Fabrication Games: Using 3D Printers to Explore New Interactions for Tabletop Games

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ABSTRACT
Personal fabrication technologies such as 3D printers are becoming increasingly affordable, enabling many to own and use 3D printers in their own homes. Yet we have little understanding of how fabrication tools and technologies can be used and appropriated within the home. In this paper, we explore the opportunities and challenges related to using personal fabrication technologies as part of play, specifically in the context of board and tabletop games. We present an overview of existing uses of 3D printers in the context of gaming, which has largely focused on creating and replacing pieces for existing games. Drawing on existing uses of 3D printing in games, and on prior research in interacting with fabrication tools, we then introduce a set of gameplay elements that use the affordances of the 3D printer to enhance and extend gameplay. We evaluated these gameplay elements through a focus group with 9 gaming hobbyists, who provided feedback on these elements and designed new games that used these elements. Our contributions include an extended set of gameplay elements that leverage fabrication tools, a set of reference games, and guidelines for augmenting existing fabrication tools to support playful interactions.

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3D Printing; Fabrication; Tangible Computing; Tabletop Games.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Driven by open-source hardware platforms and international competition, personal fabrication tools such as 3D printers have rapidly transitioned from expensive professional tools into affordable mainstream consumer devices [36]. Fully-featured 3D printers now cost less than many PCs and mobile devices. The opportunity to make 3D printers a standard household item has attracted interest from fabrication-oriented companies such as MakerBot and LulzBot, but has also drawn attention from companies that produce other types of household technologies. Home 3D printers have been produced or announced by companies such as Dremel, a manufacturer of household tools, and Mattel, a toy company. Personal fabrication technologies may support practices of "everyday making" around the home [45]. However, transitioning from being a consumer of existing 3D models to a designer of original creations can present challenges for novice users [25].

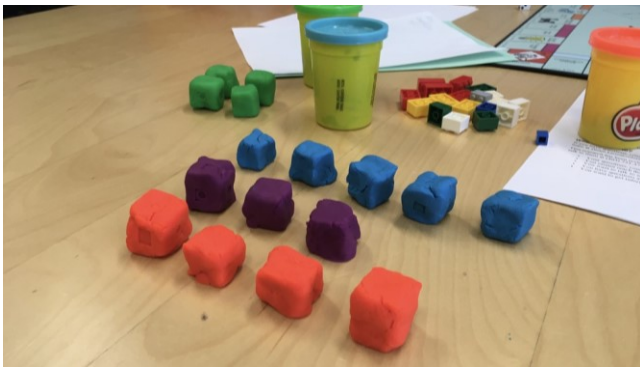

Figure 1. Prototype of *Star Dice,* a 3D-printed dice-rolling game created by a team of tabletop gamers. In *Star Dice,* players customize and print a set of personalized dice that matches their chosen gameplay strategy.

In considering the role of fabrication technologies in the home, we should look beyond their intended use to consider how end users may appropriate these technologies. As technologies are integrated into a home context, they are often repurposed for unexpected uses. For example, while early PCs were marketed as business tools, games rapidly became a primary use for PCs in the home [7], and today's PCs support a wide variety of activities, including office work, gaming, education, creativity, and social interaction.

Coincident with the rise of personal fabrication is a resurgence in board, card, and other tabletop games [26]. This trend is seemingly driven by an interest to engage in collocated social interaction, and to engage in more tangible forms of play [42]. Our present work lies at the intersection of these trends: as personal fabrication technologies enter the home, they present opportunities for supporting real-time, tangible, and collocated interactions, via the concept

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of 3D-printer-enhanced *fabrication games.* For example, a 3D printer could enhance gameplay by generating new physical game pieces during the course of a game, and could customize these printed objects based on the game state, history from prior games, random effects, or external data sources.

In this paper, we explore the opportunities enabled by integrating personal fabrication tools into collocated tabletop games. We first present a brief overview of existing practices surrounding the use of 3D printing in tabletop games. Next, we introduce a set of gameplay elements that build upon the capabilities of a 3D printer to dynamically create physical game objects. We evaluated these gameplay elements through a focus group with 9 gaming hobbyists, who provided feedback on these elements and designed new games that integrated 3D printing features. Our contributions include a set of gameplay elements for 3D-printer-enhanced fabrication games, feedback on these gameplay elements from hobbyist gamers, and a collection of reference games that implement these new gameplay elements.

RELATED WORK

Our work draws on prior studies of board and tabletop gaming, the adoption of personal fabrication tools in the home, bridging digital and physical games, and interactive, data-driven use of 3D printers.

Tabletop Games

Tabletop games, including board games, dice games, and card games, have been a part of human society for thousands of years. While traditional tabletop games must now compete with video games for players' attention, there has been a growing interest in board games in recent years, centering around a new generation of modern board games, and often featuring collaborative rather than competitive gameplay [26].

