead of time" [74].

Generating such attention and engagement is of interest when modern technologies take over the thoughtful use and consumption of technologies, media content or social experiences and instead turn these into addicting application models [94, 125], which with the help of dark patterns [52] coerce, steer, or deceive actants. In this respect, we see the potential of irreversibility to actually create "reflective" technologies that incorporate implicit "mindful" actions helping us being present during our interaction [116], instead of designing technologies which explicitly teach us how to be mindful [34]. This can be considered to follow along with the work of Niedderer [104] on performative objects. While these achieve "mindfulness as caused by a modification of function" [104], irreversible interactions achieve mindfulness as caused by the modification of the typically reversible interaction consequence – by employing an actual consequence compared to a state of no consequence at all. Thus, in both cases the actions become focus of the reflection, forcing the actants to pause their automatized *interaction flow* and focus on what is actually done in the situation.

6.2 Create Meaningful Threshold

While the aspect of mindful acting is in general about a constant change of actant behavior, irreversible interactions can as well function as intended thresholds the actants have to cross actively in order to selectively trigger conscious decision making in the context of high-stake interactions. This function of irreversible interactions is comparable to research about microboundaries [30] that make use of design elements interrupting an interaction flow to hinder the actant to unconsciously make momentous decisions. These design frictions [91] take on the functionality to stop our action and remind us in the scope of the action to be performed. While the unlimitedness of virtual systems implies "there are no restrictions", the causality of the physical world tells us "everything you do has irreversible consequences". Thus, breaking a robot in pieces to prevent its information being passed onto other entities [9] conveys this message in total clarity, whereas confirming the deletion of all data via, e.g., an app is intransparent and consequences are not comprehensible from the outside [81]. In this regard, pushing a button to confirm an action is meaningless in itself since it is the same for saving a file, sending an e-mail, or deleting the hard-drive. Irreversible interactions, however, can emphasize the causality and the action's finite character, thus creating a meaningful [35] experience.

6.3 Embed Narrative

While we previously focused on how irreversibility shapes the way we interact and think, irreversibility also changes the artifact itself. This is interesting since people naturally develop an attachment to regularly used objects, which can be perceived as "evocative objects", that "carry memories, generate identities and provoke new ideas" [24]. When they get used and the use is reflected within them, they transform from the arbitrary to the personal [20, 135], creating subjective value. Basically, the alteration of the materiality [122], such as crumpling as an illustrative action, embeds a story into the material. This shows the preceding interaction and implies what Odom et al. call a history [107] of the actant's behavior or even the behavior of many generations before. When we contemplate how this embedded narrative benefits HCI, we see connecting points in the literature. Such narrative aspects are used in board games to individualize the playing experience, which is hard to replicate within digital equivalents [88]. The meaningful change of a systems could function in Human-Robot Interaction (HRI) to create designs that show the temporal development and thus stimulate an empathetic connection based on shared memories and stories [85]. Such a relation could also positively affect the consume-oriented society (invention & disposal) towards more sustainability (renewal & reuse) [13]. If we perceive a strong connection with objects, they might be worth preserving, repairing, and keeping instead of instantly replacing, as we value the aura that is connected to and represented by the artifact [128]. In that regard, the *wabi-sabi* aesthetic and the *Kintsugi* practice of repair value the imperfections of objects. By applying them to design, a deep relationship between actant and product can be created [132]. Technology enhanced *Kintsugi* objects have been explored to facilitate more human-to-human or human-to-self connection [23], explored pivotal interaction and the value of transformation of objects [63], and were used to preserve interactive objects [108]. Expanding on this idea, irreversible interactions show the potential to "design for long-term interaction through conscious use of impermanent materials" [136] and thus to provoke the conscious engagement and empathetic relation with technology.

6.4 Irreversible Interactions as Transformations

While the material speculations presented in this paper primarily focused on the finite character of irreversibility, such as breaking to destruction, shredding to dissolution, or inaccessibility due to physical constraints, the research on unmaking points to design possibilities that focus on the transformative character of irreversible changes. Rather than relying on consumers to initiate the "reuse and creative repurposing" [65] of obsolete technology or the repair [114] of broken things, Song and Paulos [128] propose objects with *evolving designs* that, rather than becoming obsolete after a period of time, renew their functionality. Instead of simply breaking down, objects deconstruct into new forms with their own individual functions and meanings [120]. As some participants in our experiments noted, they had difficulties connecting the seemingly nihilistic action of destruction with a purposeful process (**O3**). Or, as Paul Dourish puts it, "HCI has often transformed the problems of sustainability into the cost-benefit trade-offs of rational actor economics, promoting sustainability as a matter of personal morality" [40]. Linking irreversibility to transformation could counter the economic argument, since the trade-off is between two types of functionality rather than between function and nonfunction. The concept of *evolving design* points towards design solutions which, despite being irreversible, present purposefulness in a destructive process. Instead of being broken and subsequently unusable, the act of breaking transforms one object into another still desirable object. As demonstrated through the paper game controller by Zheng et al. [141] the permanent change of physical structures can be used to redefine functionality.

