Scotty: Relocating Physical Objects Across Distances Using Destructive Scanning, Encryption, and 3D Printing

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ABSTRACT
We present a simple self-contained appliance that allows relocating inanimate physical objects across distance. Each unit consists of an off-the-shelf 3D printer that we have extended with a 3-axis milling machine, a camera, and a microcontroller for encryption/decryption and transmission. Users place an object into the sender unit, enter the address of a receiver unit, and press the *relocate* button. The sender unit now digitizes the original object layer-by-layer: it shaves off material using the built-in milling machine, takes a photo using the built-in camera, encrypts the layer using the public key of the receiver, and transmits it. The receiving unit decrypts the layer in real-time and starts printing right away. Users thus see the object appear layer-by-layer on the receiver side as it disappears layer-by-layer at the sender side. Scotty is different from previous systems that *copy* physical objects, as its destruction and encryption mechanism guarantees that only one copy of the object exists at a time. Even though our current prototype is limited to single-material plastic objects, it allows us to address two application scenarios: (1) Scotty can help preserve the uniqueness and thus the emotional value of physical objects shared between friends. (2) Scotty can address some of the licensing issues involved in fast electronic delivery of physical goods. We explore the former in an exploratory user study with three pairs of participants.

Author Keywords: fabrication; rapid prototyping; 3D printing; 3D scanning.

ACM Classification Keywords: H.5.2

INTRODUCTION

Personal fabrication tools, such as 3D printers, enable a wide range of new applications, including creating one-off physical objects [9], fast iterative prototyping (*faBrickation* [18]), creating interactive objects (*Sauron* [23]), and repairing broken parts (*Hybrid reAssemblage* [28]).

When combined with 3D scanning, 3D printing allows converting physical objects to a digital state and back. While in digital form, users can vary the shape and design of objects (*OpenFab* [26]) or even more importantly share it with others [22]. As a result, many envision a future in which any object will be available to anyone anywhere anytime [9].

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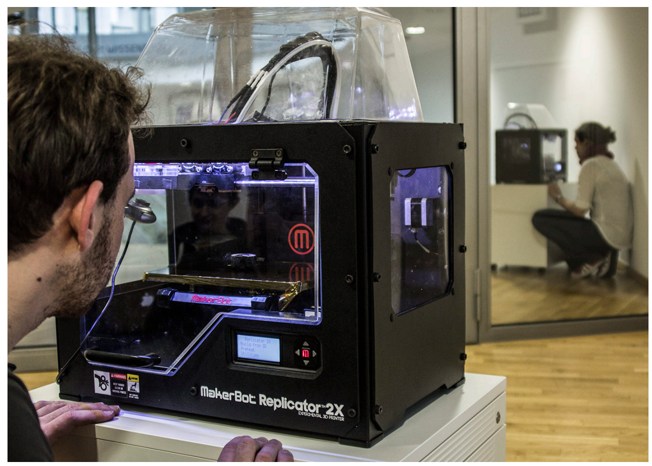

Figure 1: Johannes, (front) has placed a physical necklace pendant into his Scotty unit and is now sending it to Julia (back). Each Scotty unit consists of an off-the-shelf 3D printer (MakerBot) extended with a milling machine, a camera, and an additional processor. By destroying the necklace during scanning, encrypting it during transmission, and preventing reprinting, Scotty assures that never more than one pendant can exist, thereby preserving the pendant's uniqueness throughout the relocation process.

Some researchers in psychology, however, have looked at the sharing of physical objects from a different perspective. They question whether replicating an object is always desirable, as additional copies affect the uniqueness and thus the emotional value of a physical object [10]. Consequently, they speculate whether the value of an object might not be better preserved if one were able to send the object by *"teleporting"* it, rather than by copying [11].

Unfortunately, all these studies were carried out as wizard-of-oz experiments [10] or written scenarios [19] as no functional system existed.

In this paper, we demonstrate a simple, yet functional device that allows us to relocate inanimate physical objects by means of destructive scanning, encryption, and remote 3D printing. Our prototype, currently still limited to single-material plastic objects, allowed us to carry out an exploratory study in which we interviewed participants who had just sent handmade personal objects using our device.

RELATED WORK

The work presented in this paper is related to personal fabrication, duplication psychology, destructive scanning, and digital rights management.

Replicating objects, telefabrication, and 3D faxing

Researchers have demonstrated how to replicate physical objects by combining reverse engineering and rapid prototyping [6]. They first 3D scan the object's surface and then print copies of the object on a 3D printer. Since no intermediate models, such as CAD and STL, are required for replication, Chen et al. [5] show how to output scanned geometry directly to a 3D printer.