While games have existed in some form for much of human history, the study of why and how people engage in games is relatively new. In the 1980s, Malone studied the intrinsically motivating factors within games, and identified three motivating factors: challenge (which includes variable difficulty level, hidden information, and randomness), fantasy, and curiosity [33]. More recently, Rogerson et al. [42] conducted ethnographic research with tabletop gamers to understand their interest in tabletop games as opposed to, or in addition to, video games. Rogerson et al. identified sociality, intellectual challenge, variety, and materiality as key components of the tabletop gaming experience, and further deconstructed materiality into four domains: the physical construction of the game board and pieces, the game box and related art, the space in which the games are played, and the places in the home where games are stored and displayed. This emphasis on the material qualities of tabletop games was also explored by Darzentas et al. [13] through an ethnographic study of players of miniatures-based games. In both studies, the creation, customization, and display of the tangible components of games were key to players' engagement with the game. Outside of gaming, interaction with tangible objects has been shown to increase engagement in collaborative tasks [51]. The present work aims to maintain the materiality of tabletop games while exploring new types of gameplay.

While many tabletop games rely on non-technological components such as boards, cards, dice, and miniatures, gamers have long adopted new technologies to support their hobby. For example, many players have used postal mail and email to play games over a distance. More recently, software applications such as Tabletop Simulator [24] have enabled players to play games together over a distance by emulating the physical components of common games in software, supporting play via PC or even through virtual reality. The present work explores how an emerging technology, 3D printing, can be used to extend traditional tabletop gaming practices.

Combining Tabletop and Video Games

While tabletop games may present advantages in terms of materiality and engagement, video games offer a set of complementary advantages. For example, video games enable players to add additional game content without needing to purchase additional physical components, enable play over a distance, and support large games with many players.

Prior research has explored the intersection of tabletop and video games, often with the goal of balancing the benefits of each medium. Prior games have used augmented reality technologies to add dynamic behavior to tangible games (e.g., [30,31]), such as by adding atmospheric audio, representing the game state through a visual display, and supporting private input through personal mobile devices. Other games have retrieved information over a home network, and used that information to modify the gaming experience. Open Data Monopoly [18] uses real-world finance data to create dynamic versions of the Monopoly board [32]. Invasion of the Energy Monsters [3] is a tabletop game for families that explores issues around energy conservation; one version of the game can be linked with a household energy meter, providing players with extra points for following conservation guidelines in their own home. Recent work from Noble and Crabb [38] projected information on top of a traditional board game in order to provide dynamic feedback about the game state.

Some recent projects have repurposed fabrication tools to create specific types of games, such as using components of a CNC mill to create an automated air hockey table [10]. Destructive Games [16] consist of several games that use a laser cutter to destroy valuable objects when a game is lost, increasing the stakes of losing a game. Our work complements this recent work in repurposing fabrication tools for gaming by introducing new gameplay elements that use 3D printing to dynamically create game objects during play.

Personal Fabrication Technologies in the Home

Although the 3D printer manufacturing industry has shown great interest in the role of home 3D printers, relatively little research has explored how 3D printing is currently being used by everyday users. Shewbridge et al. [45] conducted a design probe in which families were given a mockup of a home 3D printer and asked to record their desired uses for the device. Family members were often interested in using the 3D printer for maintenance tasks around the home, such as replicating existing objects and modifying or repairing existing objects, and were hesitant to create or design new objects. Hudson et al. [25] interviewed novice users of 3D printers and identified several barriers to transitioning from a casual user of 3D printers (i.e., printing objects that others have designed) to designing and printing their own creations. Recent research from Mizrahi et al. [35] has explored alternative uses for fabrication tools, specifically in the process of preparing food. Our work explores gaming as an additional use for home 3D printers.

Interactive Fabrication

A limitation of most current 3D printers is that they do not support interaction while printing. Instead, most 3D printers expect the user to upload a complete 3D model, and to leave the printer undisturbed until that model is fully printed. However, many of our intended usage scenarios involve dynamic printing of an object that may change based on user behavior. Recent projects such as Linespace [46], Encore [9], and On-the-Fly Print [40], as well as work from Teibrech et al. [47], have explored alternative printing techniques that enable iterative cycles of interaction with a 3D printer. The present work explores the use of interactive control of a 3D printer to support gameplay.

Other research has used data streams to dynamically generate trophies or other artifacts representing the user's achievement. SweatAtoms [28] is a prototype system that can create physical artifacts based on fitness data; users of the system collected the printed artifacts and used them as rewards and as objects to support reflection. TastyBeats [27] builds upon SweatAtoms, but prints edible artifacts made of chocolate. Our study includes the creation of award artifacts as one of several fabrication-enhanced gameplay elements, and introduces several additional elements.

EXPLORING FABRICATION-BASED GAMEPLAY

Our primary focus in this research is to explore how use of 3D printing technologies can support new and enhanced modes of gameplay. However, 3D printers are already in use by some game hobbyists. Here we present a brief overview of current uses of 3D printers to support tabletop gaming. We then introduce an initial set of gameplay elements that demonstrate how use of a 3D printer during play could enhance the gameplay experience.

Existing Use of 3D Printers in Tabletop Gaming

Game players and designers use a variety of online communities to discuss the use of 3D printing in games, and to share 3D models that they have created. For example, Reddit hosts discussions about 3D printing in tabletop games across several subsites (r/boardgames, r/3dprinting, and r/3dprintedtabletop). BoardGameGeek, a web site dedicated to tabletop gaming, contains thousands of forum posts that discuss 3D printing. Although we did not conduct a systematic evaluation of 3D-printing-related gaming posts, we observed that posters asked questions about the process of 3D printing, posted links to 3D-printable objects on other sites, and shared demonstrations of items that they had printed. These 3D-printed items were sometimes created by the poster, but were often downloaded from other sites. Posters shared a variety of 3D-printed objects, including alternate pieces for existing games and accessories such as containers for storing dice.

