Columbia University
MECE E3408 002 Computer Graphics and Design

Final Project Report
Educational Toy for Addition and Subtraction

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1 Introduction

Our educational toy is a handheld gear-based toy that assists children aged five to seven in learning addition and subtraction of single digit numbers. It allows the child to manipulate three inputs, say *x* (0-9), *y* (0-9), and *z* (0-9) in the expression $x + y - z$, automatically evaluating the expression and outputting the solution. This toy is operated purely mechanically (requiring no batteries) and has no loose or protruding parts that may pose hazards to young children and headaches for their parents..

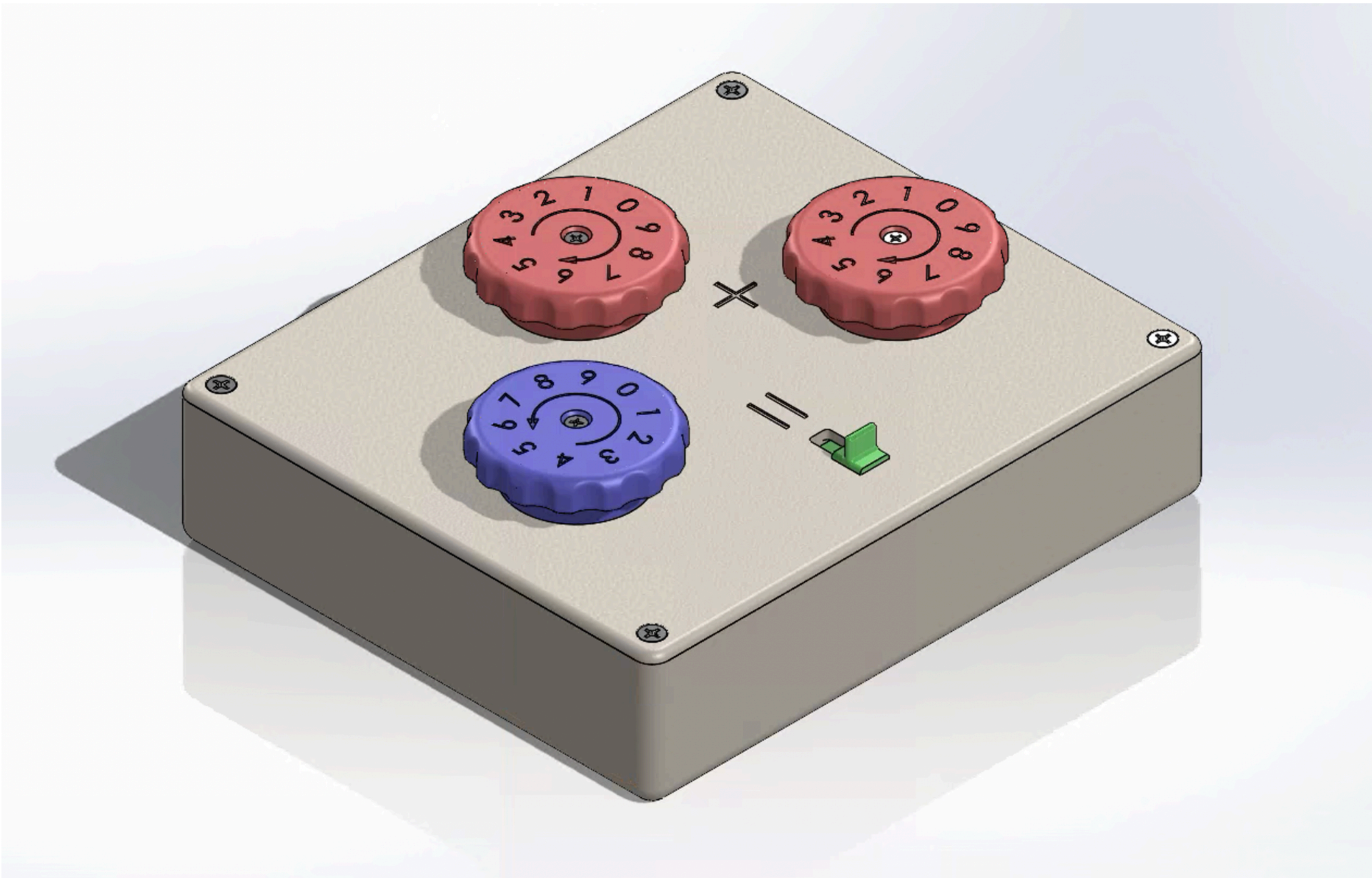

Fig 1. *Isometric view of the toy.*

2 Background Research

2.1 Age group

Children begin to learn and grasp the concept of addition and subtraction in the age range of five to seven. We market this toy towards this range of five to seven—especially for those (whose parents are) seeking an extra challenge given this toy's capability to perform simultaneous addition and subtraction. This decision is based on the research that a typical five-year-old can count and sum small numbers, a typical six-year-old can understand the "complimentary of addition and subtraction," and a typical seven-year-old can retrieve arithmetic facts from memory [1].

Our design contains no visual representation of numbers other than the written numerals for simplicity, and because at around ages three to four, children are typically already able to associate numbers with written numerals [2].

2.2 Market research

Many current adding/subtracting educational toys do not feature automatic answer output and only serve as aids for children—they would need a "supervisor" to use the toy to help them teach. Many of these also are choking hazards with many loose parts, like the "See & Solve Math Center" toy that requires putting together equations with loose beads and tiles [3]. Other arithmetic educational toys with visual representations of numbers, like an abacus (see "Add and Subtract Abacus"), require more complex mental intuition of how to represent numbers with sliding beads and utilize counting more