In telefabrication, digital files are transmitted via the Internet to a remote rapid prototyping facility [17]. Combined with a 3D scanner, telefabrication setups can copy physical objects over a distance (*3D fax machine* [22]). One application scenario for such devices is to share hand-annotated physical prototypes among distributed product teams [8]. 3D faxing potentially allows bypassing shipping costs and customs [21].

Duplication Psychology

Already in the 1980s, psychology researchers studied how duplication affects the value of an object: They found that people prefer personal objects, such as their child's first baby shoes, to perceptibly identical copies even if they can't tell the difference [2]. Newman et al. [19] list possible explanations, such as that the object had physical contact with a loved person or documents a special experience (similar to what Walter Benjamin calls the *aura* of an object [3]). In their personal attachment framework [20], Odom et al. list additional reasons, such as the personal engagement with the object. Using a mock-up duplication machine, Hood et al. [10] showed that this bias already exists in young children.

Researchers also investigated whether the co-existence of the original affects the value of the duplicate. Using written scenarios, Newman et al. [19] found that scarcity affects the value of objects, i.e. participants ranked a recreated object as being of higher value when the original was destroyed.

Finally, Hood et al. [11] researched a hypothetical "teleportation" scenario, in which they evaluated how much of the physical and mental properties of a living being are thought of as being transferred to the remote location.

Encryption and Digital rights management

Digital rights management (DRM) restricts the use of digital content after sale to the number of purchased licenses. While DRM is most commonly used in the entertainment industry (e.g., Apple iTunes [24]), a patent on DRM for 3D printing [12] suggests that a similar process will soon apply to personal fabrication.

Destructive scanning

Destructive scanning is used to obtain a 3D model of an object in cases where the object contains undercuts or hidden internal features [13]. Destructive scanners use either a milling machine [16] or a grinding wheel [14]. They can scan plastic parts as well as metal parts (*CGI* [4]).

SENDING UNIQUE OBJECTS ACROSS DISTANCES

Figure 1 shows Scotty, a simple self-contained appliance that we created to allow users to send inanimate physical objects to distant locations.

Each unit consists of an off-the-shelf 3D printer (MakerBot) that we have extended with a custom-made milling machine and a camera (Figure 2), as well as a microcontroller (Raspberry Pi) running custom software for encryption and transmission.

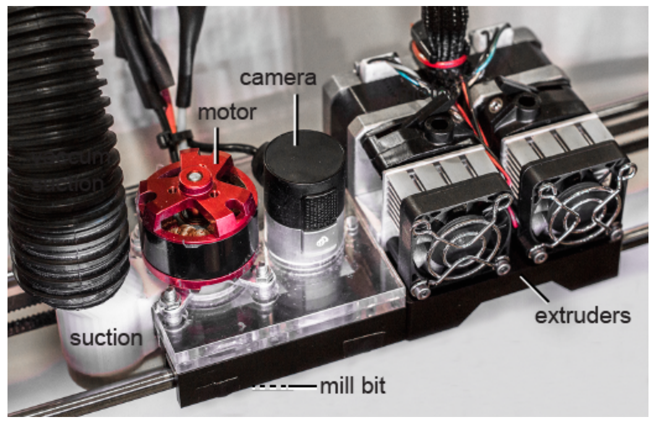

Figure 2: The standard MakerBot carriage carries two extrusion units. To allow it to destructively scan a physical object, we added a simple mill and a camera.

Walkthrough

The following figures show a user relocating a personal object, here a handcrafted necklace pendant (Figure 3).

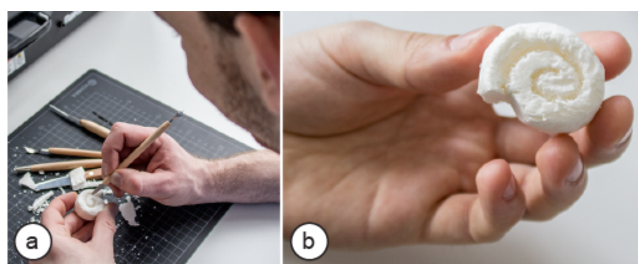

Figure 3: The handcrafted snail necklace pendant.

As illustrated by Figure 4, the user starts by (a) dipping the pendant into fast-drying black paint. This generates visual contrast for the subsequent optical scanning step, i.e. only the currently milled away surface will appear white to the camera, and the remaining part remains black. (b) The user places the pendant into the sender unit, (c) selects the Scotty unit to send to from the display, and presses the *relocate* button. This causes the sender unit to digitize the object layer-by-layer, i.e., a repeated process of shaving off a layer, taking a photo of it, encrypting it, and sending it.