Online 3D model repositories, such as Thingiverse and Shapeways, also contain numerous 3D-printable artifacts related to tabletop gaming. For example, there are over 900 objects on Thingiverse tagged with *boardgame*, including game tokens, figurines, storage for dice and cards, and game trophies. Figure 2 shows some examples of these objects. The majority of objects available on these sites are accessories for existing games, rather than new games. However, some designers have used their 3D modeling skills to create and distribute original games. For example, Pocket-Tactics [12] is a strategy game that can be downloaded for free and 3D printed at home. 64 Oz. Games [20] is a company that produces add-ons to improve the accessibility of existing games for people with vision impairments, including 3D-printed Braille dice and tactile overlays for game pieces.

Figure 2. Dice (left) [49] and miniature figurine (right) [22] models, shared on Thingiverse.com via an open source license.

While there are many 3D-printable objects available online for tabletop game players, the majority of these objects are add-ons to existing games. Also, these components are designed to be printed before the game is played, and used in the same way as any other game piece. To our knowledge, no games currently available online support interaction with a 3D printer during gameplay, as we explore in this work.

Gameplay Elements in Fabrication-Based Games

Building upon the existing uses of 3D printing described previously, our research team has explored how a 3D printer can be used during gameplay to add new elements to the experience of playing a tabletop game. In particular, we have investigated how a 3D printer might create game artifacts during play that can be integrated into the ongoing game.

To explore this concept, our research team brainstormed an initial set of 8 gameplay elements that demonstrated some of the interactions made possible by bringing a 3D printer into the experience of playing a tabletop game. We iteratively developed these concepts by reviewing related work, by playing and learning about existing tabletop games, and by conducting informal discussions with gaming hobbyists. We particularly focused on game play elements used in recently released games, as these games may introduce new gameplay mechanics. We also considered ways in which specific types of gameplay differed between tabletop and video games. For example, most tabletop strategy games either include a fixed set of game pieces or encourage users to purchase an ever-growing set of pieces, whereas many computer-based strategy games support large numbers of customizable pieces by default.

As home 3D printers vary greatly in size, speed, and features, we explored design concepts that could be implemented using most current 3D printers. Our scenarios assume the use of a contemporary consumer-grade 3D printer such as the MakerBot Replicator 2, which can print objects up to a size of 11 × 6 × 6 inches, and which can produce small tokens, such as those shown in Figure 2, in approximately 10 to 15 minutes. This reference design represents a lower bound for designing 3D-printer-enhanced fabrication games, as future 3D printers will likely support larger build volumes and faster print times. These scenarios also assume the use of a camera or some other mechanism that can track game play, enabling the system to customize printed artifacts based on previous actions in the current game, outcomes of previous games, random elements, or other data sources.

These initial scenarios describe some of the ways in which fabrication tools can enhance existing gameplay elements and support new types of play:

Generating Game Pieces During Play: Fabrication games can create new game pieces during play, including tokens, dice, or other objects. For example, a board game could print new dice with different face values throughout the game. These pieces could also be customized based on the game state, such as by printing less favorable dice near the end of the game to increase difficulty.

Expanding the Game Board: Some games, such as Carcassone [50], require players to construct the game board during play by laying down game tiles in each turn. A fabrication game could dynamically generate additional tiles to enhance or alter game play. For example, a variant of Carcassone could generate a new tile after each game to add variety and uncertainty to subsequent games.

Revealing Hidden Objects: A fabrication game can print an object in steps throughout the game, and can reveal objects if a specific game objective was reached. For example, a fabrication game based on Pictionary [2] could randomly choose a 3D model and print it; the winner is the first player who can guess the object that is being printed.

Data-Driven Gameplay: Fabrication games can print new game objects based on some external data source. Previous games have used home energy data [3] and online financial data [18] to customize gameplay. While this type of gameplay does not require 3D printing, using a 3D printer would enable players to easily incorporate external data into game pieces. For example, as in prior work [18], a finance-based game such as Monopoly [32] could produce customized pieces based on the current state of the financial market, printing large hotels if the market is strong that day, and more modest hotels if the market is weak.

Fabrication games can also use data from prior games to influence the current game. For example, a dice-based game could support handicapping by producing more favorable dice for players who have lost previous games.

Creating Trophies and Mementos: Fabrication games can create an artifact during the game that creates a record of that game and its outcome. This token could be an aesthetically pleasing trophy, a record of wins and losses over time (similar to [28]), or a new game piece that can be used in future games. For example, a fabrication game based on Scrabble [6] could generate a new tile based on the highest-scoring letter during that specific game, which could then be used in future games.

Capturing Player Input: Fabrication games can accept input from players and print objects based on player input. For example, in an alternative version of Pictionary [2], players could be asked to sketch specific objects, which would then be fabricated as 3D objects; the winner is the player whose drawing most closely resembles the actual object.

Supporting Remote Play: Fabrication games can also support gameplay between two players at different locations, with the 3D printer acting in place of the remote player. For example, a fabrication game based on chess could print out a representation of the board after each move, perhaps printing a miniature representation to save time and materials. Alternately, a 3D-printer system with the ability to selectively remove printed material (similar to Linespace [46]) could be used to print pieces, then erase and re-print each piece as it is moved.

