Circuit Assemblies: Electronic Modules for Interactive 3D-Prints

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ABSTRACT
This pictorial presents Circuit Assemblies, a design system for beginners to create 3D-printed interactive objects with embedded electronics. Circuit Assemblies are modules used to create objects that light up, move, or spin using basic electronic components like LEDs, batteries, and motors. To support beginners incorporating Circuit Assemblies into 3D designs, a set of virtual components were added to Tinkercad, a popular browser-based 3D CAD application with over 10 million users. In this paper, we begin with a set of design considerations gathered from interviews with three K-12 educators that teach electronics. We then present four different Circuit Assembly modules designed with these considerations in mind, highlighting the unique challenges that arise from combining electronics and 3D design for beginners, both in CAD software and physical assembly.

Authors Keywords
CAD, electronics, 3D printing, fabrication, education

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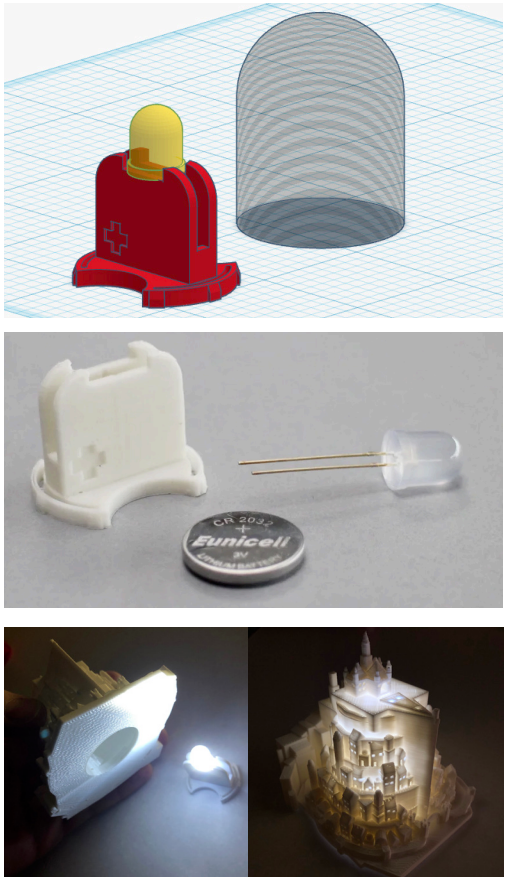
INTRODUCTION
Most consumer electronics we interact with on a daily basis, from remote controls to desk lights, are created through the combination of industrial design and electronics. Learning how to design interactive objects requires knowledge across a range of tools and skills, including 3D CAD modeling, hardware design, mechanical assembly, and programming.

While digital fabrication technologies (such as 3D printing) and hardware prototyping platform (such as Arduino) have made it possible for young audiences to engage in interaction design, few tools merge fabrication and hardware to address the unique challenges of designing integrated interactive objects, including considering assembly design and mechanical tolerances.

To make interactive product design more accessible to beginners, we developed a system called Circuit Assemblies within Tinkercad, a popular and free 3D design tool for novices. Circuit Assemblies consist of 3D-printed modules assembled with basic electronic components like LEDs and motors for building interactive 3D-printed designs. The Circuit Assembly system aids users through the process of first creating their design in a 3D CAD environment and then assembling their final creation after 3D-printing.

In this pictorial, we describe a set of needs and practices gathered from speaking to K-12 educators that teach electronics. We then share four Circuit Assembly modules that were inspired from insights from these conversations. We highlight design considerations that may inform designers of other integrated systems merging electronics and 3D design for beginners.



Glow Circuit Assembly in Tinkercad, electronic components, and user-created example [22]

RELATED WORK

This research builds upon prior work on design tools for supporting novices with 3D design and fabrication of interactive objects.

3D Design for Novices

Existing tools for introductory 3D design tend to take one of two approaches: eliminating the need to use CAD programs in favor of natural interfaces, or focusing on making CAD software more accessible.

While no-CAD options have explored natural interfaces to construct models, for example using clay-based sculpting techniques [19, 21, 33] or vision-based systems for building models with existing physical objects [1, 7], these systems often use specialized technologies and custom hardware inaccessible for large-scale use in educational settings.

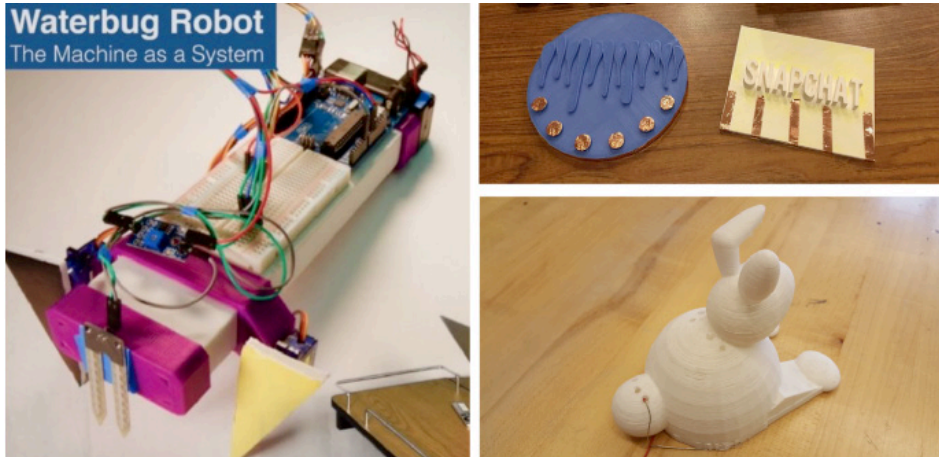
Perhaps because screen-based CAD tools are still widely used in professional work, educators see 3D design as a valuable skill to teach. This can be evidenced by the large number of teachers and students that use Tinkercad, a free browser-based 3D modeling tool for beginners with over 10 million users [36]. Tinkercad's approach to 3D design involves the grouping of basic 3D primatives (compared to the sketch-to-extrude workflow that is highly customizable but more complex in professional CAD tools). Using 3D design tools can be beneficial for learners to build spatial visualization and computation skills [25].

Design Tools for Fabricated Interactive Objects

Several tools aim to simplify the integration of electronics with digitally fabricated objects. Some combine the sculpting of 3D forms with the placement of electronic components, represented through flat stickers [33], physical electronic parts [21], or virtual components [12]. These tools then auto-generate fastening and mounting features.

Others have experimented with routing electronics on the surface of 3D forms [37, 38] or using conductive filaments for 3D-printed embedded sensors [5], targeting users already familiar with designing with electronics. Pineal offered a visual interface for creating 3D models with embedded smart devices like watches and phones for interactivity [26]. Printed Optics proposed optical pipes in 3D prints alongside interactive displays to bring objects to life [39]. Print3D utilized an AR interface for children to place electronic components into a pre-determined outline that is then extruded in 2.5D [40].