Figure 4: To relocate this pendant: the sender (a) dips it in black paint, (b) mounts it into the sender unit by placing it on double-sided adhesive tape, (c) selects the receiver name and presses the *relocate* button.

While the sender unit is still digitizing, the receiver unit starts receiving the object. It decrypts each layer and starts printing right away. Users thus see the object appear layer-by-layer on the receiver side as it disappears layer-by-layer at the sender side, until complete (Figure 5).

Figure 5: The received necklace pendant.

How Scotty works

Figure 6 shows Scotty's built-in milling machine shaving off a layer of material. Scotty moves the mill across the object using the same 3-axis mechanism that the MakerBot uses to move the extruder. The mill bit is aligned with the extruder heads to prevent the mill from cutting into the base plate of the MakerBot.

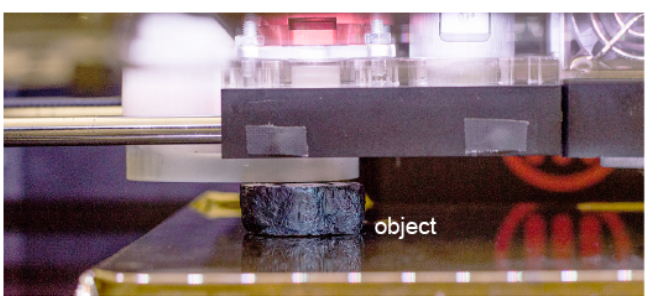

Figure 6: Here Scotty is digitizing an object by moving its mill across the object coated in black paint.

Between layers, Scotty lowers the base plate that holds the object. This moves the object away from the carriage, allowing Scotty's down-facing camera to take a picture of the object's top surface (e.g., Figure 7a). The object's black coating helps to provide good contrast against the object's off-white material. Scotty optimizes image quality by illuminating the object using the MakerBot's built-in LED strip. Scotty then encodes the captured image in .png format, encrypts it, and sends it to the other side.

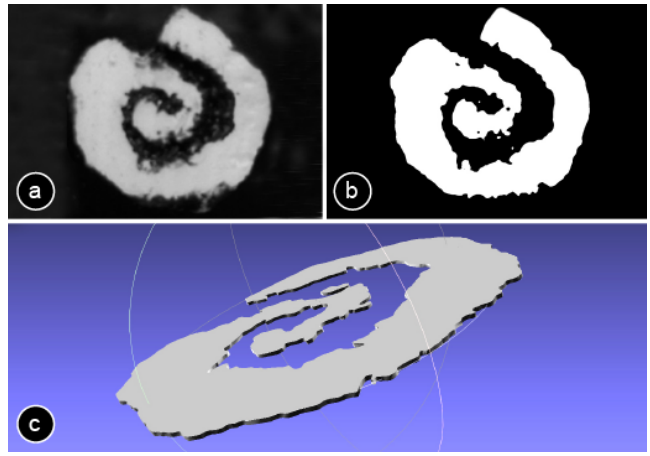

Figure 7: Scanning and 3D reconstruction process: (a) photo of one layer, (b) after thresholding, (c) reconstructed 3D model of the layer.

Figure 7b shows what happens at the receiver side. The receiver unit binarizes the image and extracts the object contour using the connected components algorithm (OpenCV). It then triangulates the 2D polygon, generates a 3D mesh of the layer by using the same polygon as top and bottom surface (Figure 7c). It then sends the 3D mesh to the MakerBot's slicer, which generates 3D printing instructions in g-code and prints them.

Preserving uniqueness using encryption

As discussed in the introduction, the key property of relocating an object is that it guarantees the uniqueness of the object, i.e., that only one instance of the object exists at all times. This means that Scotty has to guarantee that neither the sender, nor the receiver, nor any person in the middle is able to keep or produce an additional copy.

Figure 8 shows how Scotty achieves this across the three individual steps involved in relocation: *(a) scanning:* Scotty destroys the physical original during scanning. This does not only ensure that the object on the sender side disappears, but is also necessary to obtain a true volumetric scan of the object, unlike traditional (non-destructive) methods that reproduce only the façade of an object. *(b) transmission*: Scotty prevents men-in-the-middle from fabricating a copy of the object by encrypting the object using the receiver's public key. *(c) re-fabrication:* Scotty prevents the receiver from making multiple copies by maintaining an eternal log of objects already fabricated, which allows it to refuse the reprinting of objects.

Here is Scotty*'s* encryption/decryption in full detail:

Initial setup: Every relocation unit has its own public/private key pair. The private key is stored inside the unit; each unit shares its public key through a public key server.