Personalizing Game Pieces: Fabrication games can support players in creating personalized game pieces and elements. For example, while current players of games such as Monopoly [32] may fight over who gets to play using a specific piece, a fabrication game could allow each player to create their own piece. Alternately, a fabrication game could allow players to create game pieces that represent the players' personal lives, such as by replacing a generic dog token with a model of the family dog.

FOCUS GROUP

In order to gather feedback about the potential applications of 3D printing in tabletop games, we conducted two focus

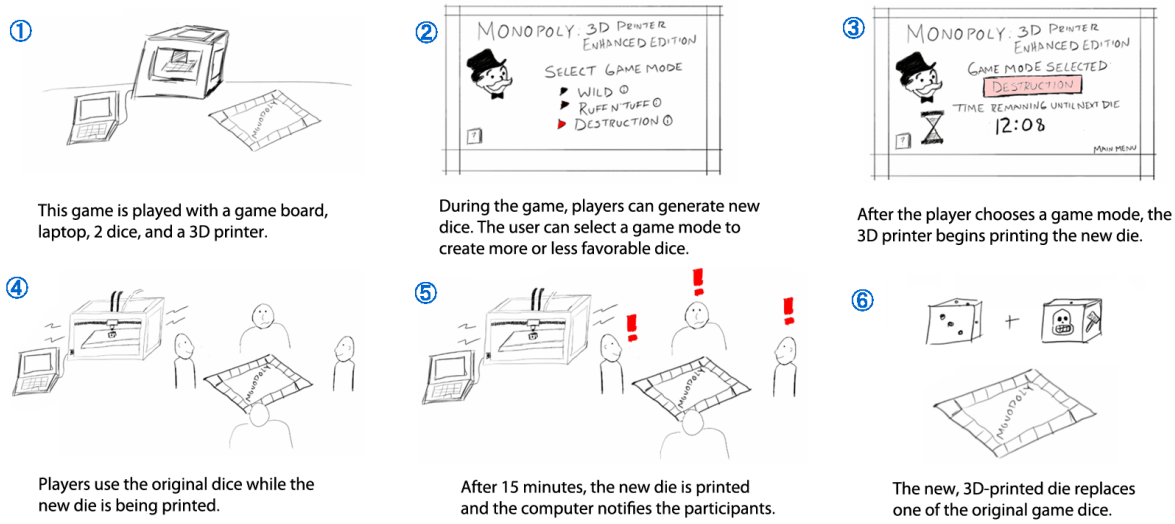

Figure 3. Proof-of-concept fabrication game designed by the research team. In this variant of Monopoly [32], players can choose to generate new dice during gameplay, thereby affecting the probability of good or bad outcomes.

group workshops with active game players. The goals of these sessions were to collect feedback about our initial set of gameplay elements, to identify games and types of games that could benefit from these elements, to develop games that use these elements, and to identify potential opportunities and areas of concern with our approach.

Participants

We recruited participants from the local community via email to student lists on campus and posts to gaming-related social media sites. We recruited 9 participants (3 female), age 20 to 61. Two participants were current students at our university, but had not previously interacted with members of our research team. All participants were regular board game players, and two participants had previously designed their own board games.

We conducted two focus group sessions: the first session included 5 participants, and the second session included 4 participants. We encouraged participants to invite friends; two pairs of previously-acquainted participants attended the first session, and one pair attended the second session.

Focus Group Sessions

Each session took place at our research lab, and lasted two hours. Participants were compensated $25 for their time. Two members of the research team conducted the workshop sessions. Each session comprised four activities: introduction, brainstorming, game design, and game presentation. Participants also filled out a brief demographic survey at the start of the session, and filled out a comment form at the end of the study.

Introduction

The focus group sessions began with a 15-minute introduction. During introductions, each focus group member introduced themselves, named a favorite game and described their prior experience with 3D printing.

Following the personal introductions, we presented a series of slides about 3D printing and the goals of the study. The slides described how 3D printers worked, and indicated that 3D models could be created using CAD software, downloaded from an online repository, or generated dynamically using code. We briefly demonstrated the 3D modeling tool TinkerCAD, showed example results from Thingiverse, and played a time-lapse video of an object being printed on a consumer-grade 3D printer.

Next, we introduced the goals of the study session. We stated that the goal of the activity was to explore ways to enhance tabletop gameplay with 3D printing, such as by tracking gameplay and dynamically printing 3D objects during gameplay. We also described the capabilities of the reference 3D printer (MakerBot Replicator 2).

During pilot testing, we found that participants were often reluctant to come up with ideas for the design sessions. As such, we started the study sessions by introducing some of our existing ideas, including our eight initial gameplay elements and a storyboard showing an example of how a 3D printer could be used to enhance a Monopoly-like game.

Figure 3 shows the game storyboard presented to our study participants; the storyboard was presented sequentially during the study, and featured shorter text descriptions. In this game, a player can choose at any time to generate a special 3D-printed die. The player could choose from one of three difficulty levels: higher difficulty levels resulted in dice with negative outcomes printed on the face. Once printed, the new die replaced one of the game's default dice, increasing the possibility of lucky or unlucky events. Following the presentation of the video, the researchers answered any questions about the study and the introductory material, and then began the next activity.