In contrast, Circuit Assemblies scaffolds the embedding of electronics into 3D objects without the use of additional technologies (such as 3D scanners) and using ready-made circuits designed for beginners. Additionally, this work considers budget and time constraints of educational environments, which makes 3D-printing large models that embed objects like mobile devices prohibitive.



Examples of K-12 student projects combining electronics and 3D printing, shared by interviewed teachers, including designs with conductive copper pads for the Makey Makey [28] and holes for threading wire.

FORMATIVE STUDY WITH EDUCATORS

To understand existing practices around teaching electronics in K-12, the main author conducted individual 30-minute semi-structured interviews with three teachers. Participants were identified through public blog posts they authored describing physical computing activities they facilitate with children. One teacher works with elementary and middle school youth, while the other two teach in middle and high school.

Interview questions involved describing the types of projects students build combining electronics and fabrication, as well as age-appropriate components used in the classroom, leading to the following insights:

Personalized simple circuits

All three teachers spoke of the power of using simple circuits that can be customized in combination with physical materials: "All the kids make the same circuit, but if they get to customize their own housing around it, it becomes more personally meaningful."

Ad-hoc fasteners and materials

To attach electronics to physical materials (such as paper or LEGO), students use ad-hoc materials like tape, rubber bands, and hot glue. Tape and hot glue can be used to connect electronic wires while eliminating the need for soldering, deemed unsafe for young children. These temporary connections are more convenient than robust.

Big components for little hands

While there are always thousands of electrical components to choose from, teachers spoke of carefully selected those that were ergonomically appropriate for small hands. As an example, the elementary school teacher used large switches with screw terminal connection points, allowing students to use alligator clips or thick single-core wire to connect to rather than thinner wire that may require soldering.

Components over kits

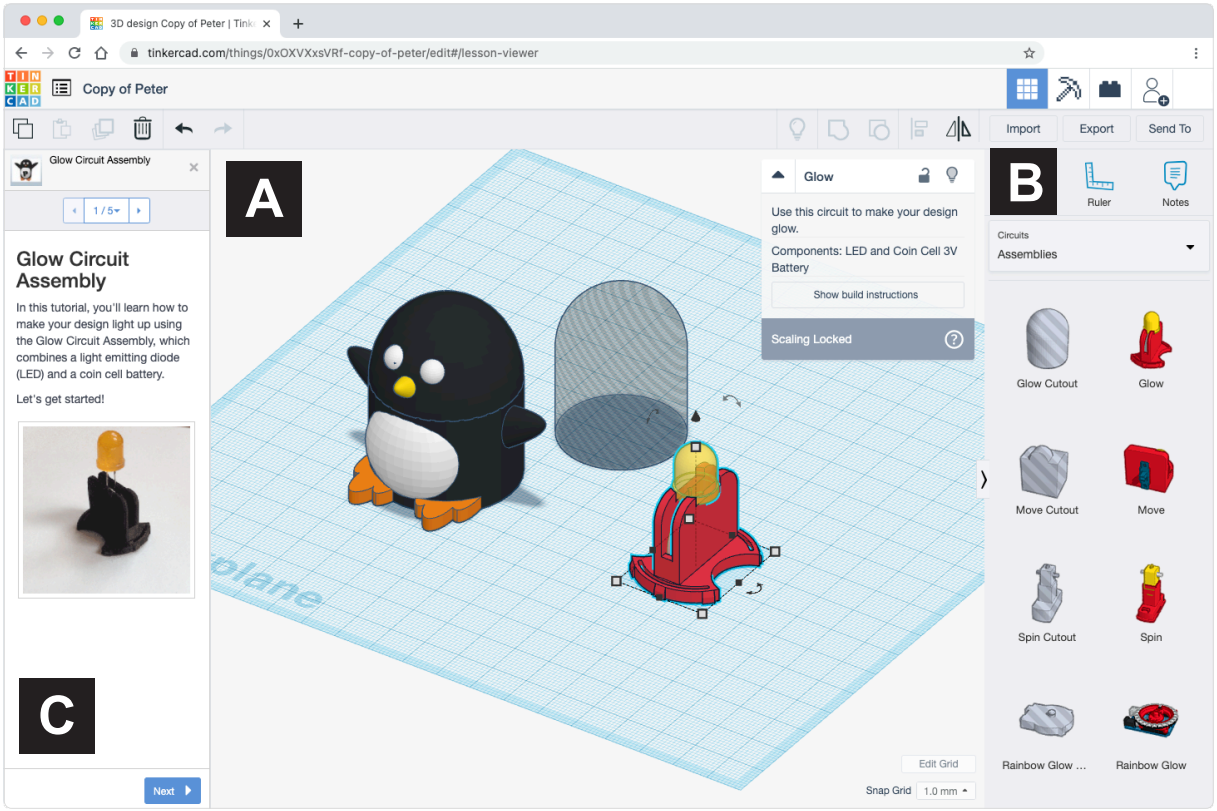
While two of the three educators have used electronic kits such as littleBits [2], they spoke of the power of using basic electronic components with their students, both because of cost (basic components cost several cents, while kit parts can cost more than $10) and because using basic components enables students to more easily transition to breadboarding.

These insights informed the design of the Tinkercad Circuit Assembly feature: modules that integrate common electronic components into 3D prints to create interactive objects. A brief overview of the Tinkercad interface is provided next for context, followed by a description of the Circuit Assemblies.

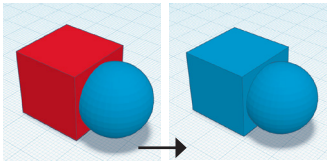
TINKERCAD INTRODUCTION

Tinkercad (www.tinkercad.com/) is a free web-based 3D modeling environment from Autodesk where models are built by combinating basic shapes. In the editor (**A**), users drag out shapes from the Shapes Panel (**B**), transform them (through scaling and translation), and group them together. Shapes can either be a ***solid*** or ***hole***, and their type affects how they combine with other objects through the action of ***grouping***.

Grouping shapes produces either a boolean union or subtraction operation; grouping two solid shapes together produces a union, while grouping a solid with a hole subtracts the hole from the solid shape.

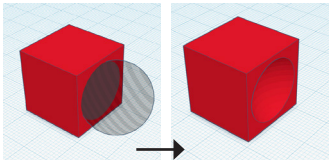


Group operations in Tinkercad



Solid + Solid = Union

Grouping two solids (e.g., square + sphere) produces a unioned shape



Solid + Hole = Subtraction

Grouping a solid with a hole (e.g., square + sphere) produces a cavity in the solid shape

Above, the Shapes Panel (**B**) is filtered to show the Circuit Assemby parts. Each Circuit Assembly is paired with a corresponding "Cutout" hole. When a user groups a cutout with their custom design, a cavity is created that enables the Circuit Assembly to fit inside. For example, grouping the cutout with the Penguin model above would provide space for the Circuit Assembly to press fit inside.

An in-editor tutorial panel (**C**) displays step-by-step instructions for how to incorporate Circuit Assemblies into a design and assemble with real electronic components after fabrication.