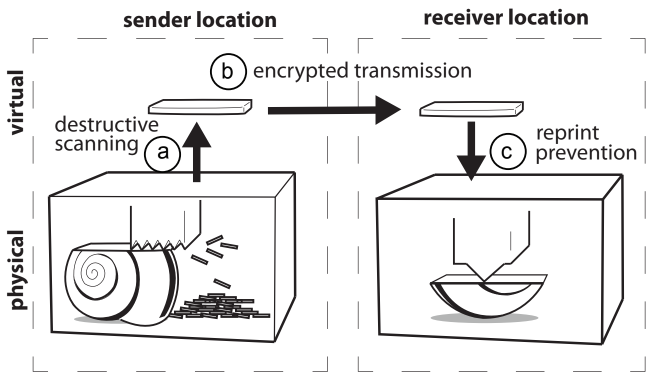

Figure 8: Scotty assures that never more than one pendant can exist at a time by (a) destroying the necklace during scanning, (b) encrypting it during transmission, and (c) preventing reprinting,

(a) Secure sending: The sender unit retrieves the receiver unit's public key from the key server and encrypts the object using this key. The sender unit also signs the object file with a hash code, which is then encrypted with the private key of the sender unit. This allows the receiver unit to verify that the object had been truly sent by the sender unit. The sender unit now securely deletes the non-encrypted object file and sends the encrypted object file to the receiver unit via a network connection.

(b) Secure receiving: The receiver unit requests the sender unit's public key from the key server and uses it to verify the signature of the file. This allows the receiver unit to confirm that the file was indeed sent by the sender unit and that the data has not been modified during transmission.

(c) Re-fabrication: To prevent objects from being fabricated repeatedly, the receiver unit looks up the hash-code in its eternal list of already fabricated objects—it only prints if the code is not contained in the list. It then adds the hash-code to the list to prevent additional copies. The receiver unit finally decrypts the object file using its own private key, prints it, and securely deletes it.

A crucial feature of Scotty is that it is an encapsulated appliance. During relocation, the object data is inherently non-encrypted (1) at the moment of scanning and before encryption and (2) at the moment of re-fabrication, i.e., after decryption. If users were able to gain access to the data at these stages, they would be able to print copies of the object, compromising its uniqueness. Scotty addresses these issues by forming a single encapsulated (and if commercially manufactured *sealed*) device, with all processing happening inside the device. This allows Scotty to perform "scanning-and-encryption" in one step inside the device and "decryption-and-fabrication" in one step inside the device, as suggested by the dashed lines in Figure 8. This prevents the undesired access, thereby protecting the object's uniqueness.

APPLICATIONS

The fact that our devices preserve uniqueness throughout the relocation process (unlike systems that *copy* physical objects) allows us to create two new application scenarios:

#1 Scotty keeps personal objects unique: As in the example shown earlier, Scotty guarantees that a personal, handmade gift remains unique when sent across distances, i.e., that there is no other copy—an important aspect that emphasizes the intimate relationship between sender and receiver.

#2 Scotty reduces licensing issues in online sales of used goods: As fabrication technology advances to the point where we can make functional copies of designed objects, replication of a purchased object starts to raise licensing issues. Imagine a seller of an online auction site, such as eBay, offers a used copy of the cleverly designed stand for a computer tablet shown in Figure 9 for sale. With instantaneous payment systems such as online banking already in place, the buyer may want to *receive* the object the very moment he or she completes the auction—by receiving the object electronically and fabricating it locally.

This raises licensing issues since the particular design of the iPad stand is currently sold on the web for $15. If a user replicates the object using $2 worth of 3D printing material, the designer misses out on being paid for the $13 worth of "design" contained in the object. This point will get raised more often as the debate around the intellectual property and licensing of 3D objects is heating up [12] and it will make it difficult to switch from slow postal delivery to fast electronic delivery based on local personal fabrication.

Scotty addresses this issue. When the seller *sends* the object through Scotty, the system guarantees that the seller's object ceases to exist the moment the buyer receives it, i.e., Scotty allows transferring objects quickly without infringing on designers' rights to be paid for their designs.

Figure 9: Application scenario 2: Selling a designed iPad stand on an online auction site. By relocating the object to the buyer using Scotty, the buyer receives the object quickly and prevents the seller from infringing on the designer's rights.

Note that Scotty only prevents licensing issues associated with the *transfer* of the object—users may still try to reproduce objects at other times, e.g., by scanning the object's façade (which works for objects without cavities and no internal mechanisms).

CONTRIBUTION

We make a technical contribution by demonstrating how to actually implement physical relocation. We have created two functional units including software and hardware and we demonstrate how to use them to send objects across. To help other researchers replicate our design, we provide a detailed description of our design (see section "Implementation Details" below).