Brainstorming Activity

After the introduction, our focus group participants discussed each of the 8 gameplay elements described above. This activity lasted approximately 45 minutes.

During this session, one member of the research team introduced each gameplay element, and asked the focus group members to discuss how existing games might be enhanced by this type of gameplay. Comments from participants were recorded on a whiteboard in the study location. In some cases, the focus group participants suggested ideas that did not fit with the current discussion topic, and either fit in with another discussion topic, or addressed a new gameplay element that had not been mentioned previously. To support a lively discussion, we recorded each idea as it was discussed, and later matched participants' ideas to the corresponding theme.

While presenting our ideas to participants may have directed participants to come up with ideas like our own, we felt that providing this additional context would help participants generate ideas for a concept that was quite new to them. Our participants were successful in using this information to build upon our initial ideas, to connect these ideas to existing games, and to explore ideas beyond those that we provided.

Game Design Activity

Following the brainstorming session, we instructed participants to form groups. Each group was instructed to design a new game that used one or more of the ideas from the brainstorming session. For this activity, participants divided themselves into groups of two or three people. Participants chose their own groups.

Because coming up with a new game idea can be difficult, we provided a series of prompts to help each group to select a game concept. Each group was instructed to roll three six-sided dice. These dice were used to select starting parameters for their game from a pre-defined list (Figure 4). We informed participants that these game parameters were suggestions only, and that each group was free to reroll their dice or choose a different option if they preferred. Because both groups in the first session selected dice games using this method, the groups in the second session were asked to create a board or card game.

Participants were given about 30 minutes to design their game, and were offered a set of craft materials, including paper, pens, pencils, colored markers, index cards, clay, Lego bricks, pieces from existing games, and blank game boards that could be drawn on. Participants were instructed to use whatever materials they wished to create their game, and were told that they would be presenting their game back to the entire group at the end of the activity.

To further assist in the game design activity, participants were given a game design worksheet that contained questions about the game. This worksheet included the name of the game, the game type (selected from the options in Figure 4), a brief description of the game, the number of players, the suggested age range, the contents of the game box, instructions for the game, and a description of how 3D printing could be used within the context of the game.

After 30 minutes, each group presented their game to the group. Finally, participants then filled out the comment form to complete the study session.

Choose a game type (roll 3 dice)

Game Style	Game Play	Theme
1 or 2: Board Game	1 or 2: Competitive Game	1: Science Fiction
3 or 4: Card Game	3 or 4: Cooperative Game	2: Fantasy/Adventure
5 or 6: Dice Game	5 or 6: Party Game	3: Money/Finance
		4: Mystery
		5: Zombies
		6: Animals

Figure 4. Study participants rolled dice to choose random game parameters, and used those game parameters as a starting point for designing an original game.

Data Collection and Analysis

Participants completed an introductory demographic questionnaire and a post-activity comment form. The focus group sessions were video and audio recorded, and we recorded field notes during the session. We also collected copies of the artifacts produced during the study, including the whiteboard, game design worksheets, and images of the game prototypes.

Data collected during the study was analyzed by the entire research team and sorted into categories. Our analysis focused on new gameplay themes suggested by focus group members, comments and suggestions for our initial set of themes, components of the games designed during the session, and concerns and challenges about 3D printing that were raised during the study.

FINDINGS

Our findings include participants' comments on their prior experiences with 3D printing, ideas generated during the brainstorming session, proof-of-concept games created by participants, and participants' comments and concerns about the viability of using 3D printers during gameplay.

Experience with 3D Printers

We did not require that participants have experience with 3D printers in order to take part in the study. However, three participants had either prior experience in using a 3D printer, or were interested in using a 3D printer to support their gaming practices.

One participant owned a consumer-grade 3D printer, and used it as part of his tabletop game practices. This participant used his 3D printer to create miniatures and accessories for tabletop strategy games. He did not create his own 3D models, but instead downloaded free models from the web, printed them, and painted them by hand. Another participant did not own a 3D printer himself, but was in the process of shopping for one, and intended to use

the 3D printer to create parts for tabletop games that he was currently designing. A third participant had received a set of 3D-printed miniatures that were designed and printed by his brother, and used these miniatures to play role-playing games, but had not designed or printed his own miniatures.

Ideas for Integrating 3D Printing into Games

Participants suggested a variety of ideas during the brainstorming session. While some of these suggestions fit into the initial gameplay themes presented during the session, others addressed areas that we had not previously considered. Here we will briefly describe examples of how participants extended our initial gameplay elements, and identified applications of these elements to existing games.

Generating Game Pieces During Play: Participants saw the value of 3D printing game pieces, although they suggested printing pieces before the game was played, rather than as part of gameplay, to compensate for slow printing time. Participants were especially interested in creating their own customized game pieces.

*Expanding the Game Board***:** Participants noted several games that use the mechanic of an expanding game board, including Carcassone [50], Escape [39], and Tsuro [34]. Participants expressed excitement about the opportunity to download and print new content for these games, either from the game's original designers or from fans. Participants noted that printing map tiles could be especially useful for games with a strong exploration element, such as Dungeons & Dragons [21], and that customizing game tiles could enable more control over the difficulty of a particular game.