than true arithmetic [4]. The simple "Addition Pop It Math Game" toy provides a simple addition visualization (but not necessarily direct subtraction) between numbers, but it is difficult to grasp the connection between the 144 number options and the arithmetic behind it [5]. iPads are also becoming increasingly popular for parents to give their children, yet studies show iPad screen time may stunt a child's growth and development [6]. Especially with games other than educational games, using an iPad as a child may be more harmful than helpful in learning. An iPad also requires repeated recharging and is fragile when dropped onto hard surfaces, causing hundreds of dollars to repair or replace.

One product that does feature automatic outputs for adding and subtracting numbers is the pinwheel calculator. While fully mechanical and self-contained, it is more of an advanced calculator than a toy and is therefore not suitable for younger age groups. Its mechanism is extremely complex, posing difficulties both in manufacturing and repair. This, along with the fact they have been phased out as largely obsolete, mean they are difficult to find and cost hundreds of dollars [7].

Our design addresses all of the above-mentioned deficiencies in a lightweight, portable, and affordable toy. All components have been designed with assemblability and repairability in mind should the need arise, and all components are easily injection-moldable with minor modifications (such as the addition of draft angles and proper wall thicknesses). In essence, it boils down the complex pinwheel calculator's gear-based calculations into a simple child's toy. With automatic output and no loose or hazardous parts, this toy will make a great addition to any child's collection.

3 Original concept

Our original design is presented in the following SolidWorks CAD screenshot and uses three knobs—one as the first number x, and the second and third as the numbers to add (y) and subtract (z), respectively (Fig 2). Simultaneous addition and subtraction is achieved by setting both of the secondary knobs to non-zero values. Gearing ensures that the output gear (shown in green) always updates to the correct output value, which is shown in the window to the right.