By engineering an actual solution, we take the question of physical relocation out of the mock-up space, where it has traditionally been handled in psychology and other disciplines and into the space of engineering where we can actually operate and test.

The engineering of functioning units also allowed us to conduct an exploratory study in which participants used an actual functioning system rather than a mock-up.

Finally, the fact that our devices preserve uniqueness throughout the relocation process allows us to create two new application scenarios.

Design decisions and limitations

Unlike the aforementioned research in psychology that used mock-ups to create an impression of relocation, Scotty is a real-existing, functional system. However, this also causes it to have real-existing, functional limitations.

First, since the 3D printers used in our current prototypes print only single-color ABS of comparably low resolution, only coarse objects made from that specific type of off-white ABS plastic will look the same after being relocated. However, the set of objects that remain indistinguishable will increase with future versions of Scotty as we employ high-resolution printing, full volumetric color, and mixed materials (e.g. Objet500 Connex3 [25]).

Second, unlike the mock-ups, we deliberately designed Scotty to expose its inner workings. In particular, we allow users to see that the received object is fabricated from a roll of ABS string and that the sent object is being destroyed and sucked into a shop vacuum cleaner. This design choice has two implications.

(1) Users know that the received object is not made from the same atoms as the sent objects. This clarifies that even if the received object should look identical to the original, it is not physically the same object. Consequently, one would *not* expect users to feel that the received object "*is*" the sent object.

(2) Users witness the original object being irrevocably destroyed. For objects to which users attribute a "soul", such as a wedding ring, this can make a difference. In psychology research, these types of objects are called *attachment objects* and it is still an open research topic why people prefer these to perceptibly identical copies even if they can't tell the difference [10].

Designers of future versions of Scotty may thus choose *not* to expose the inner workings (e.g., by simply using opaque blinds) resulting in a system that allows users to make up their own conceptual model of what happened (similar to how the mock-up studies in psychology research allowed for this). For our current version of Scotty, however, our goal was not to trick users into believing in a super-natural process, but to deliver a working mechanism for relocating physical objects.

QUALITATIVE EXPLORATIVE USER STUDY

We conducted a small-scale qualitative user study to explore the use of Scotty in the first of our two application scenarios, i.e., sending objects of personal emotional value between couples and close friends. (Whether our second use case—online sales—becomes relevant in the future seems to be more a matter of legislation than of user experience, we thus chose not to user test it).

Our goal was to study whether the fact that Scotty preserves an object's uniqueness allows it to preserve the emotional value of the object better than a regular 3D printer that allows for duplication. Unlike existing studies on this topic in psychology research, all of which had to rely on hypothetical cases such as text scenarios [19] or mock-ups [10], Scotty allowed us to test in a situation where participants *witnessed that and understood how* the object was being relocated.

Study set-up

We set up a *sender* and a *receiver* unit in two different rooms in our institution. Participants could not see the respective other room with the second device. To allow both sides to witness the sent object disappear, we added a webcam to the sender unit and displayed the image on an iPad on the receiver side.

Studies were conducted with two participants at a time, i.e., a sender and a receiver participant.

Each study began by the sender participant handcrafting a personal object to be gifted to the receiver (Figure 10). To assure that the object would be worth giving, we required senders to spend 60 minutes on creating it. We enforced good design process, i.e., we required sender participants to create multiple ideas and to sketch them before picking one design to execute. After they made a choice, sender participants carved the object from an off-white block of hard foam material using the carving tools we had provided. Senders then placed the object into the sender unit and relocated it to the other participant.

Receiver participants waited in the room containing the receiver unit. We told receiver participants that the respective sender participant had handcrafted an object for them as a personal gift and that it would be sent to them using the device.

The process of transmitting the object took 2-3 hours, depending on the size of the object. In order to not over tax participants' time, we brought receiver participants in only for the last 30 minutes of the transmission. For additional context, we asked receiver participants to also rewind the webcam transmission so as to watch the object starting to disappear on the sender side. Upon completion, receiver participants took out the received object.

Finally, receiver participants filled in a questionnaire. The questionnaire asked receiver participants to rate the value of the received object and rate how its value would be affected by different ways how Scotty might have allowed copies to be made along the way.

Overall, the study took about 4 hours per participant pair.

Participants

We recruited six participants (3 female) in the form of three pairs. Each pair was selected so as to know each other well, i.e. was either a couple or close friends. From each pair, we assigned one participant the role of *sender* (2 male, 1 female) and one the role of *receiver* (2 female, 1 male). Participant's ages ranged between 22 and 26 (mean=25, s=1.53).