Next, we provide an overview of Circuit Assemblies followed by design considerations for each module:

CIRCUIT ASSEMBLIES

Informed by feedback from educators, we developed a set of electronic modules to bridge electronics and 3D design in Tinkercad, with the following design goals:

Customize basic behavior through 3D design

We use common basic circuits but enable users to build on top of them and customize through 3D design.

Use inexpensive electrical components

Basic electronic components, many of which cost no more than $5 each, were incorporated for budget-sensitive classroom environments. We also aimed to eliminate the need for soldering for most modules to be classroom-friendly.

Minimize fabrication time and material

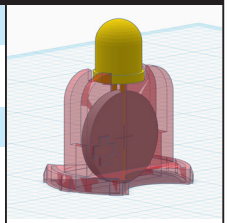
We tried to account for the limited budget and time of classrooms by minimizing part size.

Four Circuit Assembly modules were created and added to the Tinkercad Editor: Glow, Move, Spin, and Rainbow Glow. We chose this set of behaviors because their underlying circuit can be built with just a couple components. Each has a pre-designed single function and can be embedded into custom 3D models. Glow, Move, and Spin use analog circuits while Rainbow Glow incorporates a programmable Arduino.

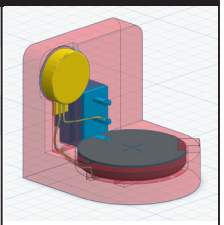
The Circuit Assemblies exists in two forms: as virtual components in the Tinkercad 3D editor that users design 3D models around, and as physical 3D-printed parts that are assembled with electronic components.

The four assemblies are summarized on this page. Next, we walk through the design process of building 3D designs with Circuit Assemblies, followed by more specific design considerations for each module.

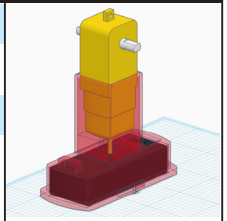
Glow

EFFECT	
Lights up	
PARTS [TOTAL COST USD]	
LED, coin cell battery [$2]	
TIME TO PRINT	
30 minutes	
OVERALL DIMENSIONS (MM³)	
25 x 32 x 25	

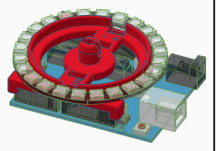
Move

EFFECT	
Vibrates / bounces	
PARTS [TOTAL COST USD]	
Vibration motor, switch, coin cell battery [$6]	
TIME TO PRINT	
32 minutes	
OVERALL DIMENSIONS (MM³)	
25 x 28 x 24	

Spin

EFFECT	
Rotates 360° continuously	
PARTS [TOTAL COST USD]	
Hobby gearmotor, 2xAAA batteries, battery pack with switch [$7]	
TIME TO PRINT	
130 minutes	
OVERALL DIMENSIONS (MM³)	
35 x 77 x 60	

Rainbow Glow

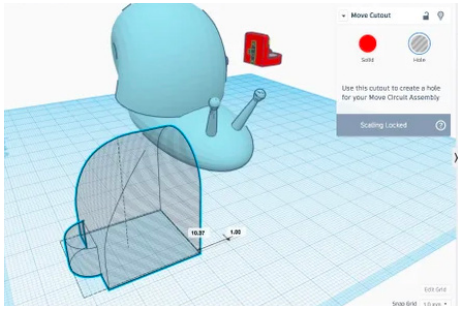
EFFECT	
Lights up with tricolor LEDs	
PARTS [TOTAL COST USD]	
Arduino Uno [$23], Neopixel 24 ring [$20]	
TIME TO PRINT	
58 minutes	
OVERALL DIMENSIONS (MM³)	
54 x 55 x 16	

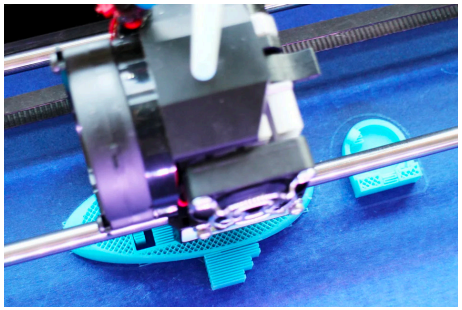
Part cost is gathered from Sparkfun Electronics for single quantities.
Time to print is determined from Normal print settings in Cura (18% infill density).

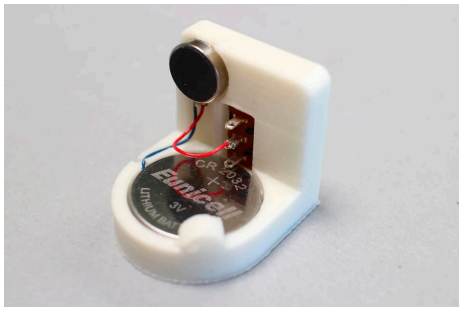
Workflow

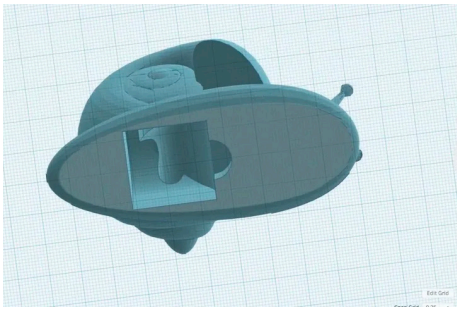
The following example shows how a user goes from designing a custom 3D model in Tinkercad to fabricating their interactive 3D print. Images from this tutorial draw from a example of an interactive snail design using the Move Circuit Assembly [32].

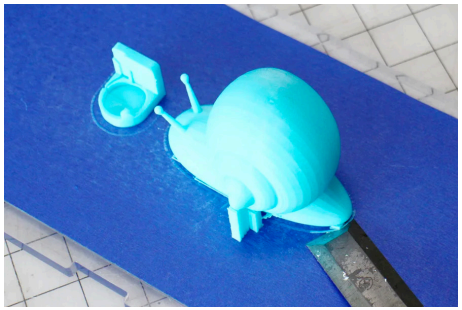
Photographs by Paige Russel [32]

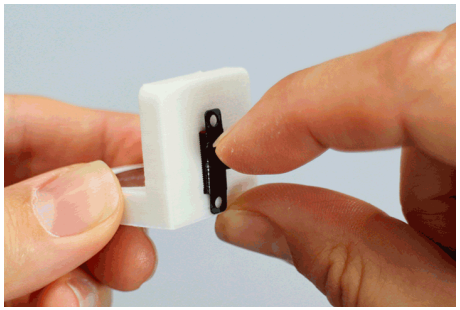


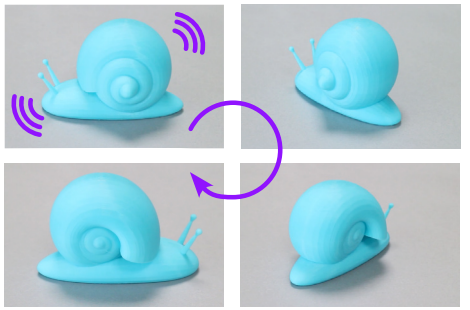












Step 1: Create 3D design

In Tinkercad, users create their own 3D model (in this example, a snail design).