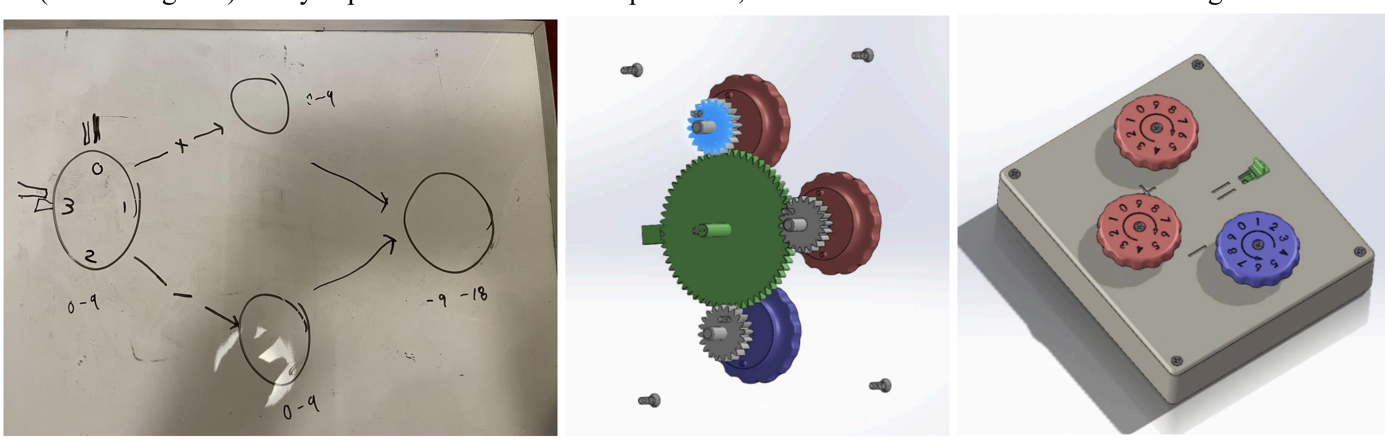

Fig 2. *Original concept ideations.*

4 Design Features: Operation and Aesthetics

4.1 Size and shape

We kept the original concept of the toy and added internal mechanisms that make it more robust. The final design fits in a 7in × 6in × 2in box and can be operated both when handheld and when placed on a surface. It is also lightweight (coming in at just under 1lb) and is easily portable in backpacks and bags.

4.2 Operation

To operate the device, the child rotates one knob at a time to set the desired inputs. We name the leftmost red knob x, the upper red knob y, and the lower blue knob z (see Fig 3). To rotate a knob, the child must pull upward on the desired knob before rotating to adjust the digit. The inputs are mechanically guarded against exceeding 9 or dropping below 0. The possible outputs range between 0 and 18. The output displays the answer to $x + y - z$ that automatically updates as each knob is turned to reflect a running evaluation of the expression.

4.3 Aesthetic Decisions

The *x* and *y* knobs are both colored red knobs—these indicate an "addition" type operation. An increase in the value of these knobs results in an increase in the value of the output, whereas the *z* knob (blue) represents subtraction and thus lowers the output value by the number selected. The output is represented in green through a window. There are notches above each of the three knobs to indicate which numbers are currently selected.