Findings

Figure 10 shows the handcrafted gifts sender participants made: (a) the grazing alpaca the couple had recently seen, (b) the van the couple had used to travel the US, and (c) a foot as a memento of the moment he had given her his own shoes and continued to walk barefoot.

Figure 10: Each sender participant hand-carved a gift and send it to the receiver participant using Scotty: (a) the grazing alpaca the couple had recently seen, (b) the van the couple had used to travel the US, and (c) a foot as a memento of the moment he had given her his own shoes and continued to walk barefoot.

Figure 11 shows the corresponding objects as received by the receiver participants after relocation through Scotty.

Receiver participants rated the value of the received object through Scotty as very high (7, 7, 6 on a 7-point Likert scale). Receiver participant p2 rationalized this as "it is one-of-a-kind, it is specifically made for me and nobody else will ever have an exact replica".

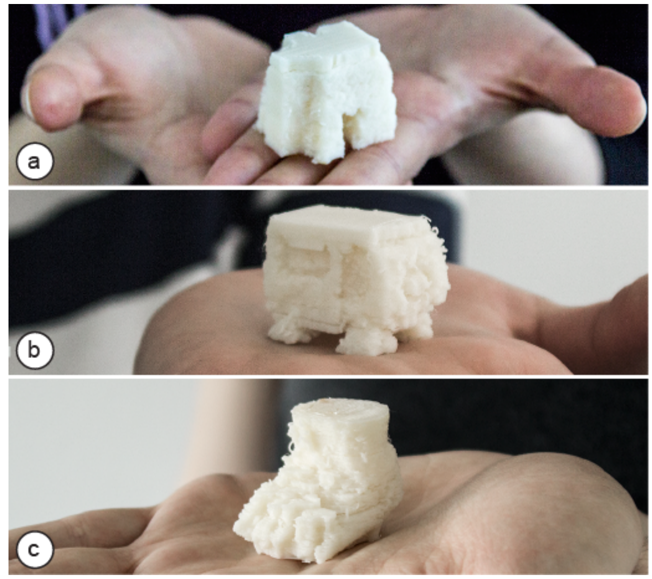

Figure 11: Receiver participants showing off the objects they had received by means of relocation.

To investigate the value of object uniqueness, we asked receiver participants three questions, each of which investigated the value of one of the three arrows from Figure 8.

(1) Sender side uniqueness: Had the Scotty device *not* destroyed the object, receiver participants rated that this would have made the received object less valuable (3, 2, and 1 respectively on a 7-point Likert scale with 1 meaning "less valuable" to 7 meaning "more valuable"). Participant p3 explained: "In that case, mine would just be a replication and the other person would posses the original". Participant p2 said "it's about a moment we shared with each other early in our relationship and if the original was given to someone else […] that would make me associate my object with them."

(2) Man-in-the-middle uniqueness: Had the Scotty device allowed a man-in-the-middle to tap the transmission and fabricate additional copies, receiver participants rated that this would essentially not affect the value of the received object (4, 4, and 3 respectively on a 7-point Likert scale). Participant p2 explained: "it would not be completely unique anymore, but that would not really matter. My boyfriend made it only for me." Participant p1 said: "The idea of my *unique object* stays unique […]—the object *is* made for me."

(3) Receiver side uniqueness: Had the receiving Scotty device stored a digital copy of the received object, allowing the receiver participant to fabricate additional copies when necessary, receiver participants rated that this would have made the object *slightly* less valuable (4, 3, and 2 respectively on a 7-point Likert scale). Participant p1 explained: "I can't reprint my feelings. My emotional state will be different when I get the 'same' object again. The object won't be the same actually."

Discussion
Our results suggest that users do care about uniqueness, when it comes to sharing among close friends and partners. Overall, the social effects we learned about in our exploratory study are congruent with what psychology researchers had hypothesized based on their mock-up experiments [10]. However, previous studies in psychology were limited to very young children that could be made to believe in mock-ups. In contrast, we conducted our study with adult participants who interacted with a functioning prototype. In summary, our results are encouraging and afford additional studies with a larger sample size.

IMPLEMENTATION DETAILS
To help readers replicate our system design in order to build their own Scotty units, we now present the technical details behind our design.

Figure 12 offers a look under the hood. (a) A RaspberryPi processor board runs Scotty*'s* software. (b) A USB hub connected to the RaspberryPi contains the cable for the MakerBot, the camera, and (c) the Arduino that controls the mill. (d) A switch-mode power supply for powering the mill. All components are mounted to the bottom of the MakerBot. Normally, all components are enclosed in the MakerBot's bottom casing; the photograph was taken with this cover removed.