They group the cutout hole with their model to create a cavity that the Move Circuit Assembly can fit inside.

In the example shown above, the Move Circuit Assembly will be inserted at the bottom of the snail.

Step 2: Print design

From Tinkercad, they export their custom 3D model and the Circuit Assembly component (the "holder") as STL files, import into 3D printer software (such as Cura or Makerbot Print), and send the designs to their 3D printer to fabricate.

Step 3: Assemble the Circuit Assembly

After printing is complete, they assemble the Circuit Assembly using physical electronic components.

With the Move Circuit Assembly shown above, users connect a vibration motor, switch, and battery.

Step 4: Embed Circuit Assembly in print

Finally, they embed their Circuit Assembly module into their custom 3D design and power it on.

In the example above, the snail model glides on the surface when the Move Circuit Assembly is turned on.

GLOW

The Glow Circuit Assembly is the simplest module, designed to make a 3D-printed design glow with an LED and coin cell battery. The example on the right shows an example penguin model, where the Glow module makes its eyes light up.

3D Design

To make embedding into 3D designs easier, the module was designed to be symmetrical so that it can be inserted in any orientation. Its accompanying cutout is dome-shaped (**A**); in the example shown with a penguin 3D design (**B**), users can center the dome cutout with the penguin and group the shapes to create the cavity for the module to fit inside.

Assembly Design

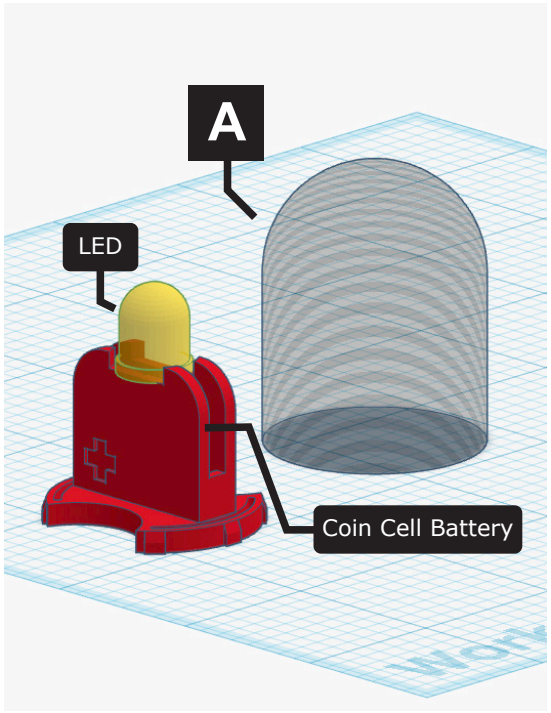
Since the LED and battery both have polarity, requiring them to be connected in a particular direction, a physical label for the positive terminal was designed into the module to aid with assembly, shown as the + marker on the holder (**C**).

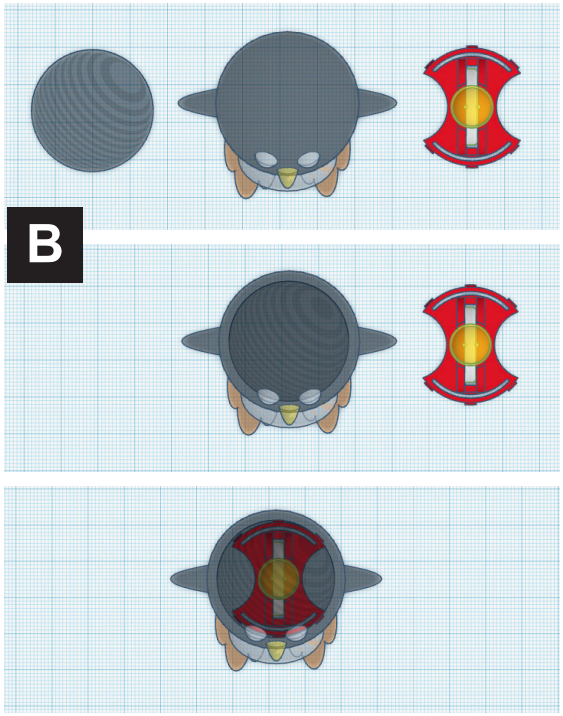
To account for variations in 3D printer resolution and infill, the base of the module has built in flexures and detents that allow it to compress if needed when press-fitting into a design (**D**).

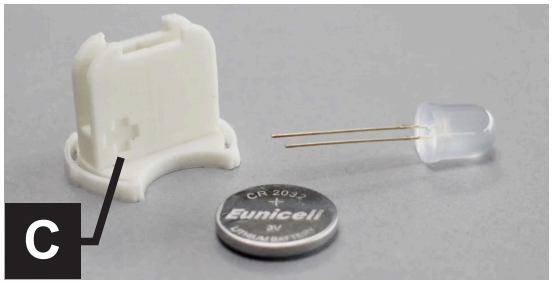
Finally, to make it possible for users to remove their modules from their prints (for example, to replace electrical components or use it in another design), the base of the module is half-moon-shaped so users can insert their finger to wedge the component out (**E**).

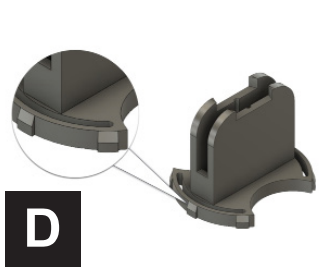
User Considerations

In creating a design that goes around the Glow modules, users need to consider material factors like the thickness and color of the material, which will determine whether or not the light shines through. These material factors were not ones that could be easily simulated in the editor itself and thus requires experimentation when fabricating.









Tutorial of Glow Circuit Assembly available at https://www.instructables.com/Glow-Circuit-Assembly-1/

MOVE

The Move Circuit Assembly (**A**) combines a vibration motor, slideswitch, and coin cell battery and is used to create 3D objects that can bounce or glide. This page shows an example bumblebee model with an embedded Move module; the design moves across a flat surface when turned on.

3D Design

In Tinkercad, users align the front face of the cutout (**B**) with a face of their design and group to build the cavity for the assembly. The cutout has a lip (**C**) to aid with removing the assembly if needed (to replace the battery, for example). Note that this disassembly feature was built into the cutout, rather than the module itself, as there was limited space on the assembly.