Two participants discussed how printing new game board tiles could be used to enhance the new series of "legacy" board games. These games, including Risk Legacy [14] and Pandemic Legacy [15], feature elements in which the game board is permanently altered after a game session, either by placing a permanent sticker over part of the game board or tearing up a game card. Currently, these games can only be played a fixed number of times, after which the players must re-purchase the game. These participants suggested that a 3D printer could be used to re-print destroyed pieces, or to print add-ons that could be attached to existing pieces to temporarily indicate a change in state. One participant suggested that a 3D-printed legacy-type game could follow a season-based model, where players upload a representation of their board after each game and receive a new custom board from the game designer.

Revealing Hidden Objects: Participants agreed that interacting with the 3D printer while printing could be useful for games such as Battleship [48], which involves incrementally revealing the board, as well as party games such as Hangman or Pictionary [2].

Data-Driven Gameplay: While participants did not offer any suggestions about how external data sources could be used to influence the game, one group eagerly discussed the possibility of using data from previous games to re-balance games or to handicap experienced players. Participants noted that some games were designed in an unbalanced way, favoring specific player positions or strategies, and noted that a 3D-printer-enhanced game could track gameplay over time, detect imbalances, and push an updated version to the game players.

Creating Trophies and Mementos: Participants noted that some recent board games, such as 7 Wonders [5], include a paper sheet to track video-game style "achievements", such as the first player to win the game, or the first player to lose by a significant amount. These participants agreed that records of previous games could be recorded as a 3D-printed artifact, but preferred if the system could produce an artifact that could be integrated into the game, such as a tile or game piece, rather than a non-functional trophy.

Capturing Player Input: Participants noted that this feature could be useful for party games such as Cranium [1] or Pictionary [2], and discussed the idea that the system could combine inputs from multiple players into a new artifact, such as 3D-printing a figure in which each body part is drawn by a different player.

Supporting Remote Play: The majority of participants were not interested in using a 3D printer to support remote play, and expressed concern about the waste of printing a game board multiple times. One participant, who was active in playing games by mail, noted that a 3D printer could enable remote play using existing game pieces.

Personalizing Game Pieces: Most participants expressed interest in using 3D printing to create more customized pieces, and to create their own personalized pieces. This feature was especially popular in the context of miniatures-based games, where participants could create figurines to represent themselves, family and friends, or beloved fictional characters.

Emergent Gameplay Elements

In addition to the themes that we provided, participants suggested a number of additional possibilities for using 3D printing as part of a tabletop game.

Participants suggested several ways in which 3D printers could be used to replace or enhance existing game pieces:

Replacing Broken or Missing Pieces: Multiple participants mentioned that they had lost pieces from their games, and that they could use the 3D printer to replace those pieces without having to buy the game again.

Upgrading Game Pieces: Several participants expressed interest in using the 3D printer to print more aesthetically appealing parts for their existing games, such as replacing cardboard tokens with 3D-printed miniatures. This suggestion is not surprising, as many posts on communities such as Reddit and BoardGameGeek involve sharing and discussing upgrades to existing games. One participant mentioned that he was unsuccessful in convincing his

friends to play one of his favorite games, as the game board and pieces were unattractive, but that upgrading the pieces might convince his friends to try the game.

Bootlegging: Several participants described playing games that involved purchasing collectible miniatures, such as Warhammer 40,000 [8]. These pieces are often quite expensive, and participants were interested in using 3D printed pieces (either copies of existing pieces or fan-made content) as an inexpensive alternative.

One participant expressed interested in acquiring a game that is currently out-of-print, but found that it was only available from resellers at a greatly inflated price. This participant felt that it would be reasonable to print a copy of this game, as the publisher was no longer able to sell or profit from the game.

Participants also suggested several ideas that involved adding new attributes to the game pieces and gameplay:

Supporting House Rules and Extensions: One participant mentioned that he had purchased two copies of a game, and had hand-painted pieces from one copy into different colors, so that he could play the game with more players than was originally intended. He noted that using the 3D printer would allow him to create his own modified pieces without having to combine multiple game sets.

Another participant suggested creating customized pieces to support hybrid games, such as converting word games like Boggle [11] or Scrabble [6] into a multilingual game. More generally, several participants discussed how 3D printing could be used to create versions of games that incorporated house rules, such as changing the point values of a game piece or increasing the number of pieces of a given type.

Making Game State Visible: Several participants mentioned that it can often be difficult to introduce new players to games, as new players may have trouble following along with the rules. One participant suggested that game pieces could be augmented to show their current state by 3D printing a game piece and adding electronic components such as LEDs. Several participants were excited by this idea, and suggested additional uses for electronically-enhanced game pieces. For example, an augmented checkers piece could feature an integrated LED that indicates whether the piece had been promoted to king. Likewise, a game board itself could light up to indicate the current player's turn, which could be especially useful for games that often require players to skip a turn, such as UNO [41]. While these examples rely more upon embedded electronics than 3D printing, they suggest that game players may be interested in creating and customizing new game pieces, and that this customization could involve both aesthetic and functional changes.

Accessibility: Several participants offered suggestions about how customized, 3D-printed pieces could be used to increase the accessibility of games for people with disabilities, older adults, or children. Suggestions included creating brightly colored pieces for players with low vision, creating larger pieces for people with dexterity issues, and adding rails to some board games to prevent less dexterous players from accidentally knocking pieces over.

Theming: One participant suggested that 3D printing could be used to create different themes or skins for a game, enabling players to replay the same game with different background stories. This idea was later incorporated into the game Zombie Twister, discussed below.