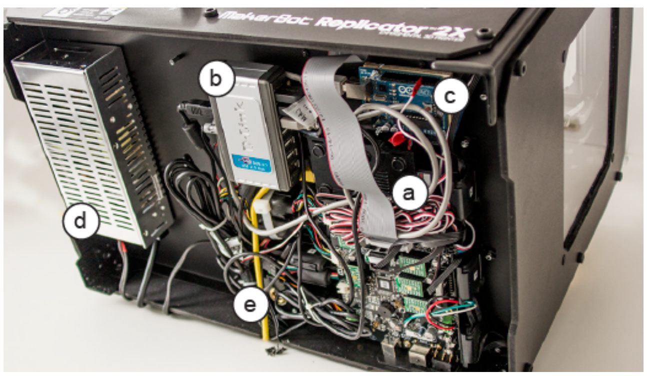

Figure 12: The Scotty hardware enclosed in the bottom of the MakerBot: (a) RaspberryPi (b) USB hub with camera, MakerBot and (c) Arduino for controlling the mill, (d) mill power supply, (e) Ethernet cable.

Digitization using mill and camera
Figure 13 shows an exploded view of the carriage extension that holds our digitizing apparatus consisting of a custom mill and a camera. We rigidly coupled the second carriage [1] to the MakerBot's standard extruder carriage; this allows Scotty to actuate the mill using the same mechanism that moves the extruder heads. To minimize friction, the carriage rests on four linear ball bearings (LM8SUU). A custom laser cut assembly attaches the milling head and the camera (model: MSLifeCam) to the top of the carriage.

The mill itself uses a fast-turning, low-torque brushless motor (KV890) as they are commonly used in quad copters. In Scotty, it drives a two-sided flat milling head.

The 3D printed nozzle on the left of Figure 13 allows connecting a shop vacuum cleaner. The 3D printed part redirects the suction to the mill head to provide cooling and to make sure milled-off chips are removed from the object's top surface before Scotty captures the next picture.

Scotty moves the milling head by sending g-code commands to the MakerBot API. Scotty uses that same API to move the object into the focus plane of the camera and to control the MakerBot's LED strip.

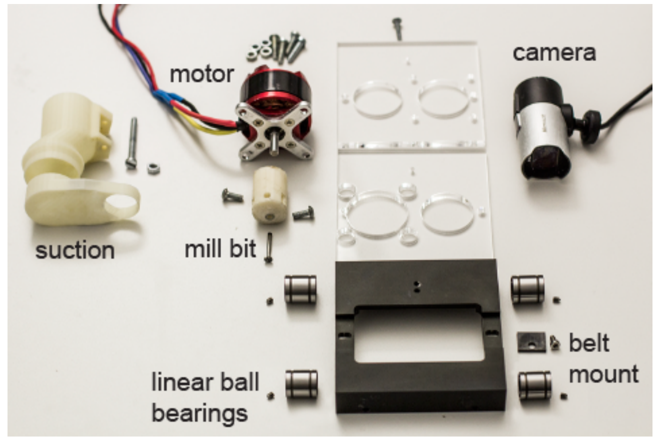

Figure 13: Exploded view of the milling carriage.

Encryption and transmission
Scotty encrypts the thresholded binary image using the ecliptic curve cryptography implementation of the libsodium library [15]. Scotty transmits the data via a TCP connection to the receiver (for easy control we use a TCP abstraction layer called zmq4 [27]). For decryption, Scotty again uses the libsodium library.

Re-fabrication
Scotty converts the threshold image into a 2D polygon using OpenCV's contour detection. It then triangulates the 2D polygon using Seidel's algorithm from the poly2tri library [7]. Scotty's code then triangulates the polygon and transforms it into a 3D object using the polygon as the bottom and top surface and closing the space between with a triangle strip. The generated 3D mesh is written into an .stl file, which Scotty sends to the MakerBot's slicer (called *miraclegrue*). Scotty overwrites the slicer's default z-position (normally the base of the platform) so as to reflect the number of layers already printed.

Transmit at once
Objects with overhanging structures require support material in order to be printed. To support such objects, Scotty offers a *"transmit as a whole"* option in the MakerBot display. If this option is active, Scotty delays 3D printing until the entire object has been received, allowing the receiver unit to generate support material.

CONCLUSION
In this paper, we presented the design and implementation of simple, yet functioning relocation units that allow relocating inanimate physical objects to remote locations. We

discussed two application scenarios, i.e., sharing unique personal objects among close friends and preventing licensing issues in online sales. The findings of our exploratory study suggest that users do care about uniqueness, when it comes to sharing personal objects among close friends and partners. As future work, we plan to create high-definition versions of Scotty that allow transmitting objects in much higher fidelity and to study users' conceptual models in study conditions where we do not reveal the mechanism.