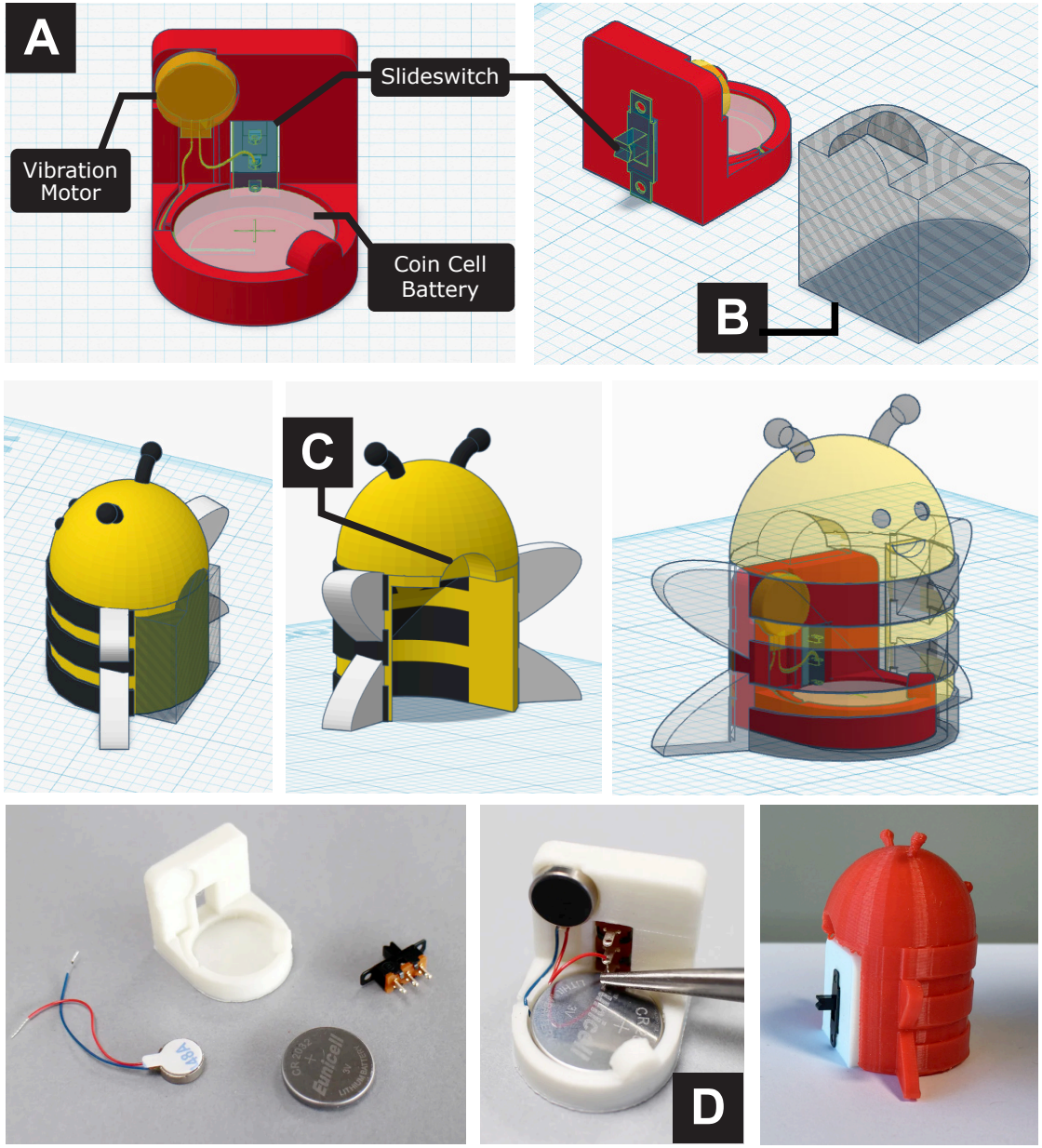
Assembly Design

To enable assembly without the need for a soldering iron, we specifically chose a slideswitch with solder lug terminals (a hole on each pin) rather than straight leads. This allows users to thread the wire from the motor directly through the lead of the switch to make a connection as shown in (**D**).

We also used the mechanical design to further aid with assembly without the need to solder. As displayed in (**A**), the vibration motor, which has an adhesive backing, is attached directly to the 3D-printed holder. The negative end of the motor lead is placed underneath the coin cell battery, while the bottom pin of the switch makes a connection with the positive side of the battery when inserted from the front. The positive motor lead is then threaded through the middle pin of the slideswitch. When the switch is pushed down, the motor turns on.

User Considerations

Because the strength of vibration is affected by how heavy the overall design is, users need to be sensitive to how large and dense their custom model is. Lighter designs will bounce, while heavy designs have more moderate movement.



Tutorial of Move Circuit Assembly available at https://www.instructables.com/Move-Circuit-Assembly-1/

SPIN

The Spin Circuit Assembly lets users create designs with 360 degree continuous motion. It combines a hobby gearmotor with two spinning axes (140 RPM) and a AAA battery box with a built in switch (**A**). In the example shown, the Monkey's arms swing back and forth when the motor is powered.

While a regular DC motor would have a much smaller footprint compared to a hobby gearmotor, normal DC motors have a high speed (of over 6000 RPM), which is a potential safety hazard when combined with 3D printed parts. We thus chose a popular hobby gearmotor used in educational robotics kits, which subsequently affected the overall footprint.