6.5 Shaping the Human-Technology Relation

As explained, irreversible interactions present diverse applicability in the interface design. Yet, at their core, they share a unifying characteristic which is the question of how the human-technology relation is affected by the introduction of irreversibility. What we observed was the increased influence of the system on the human: The flow of interaction was interrupted, actions were carefully considered, and reflection was stimulated. Compared to non-irreversible interfaces, the influence of the system on the human was emphasized in its active role. Following Actor Network Theory (ANT) [45], both actors – the human and the machine – are active, since they have their own goals and activities [78]. The human who wants to achieve an objective through the system and the system which tries to enforce behavior on the human. Here, also the non-use as a consequence of a system's design [46] is an active influence.

Through the use of irreversibility the technological artifacts gain agency over the human actants. This gain in agency can be interpreted as power which is enacted between the system and the human [69]. While this power can be utilized positively as described earlier ("mindful" acting, meaningful threshold, narrative), it is important to be aware of the negative possibilities as well. If irreversibility, e.g., restricts accessibility due to financial capabilities the intended objectives of this exploration do no longer apply. However, if implemented consciously, irreversible interactions present the opportunity to disclose already existing power relations such as in the case of social media interaction and implicit data collection. While still agency and thus power of the system over the human actant is created, we can conversely interpret the resulting awareness of the actant as an enabler of empowerment [123]. Thus, irreversibility not inevitably leads to "giving away" power, but can, in itself, be empowering.

7 CONCLUSION

We started this paper as a thought experiment, asking ourselves, "How can irreversibility, as a design strategy in HCI, be conceptualized?" and "What are advantages and implications of using irreversibility as design strategy in interactive technologies?". Building on these questions, we executed three material speculations focusing on the exploration of irreversibility in the context of UX design of physical computing systems. These explorations led us to the realization that, with designing for irreversibility, the design must be as concerned with the experiencing actant as it is with the irreversible action and the artifact itself. Although this is true for any interactive system, we see it as even more important for the design of systems with irreversible interactions.

Whereas other research works strive for goals such as the effectiveness of their systems, our goals lie within the actants themselves. While the included irreversibility does not achieve faster usage or less errors, it ultimately lines up with the question what we as actants expect from future technologies. Current expectations, such as that technology supports our health, well-being, and meaning in life, can only be achieved if we change the way we interact and consume technology and media lastingly. One important step towards that goal is to design for self-reflection, meaningful acting, and a sustainable relationship with technology.

Looking into the near future, we can anticipate that certain technologies will demand mindful design considerations to make actants aware of the underlying irreversibility, which actants face during interaction. New forms of technologies are emerging, that incorporate irreversibility and which underlying operational processes and policies are hard to comprehend for an average actant. This includes technologies such as, for example, block-chain, urban robots or fully autonomous vehicles. In case of the latter, irreversibility in interaction can have fatal consequences for the human in the loop. Our learning and insights, even if based on thought and idea-provoking *critical designs*, can inform future technologies that infuse a sense of *conscious presence* for certain interactions which otherwise might blur in with the background noise of the other media elements surrounding us.

However, user interfaces, interaction vocabulary and familiar mental models are not defined for these domains and have yet to be established for these technologies. Consequently, current actants' experiences remain cloudy and ambiguous. As the past tells us it can be limiting, unsuccessful and lead to bad user experiences if familiar interaction paradigms for one domain (e.g. smartphones, PCs) are simply copy-and-pasted to novel technology forms. Yet, these forms of computing systems (i.e., purely virtual) and interactions (e.g., touch) could make use of irreversible interactions too. Currently, virtual systems incorporate almost always the same interaction (i.e., a simple button click) for a whole plethora of actions – the message of the "weight" of interaction is thus getting lost (sending a casual email to a friend vs. sending a super-critical email to the employer). Our work could thus spark discussion and reflection of whether, and how, irreversible interaction might be transferred to virtual systems, which are missing the richness of materials.

We would like to open and broaden the discourse to other persisting issues and topics in our world. These could, for example, include eco-challenges such as the *disposable device economy* in the IoT segment, strong shifts in society / *ethical HCI* aspects and discussions on regulation vs. non-regulation where we suspect that irreversible interactions could be used as a conscious design element within HCI. Our provided designs and reflections should thereby be considered as *provocative and speculative* stimuli aimed at a critical discourse about fundamental future goals we, as HCI researchers, strive for and help us defining a collective future HCI vision together.

ACKNOWLEDGMENTS

We want to thank Tobias Fütterer, Sinda Bouzir, and Patricia Kimm for their work on the presented material speculations. This project is partly funded by the Bavarian State Ministry of Science and the Arts and coordinated by the Bavarian Research Institute for Digital Transformation (bidt).

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