*Adding Mechanical Components***:** Participants discussed their interest in games that featured moving parts, such as Mouse Trap [4] and Trouble [29]. These participants suggested that 3D printing could be used to add more mechanical parts to existing games, either for aesthetic reasons or to add new dimensions to the existing gameplay.

Dynamic Difficulty: One participant suggested that 3D printing could be used to adjust the difficulty of games, especially games that involve physical interactions. For example, the game Jenga [44], which involves manipulating a precariously balanced tower of blocks, could be made easier or more difficult by adjusting the size, shape, and texture of the blocks.

Proof-of-Concept Games

In this section, we briefly describe the games created by our four game design teams.

Star Dice (game type: dice, competitive, science fiction)

Star Dice is a dice-based game with the theme of spaceship battles. Each player has his or her own personal set of dice that they use across multiple games, similar to deck-building games such as Magic: The Gathering [19]. Each player's set of dice represents their ship; players customize their ship by choosing which faces appear on the dice. For example, players may create a ship with many weapons but few shields. Players engage in combat by rolling their dice and counting up each face to determine who wins the battle. Figure 1 shows the prototype version of Star Dice.

Star Dice takes advantage of the customization enabled by 3D printing: players create their personalized set of dice via a web application, and can then download a 3D-printable copy of the dice or order them by mail if the player lacks a 3D printer. The designers also discussed using 3D printing to represent different aesthetic qualities of the ships, for example creating a set that looks like a shiny space cruiser or a rusty space pirate ship. Dice could also be customized for accessibility reasons, such as large or high-contrast dice. This game demonstrates the elements Personalizing Game Pieces and Accessibility.

Zombie Twister (dice, party, zombies)

Zombie Twister is a dice-based party game based on the game Twister [17]. The game consists of a four-by-six-foot mat (Figure 5, left) and two dice, one die representing a color and the other representing a body part. As in in the original game, players need to place the specified body part on a square of the specified color. The mat is made of a set of modular tiles. Several of the tiles have modifiers on them

that affect game play. For example, touching a "Bear Trap" tile forces the player to hold their limbs still until the tile if moved, while the "Limb Decay" tile causes the specified limb to decay, meaning that the player cannot use that limb to support their weight.

Zombie Twister uses 3D printing in several ways. First, the game components are printed in bright materials to be color-blind friendly. Second, the theme of the game mat can be changed through a set of swappable faceplates on each tile. Thus, players can swap the zombie-themed tiles for another story theme. This game demonstrates the elements Accessibility and Theming, and could potentially support Extending the Game Board through its use of modular tiles.

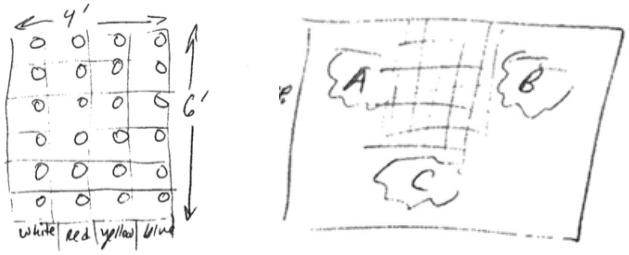

Figure 5. Game sketches. Left: Mat for the game Zombie Twister can be customized with swappable faceplates. Right: Strip Mine board shows randomly generated terrain.

Strip Mine (board, competitive, finance)
In Strip Mine, each player controls a country that is competing with every other country for natural resources (Figure 5, right). Players mine resources, capture territory, and trade resources with neighboring countries. Players win the game by accruing the most wealth, usually by monopolizing resources.

Strip Mine's board consists of a randomly-generated set of 3D tiles. Each tile is designed to represent a geological formation, and the board can be expanded by printing more pieces. The designers discussed using the 3D printer to generate random resources over the course of the game, but eventually decided not to include this feature. This game demonstrates the element Expanding the Game Board, and includes 3D-printed tangible game pieces.

Mystery Game (board, party, mystery)
In this game, a murderer is on the loose in a small town. Players act as villagers and attempt to identify the murderer before they themselves are killed. This game supports interaction through a custom computer application. Each player registers in the application, and is given a profile that shows their identity and abilities. On each turn, the player chooses to explore a specific area of the village for clues. After exploring an area, the 3D printer reveals any potential clues in that area by printing objects onto the map. This game demonstrates the element Revealing Hidden Objects.

Concerns and Challenges

Overall, our participants were eager to explore ideas related to the integration of 3D printing and tabletop gaming. However, participants expressed some concerns about the feasibility of integrating 3D printing into tabletop games.

The most commonly expressed concern related to the slow speed of 3D printing. We instructed our participants to create their games assuming current consumer-grade 3D printers, which can take between 10 and 15 minutes to print a game piece. Several participants noted that this slow speed could negatively impact gameplay. However, many of our participants' ideas involved situations in which pieces could be slowly printed between game sessions, rather than during the game. We also discussed research innovations that could print objects faster, such as WirePrint [37], which can speed up traditional 3D printing by a factor of 10. Other potential solutions that were discussed include printing smaller objects, printing at a lower quality, and printing modular and reusable components. Some activities, such as printing a game board tile, might also be performed using a faster technology such as a traditional printer or pen plotter.