3D Design

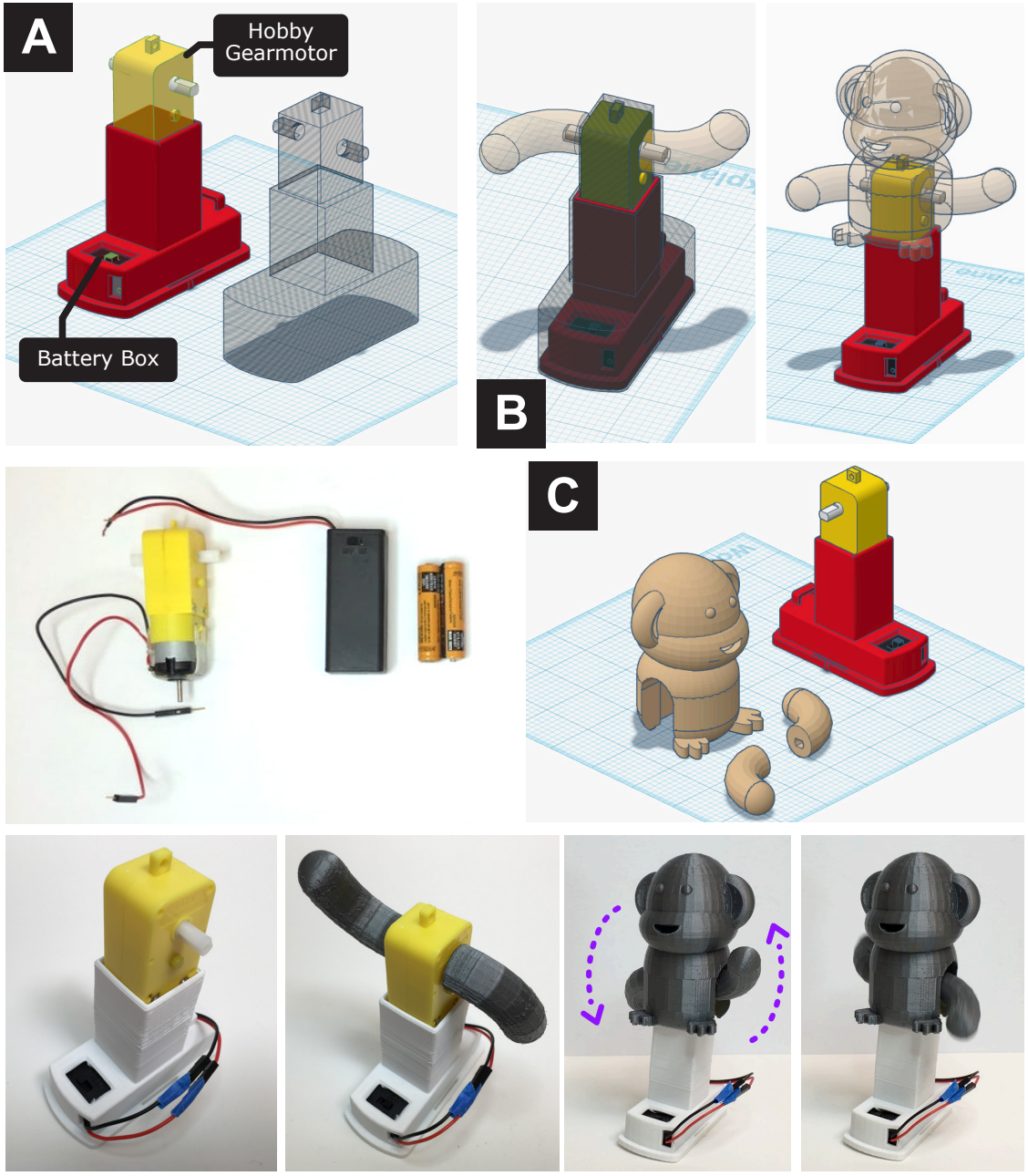
We wanted to accommodate both designs that fully encapsulate the Circuit Assembly, as well as those that may only partially enclose it (such as the Monkey example shown on the right, where the battery box is not hidden). To make the switch to the battery box accessible with either option, we designed the cutout to be taller than the battery box to allow enough space for a finger to access the switch (**B**).

Unlike the Glow and Move modules, a spinning design is likely to consist of more than one part: a stationary component and a spinning part directly attached to the axle. It is expected that users would need to group the cutout to multiple objects. In the Monkey example, there are three resulting parts (**C**): the body of the Monkey has a cavity to account for the motor body, while its two arms have smaller holes to fit onto the motor shafts.

User Considerations

The hobby gearmotor and the AAA battery box are both larger than either the Glow or Move Circuit Assemblies. As a result, the Spin Circuit Assembly takes about 4x as long to print (2 hours compared to 30 minutes for either the Glow or Move modules).

It is worth considering whether the inclusion of the battery box as part of the 3D model is needed – if not, the design can be made substantially smaller.



Tutorial of Move Circuit Assembly available at https://www.instructables.com/Spin-Circuit-Assembly/

RAINBOW GLOW

Rainbow Glow is a programmable Circuit Assembly module to be used with an Arduino Uno and a NeoPixel ring with addressable color LEDs. This module was designed in collaboration with educator Erik Nauman based on his original design on Instructables [17] and modified to include a central snap that users can attach their own custom models to (**A**). The holder is a 3D printed "shield" that sits on top of the Arduino, exposing the pins needed for programming the lights. In the example shown on the right, a butterfly 3D print has a socket that snaps onto the holder and is illuminated from below when the Arduino is powered (**E**).

3D Design

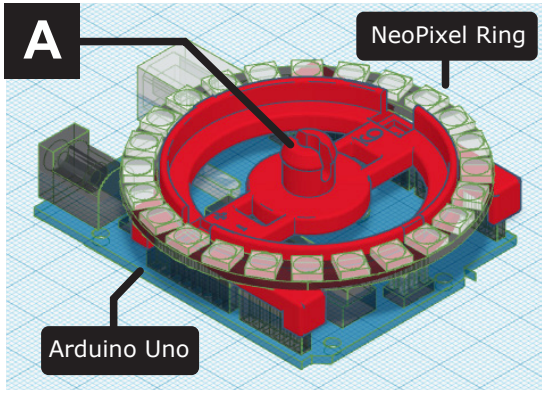
A snap-socket design is used for attaching custom designs (**A**), and the cutout is grouped with a design to create the socket cavity (**C**).

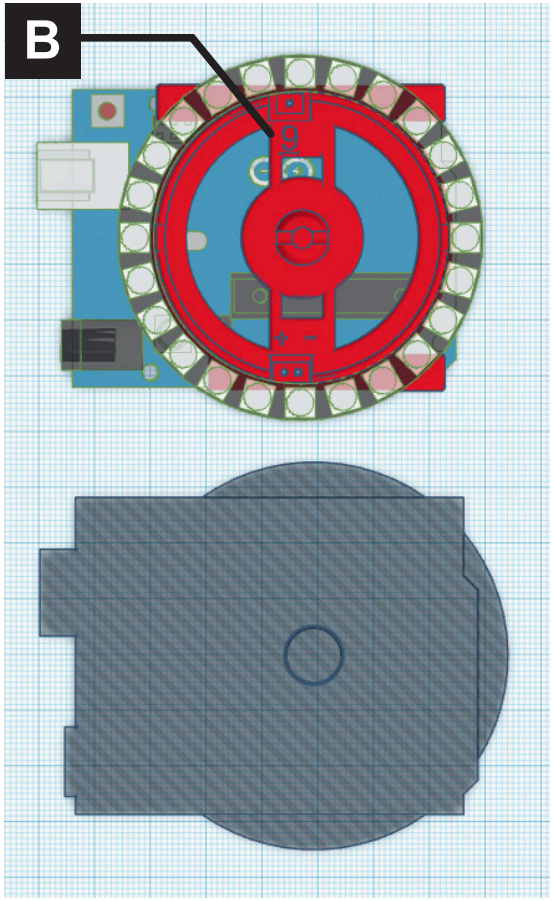
Assembly Design

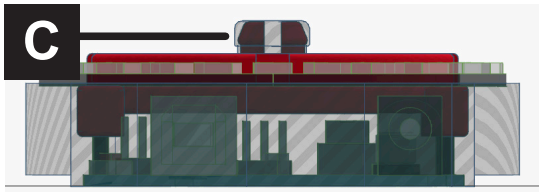
The holder exposes three pins of the Arduino microcontroller: a programmable output pin, power, and ground. These pins are labeled on the physical component to help users remember what pin of their Arduino to program (**B**).