REFERENCES

1. AluCarriage: http://shop.raffle.ch/shop/alucarriage-dual/
2. Belk, R. W. Possessions and the extended self. *Journal of Consumer Research,* Vol. 15, '88, 139–168.
3. Benjamin, W. The Work of Art in the Age of Mechanical Reproduction. *CreateSpace Independent Publishing Platform,* 1936.
4. CGI, www.cgiinspection.com/Pearl700.aspx
5. Chen, Y., Li, K., Qian, X. Direct Geometry Processing For Tele-Fabrication. *Proc. ASME '12*.
6. Chen, Y.H., Ng, C.T. Integrated reverse engineering and rapid prototyping. *Computers & Industrial Engineering*, Vol. 33, No. 3-4, '97, 481-484,
7. Domiter, V., Žalik, B. Sweep-line algorithm for constrained Delaunay triangulation. *International Journal of Geographical Information Science '08,* Vol. 22, No. 4, 449-462.
8. Galantucci, L.M., Percoco, G., Spina, R. Telemanufacturing of reverse engineered parts: A case study. *Journal of Engineering Manufacture,* Vol. 217 No. 5, '03, 727-731.
9. Gershenfeld, N. Fab: The Coming Revolution on Your Desktop - From Personal Computers to Personal Fabrication. *Basic Books,* '07.
10. Hood, B.M., Bloom, P. Children prefer certain individuals over perfect duplicates. *Cognition '08,* Vol. 106, 455-462.
11. Hood, B.M., Gjersoe, N. L., Bloom, P. Do children think that duplicating the body also duplicates the mind? Cognition, Volume 125, Issue 3, '12, 466–474.
12. Jung, E.K.Y. et al. Manufacturing control system. *U.S. Patent 8286236*, filed January 31, '08, issued September 10, '12.
13. Lan, H. A re-configurable cross-sectional imaging system for reverse engineering based on a CNC milling machine. *International Journal of Advanced Manufacturing Technology 37 (3-4),* '08, 341-353.
14. Lee, W.C., Chen, L.W. Design and fabrication of a general purpose 3D digitizer based on grinding technique. *Materials Science Forum*, Vol. 594, '08, 7-14.
15. Libsodium Encryption Library, https://github.com/jedisct1/libsodium
16. Liu, Z., Wang, L., Lu, B. Integrating cross-sectional imaging based reverse engineering with rapid prototyping. *Computers in Industry 57 (2),* '06, 131-140.
17. Luo, R.C., Lee, W.Z., Chou, J.H., Leong, H.T. The development of Internet accessible rapid prototyping system. *Proc. IECON '99,* 1498-1503.
18. Mueller, S., Mohr, T., Guenther, K., Frohnhofen, J., Baudisch, P. faBrickation: Fast 3D Printing of Functioning Objects by Integrating Construction Kit Building Blocks. *Proc. CHI'14*, 3827-3834.
19. Newman, G.E., Bloom, P. Art and Authenticity: The Importance of Originals in Judgements of Value. *Journal of Experimental Psychology '11*.
20. Odom, W., Pierce, J., Stolterman, E., Blevis, E. Understanding why we preserve some things and discard others in the context of interaction design. *Proc. CHI'09,* 1053-1062.
21. Paul, C. Fluid Borders: The Aesthetic Evolution of Digital Sculpture. *International Sculpture Center, Web Special.* http://www.sculpture.org/documents/webspec/digscul/digscul6.shtml
22. Reyes, R. World's First 3D Fax Machine. '91. https://webspace.utexas.edu/reyesr/self/3D_fax.htm
23. Savage, V., Chang, C., Hartmann, B. Sauron: embedded single-camera sensing of printed physical user interfaces. *Proc. UIST'13,* 447-456.
24. Sharpe, N. F., Arewa, O.B. Is Apple Playing Fair? Navigating the iPod FairPlay DRM Controversy. *Journal of Technology and Intellectual Property* 5.2, '07, 331-349.
25. Stratasys, 3D printer: Objet500 Connex3, http://www.stratasys.com/Objet500Connex3
26. Vidimče, K., Wang, S.-P., Ragan-Kelley, J., Matusik, W. OpenFab: A Programmable Pipeline for Multi-Material Fabrication. *ACM Trans. Graph* 32 (4), '13.
27. ZMQ4 TCP library, https://github.com/pebbe/zmq4
28. Zoran, A., Buechley, L. Hybrid reAssemblage: An Exploration of Craft, Digital Fabrication and Artifact Uniqueness. *Leonardo Journal '13,* Vol. 46, No. 1.