Several participants also expressed concern about the clutter and waste caused by unnecessarily printing new game pieces. One solution we discussed was to leverage 3D printers that work with biodegradable materials such as PLA, recyclable materials such as paper or clay, or consumable material such as chocolate. Some prototype 3D printers also support using recycled materials as input [23]. Regarding clutter, printed elements can be designed to be reusable, or could be integrated into future games. For example, rather than printing a trophy when a player wins a game, the system could produce a new game piece or tile that shows the winner.

Finally, some participants raised questions about the ideal form factor of a 3D printer used in gaming. On one hand, current 3D printers are relatively small, requiring any gameplay to occur on a separate surface. On the other hand, most 3D printers are too large and heavy to easily carry, making it difficult to bring one to a friend's house or to a board game meetup. It is clear that there are opportunities to explore different form factors for a game-enabled 3D printer, drawing from recent research in producing very small [43] and very large [46] printers.

DISCUSSION

Our goal in conducting this work has been to explore opportunities for enhancing tabletop gameplay by integrating a 3D printer. By this metric, we consider this preliminary work successful: our focus group members generated many examples of 3D-printer-enhanced gameplay, and created several distinct proof-of-concept games. It seems clear that there exist opportunities for supporting playful interactions with a 3D printer, including augmenting existing games and creating new games.

Many of the suggestions offered by our participants focused on improving material aspects of existing games, such as the design of the game pieces, rather than developing new types of games. While we are especially excited to explore

new types of gameplay that can be supported by this technology, it is not surprising that our participants focused on augmenting familiar games. Our participants offered many suggestions related to augmenting the physical design of the game pieces, which suggests that these players have desires that are unmet by their existing games. 3D printers may indeed address some of these unmet desires.

Furthermore, existing tabletop games have mechanisms for addressing some of the gameplay elements explored in our work, such as adding randomness to gameplay. For example, a Dungeons & Dragons player can roll a die and look in a table to see what kind of monster they have encountered in a dungeon, rather than waiting for a 3D printer to produce that model. However, there may be other benefits in leveraging the 3D printer in this scenario, such as creating a tactile representation and building suspense. The added benefits of tangible interaction may improve engagement with a game, but identifying these effects may require testing with fully developed fabrication games rather than prototypes.

Finally, it is not surprising that even dedicated game fans may have difficulty inventing new games if they have never done so before. Just as everyday computer users do not instantly become 3D modelers when given access to 3D printers, we should not expect game players to become game designers by simply giving them access to new tools. During our focus group sessions, the two participants who had previously designed their own games had many ideas around incorporating these technologies into their games, and it may be that conducting further research with game designers may result in more creative game designs.

Although our participants often focused on improving their existing games, our study did shed light on some new gameplay concepts: the murder mystery game that involved progressive printing of clues; re-balancing a tabletop games through a software update; incorporating mechanical components into existing games; and the idea of adjusting difficulty for games such as Jenga [44] by changing the size and shape of the game pieces, reflect elements that cannot easily be reproduced through traditional tabletop games or video games. Each of these ideas offers potential for designing new games that leverage the affordances of a dynamic tangible gaming environment.

FUTURE WORK

This research represents the first step in exploring a new space of 3D-printer-enhanced fabrication games, which presents several opportunities for future work.

One opportunity for future research is to conduct additional focus group sessions with game players, and to playtest some fully realized games, to better understand the opportunities and limitations of this technology. As study participants who had designed their own games in the past seemed especially engaged in this activity, it would be valuable to test these technologies with designers of tabletop games. Also, since several of the gameplay elements explored in this work involved bringing elements of video games to tabletop games, it may also be worthwhile to conduct studies with video game designers. Likewise, it would be worthwhile to evaluate this work with people of different ages, as well as families and other groups that play games together.

A second opportunity for future work is to design, develop, and test software tools that enable game designers to create playful interactions with a 3D printer. We have developed initial prototypes of a software toolkit that enables partial printing of objects, in order to support reveal-the-hidden-object games. We intend to extend these prototypes to support additional forms of game-like interaction, and to connect 3D printers to existing tabletop and video games.

A third opportunity for future work is to develop new hardware form factors that support fabrication-enhanced play. Fabrication tools could be directly integrated into a gaming table, or could be placed in a mobile form factor that could be attached to existing game boards. Future hardware devices could support additional features relevant to gameplay, such as the ability to move existing pieces around on a game board, or to quickly fabricate game pieces through alternative output methods, such as by printing cards or game tiles.

Finally, while the present work has focused on playing tabletop games, the core gameplay elements investigated here could be applied to educational games or other types of interactive applications. For example, many of the game elements explored here could be applied to educational games, providing opportunities to teach students about math, physics, and other subjects through tangible games.

CONCLUSION

As fabrication technologies become increasingly common in the home, it is inevitable that they will be used for purposes beyond what they were originally designed for. The ability to dynamically create physical objects in the home offers the promise of new tangible computing experiences. Tabletop games, which encourage social interaction and problem solving through the manipulation of tangible objects, provide an ideal environment for exploring playful forms of tangible interaction. While we are excited by the possibilities of creating fun and novel gaming experiences, we also believe that fabrication games and fabrication-enhanced gameplay provide a medium for exploring everyday interactions with fabrication tools, and for extending our understanding of fabrication tools beyond production and into our everyday lives.

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