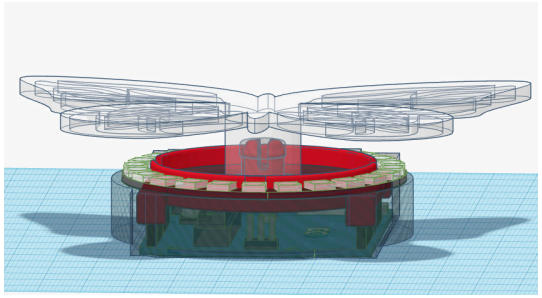
The NeoPixel ring requires soldering wires to, so Rainbow Glow is not an example of a solderless module. We recommend that users use a removable jumper wire to connect to the Arduino and to solder the other end of the wire to the Neopixel (**D**). Given that this assembly also requires the additional step of programming, we treated this module as a more advanced Circuit Assembly compared to the analog modules.

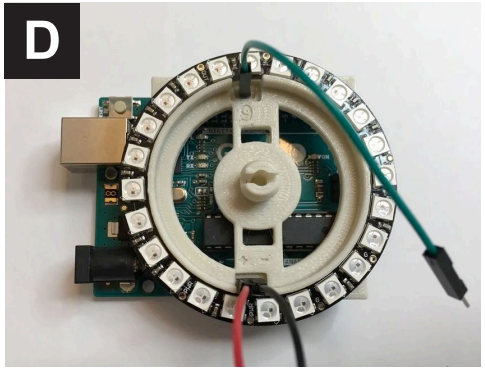
The shield design does not fully contain the electronics (Arduino) within an enclosure. The tradeoff made was that users were likely to need to access the ports of their Arduino (to program or power the device), and using a shield that fits on top of the Arduino, rather than around it, can reduce the footprint and printing time.











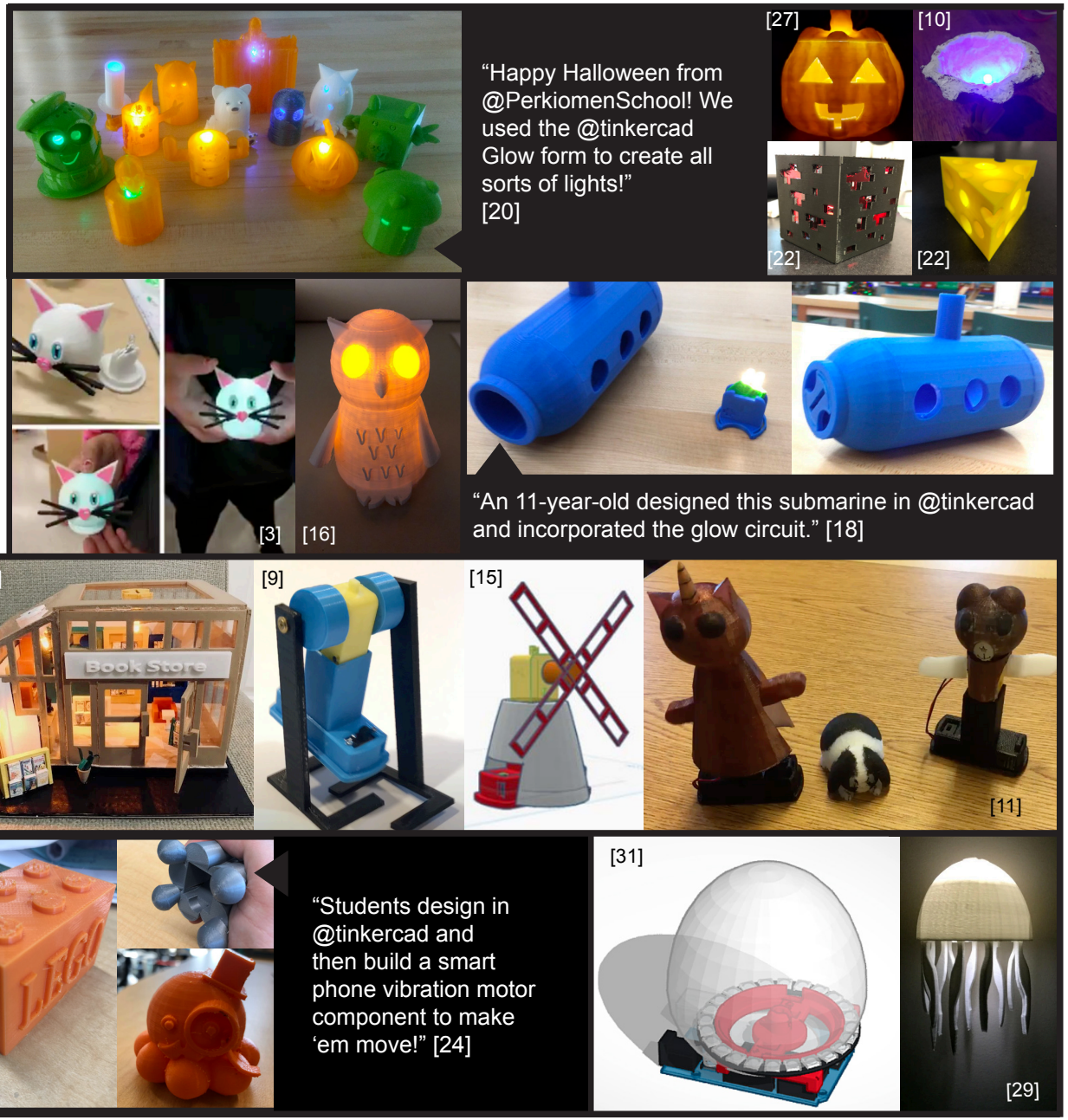
Tutorial of Rainbow Glow Circuit Assembly available at https://www.instructables.com/3D-Printed-NeoPixel-Ring-Butterfly-With-Tinkercad/

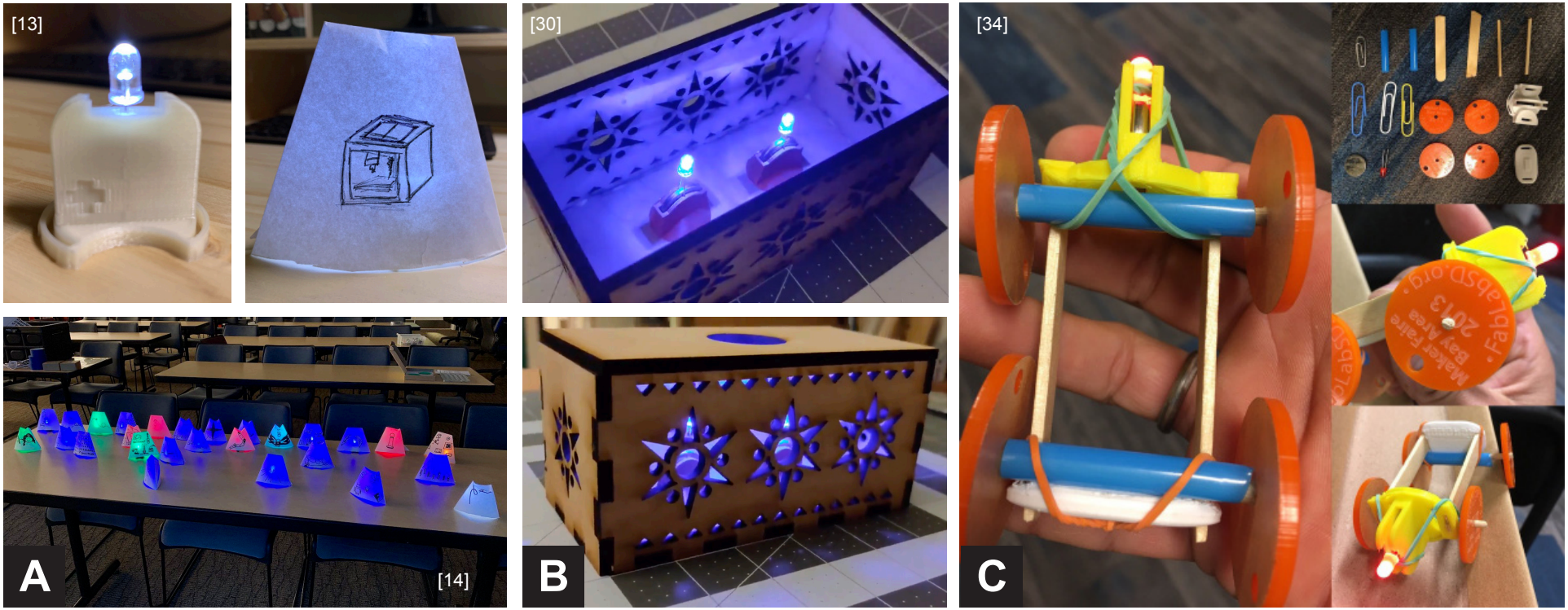
SHARED DESIGNS

The four Circuit Assemblies were progressively released on Tinkercad from 2017-2018. An initial search of publicly shared projects (on social media, blog posts, YouTube, Thingiverse, and Instructables) identified 50 unique artifacts, a selection of which are displayed here.

These examples reveal that users designed a range of custom creations, including animals, architectural models, and abstract figures. Many were shared by teachers showcasing student work.

The majority of projects incorporate the Glow Circuit Assembly. Examples of projects built using the other Circuit Assembly modules include a walking robot [9] and windmill design [15] made with the Spin Circuit Assembly, a wiggling chick [6] and LEGO brick [24] made with Move Circuit Assembly, and a light up egg using Rainbow Glow [31].





With the Glow Circuit Assembly in particular, we observed three examples of users embedding the 3D-printed Circuit Assembly into crafted objects made with material other than 3D-printed plastic.

For example, paper cones with hand-drawn designs act as lampshades in (**A**), enabling users to quickly customize creations without the overhead of 3D-fabrication time.

The wooden laser-cut box in (**B**) uses Glow modules attached to its base. With laser-cutting, the creator may have been afforded the possibility to fabricate a larger design than may be possible with inexpensive 3D printers, while also likely saving fabrication time.

Finally, the toy car set show in (**C**) is an example where the holder itself was modified – the base of the Glow module is extended, with two slots added for accommodating popsicle sticks that make up the car's chassis. Note that perhaps because of the mix of materials, the Glow module is attached to the car body using rubber bands. This example could be a particular interesting case to understand the edges in which 3D printing may feel worthwhile and at which point more flexible, crafted materials may be desired.

DISCUSSION

Creating the Circuit Assemblies brought to light considerations for supporting integrated product design across the entire workflow of 3D modeling, electronic assembly, and physical integration of electronic and 3D-printed parts.

Balancing Ergonomics, Part Availability, and Print Size

Generally, there was an ongoing challenge with balancing often competing needs of identifying age-appropriate electronic components and taking into account sourcing and availability. For example, when choosing a switch to use for the Move Circuit Assembly, we specifically chose one with solder lug terminals, or terminals that holes in them that wires can be threaded through rather than soldered to. This would enable anyone to build the module without having to use a soldering iron. However, in choosing a specific part with specific dimensions, the Move Circuit Assembly consequently develops a dependency on a particular set of distributors, in contrast to the Glow module, which can be used with any sized LED interchangeably.

An additional challenge was balancing larger electronics part sizes (for ergonomics) and fabrication needs including minimizing print time and material costs. For example a larger hobby gearmotor was chosen rather than a regular DC motor for the Spin Circuit, but this led to a significant increase in print time for designs that incorporate it. Thus, part selection (in this case, a safe motor as well as standard battery pack) directly impacts overall print size and consequently material use, cost, and time to fabricate.

User Considerations around Material Qualities

A missing element in the existing Circuit Assembly design workflow is taking into account the impact of material qualities of fabricated objects, including weight and part thickness. For example, using different colored filaments, of different thickness, will affect how visible a light source will be when embedded in a printed object (such as with the Glow or Rainbow Glow modules). In one publicly shared design for a light-up Christmas tree figure illuminated with a Glow Assembly, the creator shared that they made updates, "to make the walls thinner so the light shows through better" [35].

With the Move assembly, the size of the 3D object will affect whether the resulting assembly will bounce or slowly glide when a vibration motor is powered.

Creating opportunities to provide guidance to users about these material factors, through simulation or other means, can be beneficial to helping them build confidence in their design before fabrication.

3D-Prints as Physical Schematics

The design of 3D-printed holders for circuit components creates a type of physical schematic, where the physical form factor defines the placement and orientation of individual components. We were able to leverage the 3D design of the holder to signal important assembly features, such as labels for polarity on the Glow Circuit Assembly to show how to insert the battery and LED, as well as pin labels on the Rainbow Glow module to let you know which pins of the Arduino needed to be programmed.

Challenges for Going Beyond LED Throwies

We observed that the Glow Circuit Assembly is the most widely used and shared, perhaps both because of the universality of the parts (LEDs and coin cell batteries are readily available even from general-purpose distributors like Amazon) and the popularity of LED light-up designs as an introductory electronics activities in classrooms. Future work would be required to better understand what parameters may be potential barriers to trying out other types of interactivity like movement with motors.

CONCLUSION

This pictorial presents Circuit Assemblies, electronic modules that were integrated into the Tinkercad 3D modeling environment to support users creating interactive 3D-printed designs. We share insights gathered from interviews with three educators based on their experience teaching electronics and fabrication to K-12 students. These insights then informed the design of the Circuit Assembly modules to use basic and inexpensive electronic parts, enable customization through 3D design, and take into account needs of educational environments like minimizing part cost and print time and material.

We show how pairing each module with a corresponding "cutout" can aid the 3D design process by automatically building cavities for accommodating electronic parts. Through describing the four modules (Glow, Move, Spin, and Rainbow Glow) that support designs that light up and move, we highlight how part ergonomics, sourcing, and material considerations play a role in shaping the designs that can be created. We hope that these designs can inspire others developing ways to support beginners mixing fabrication with electronics to create interactive objects.

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