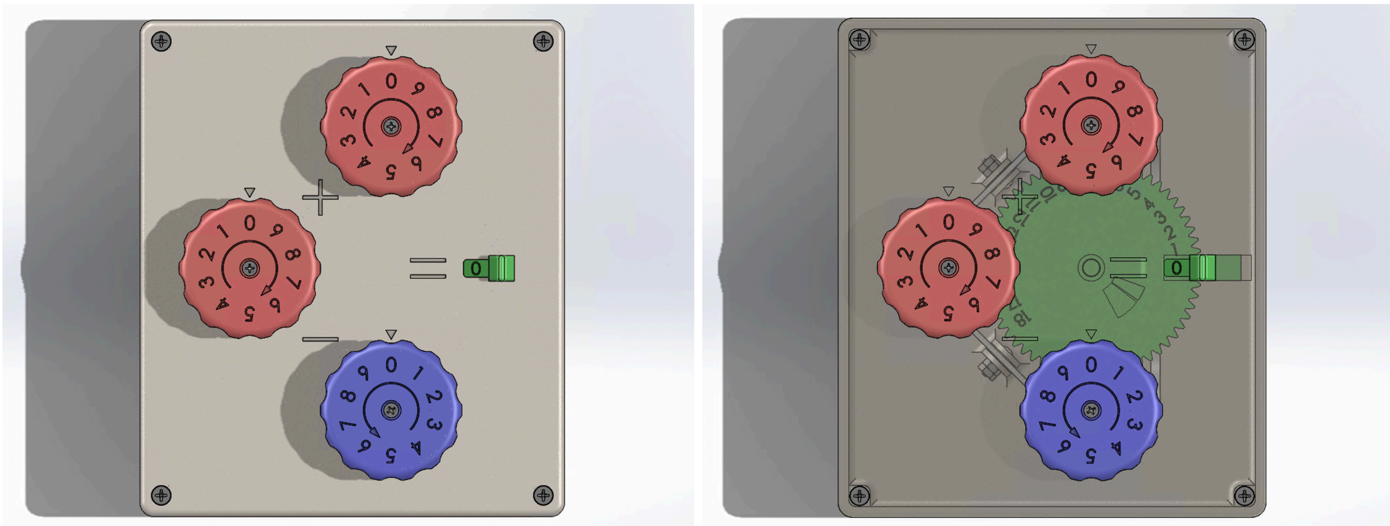

Fig 3. *Top views of the toy.*

5 Design Features: Mechanism and Engineering Decisions

We encountered numerous complications in the initial design of the toy, requiring repeated iteration and modification. The primary considerations were as follows:

- Partial rotation of a knob must not be allowed, i.e., the knobs may only take whole number values.
- Rotating one input should not change the value of other inputs.
- The inputs each must not exceed 9, and neither the inputs nor the output may go into the negatives.
- Simultaneous rotation of the inputs must be prevented.

5.1 Gearing

There are four main gears that rotate in the toy, three of which are connected to the knobs and the fourth to the output as shown in Figure 2. The *x, y,* and *z* knobs must each be coupled to the output when adjusted, yet they cannot be directly connected to each other; the mechanism for this is described in the following sections. Each of the input gears have 20 teeth while the output has 60 teeth (with matching diametral pitch), resulting in a 1:3 gear ratio. The subtraction knob is numbered in the opposite direction but geared exactly the same way as the addition knobs such that while the addition knobs turn clockwise, the subtraction knob turns counterclockwise.

5.2 Springs for disengagement and engagement

We now turn to solving the problem of asynchronous engagement. If all gears were permanently linked, turning one input would turn all the other inputs as well, resulting in an inaccurate calculation. We must therefore have a disengagement and engagement mechanism such that only one gear/knob can engage with the output gear at a time while the rest of the input gears stay disengaged. Accordingly, the input gears are offset in height from the output gear such that in their resting position, the input gears sit below the output. To engage the gearing, the input must be pulled upward (against light spring pressure) before rotating. This demands precise alignment between the input and output gearing at all times to avoid locking up—we address this with the mechanism in 5.4, while correcting for very minor shifts using chamfers at the engagement surfaces for automatic alignment.

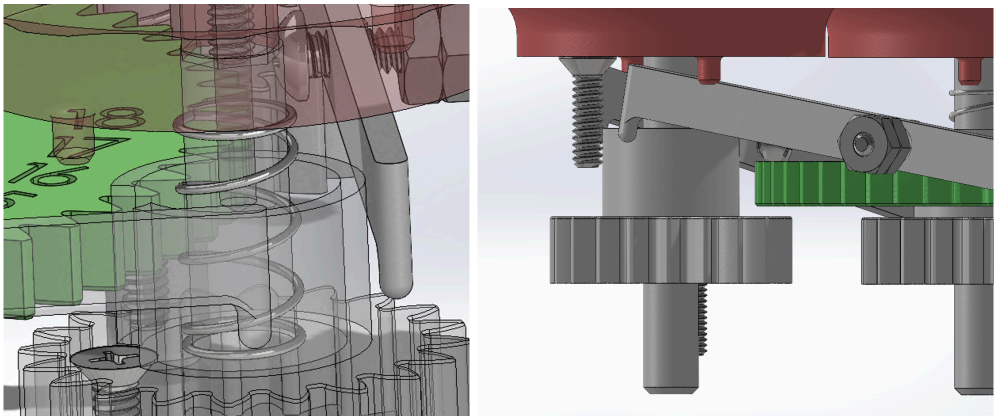

Fig 4. *Spring mechanism. Note the height offset between the gears in the resting state.*

5.3 Levers against simultaneous engagement

To safeguard against the possibility of engaging and rotating more than one gear simultaneously, levers are positioned between each pair of input gears. When one input lifts to engage with the output gear, the corresponding levers push downward on the other input gears. This prevents the possibility of jamming or misalignment if multiple knobs are lifted at once and simultaneous rotation is attempted.

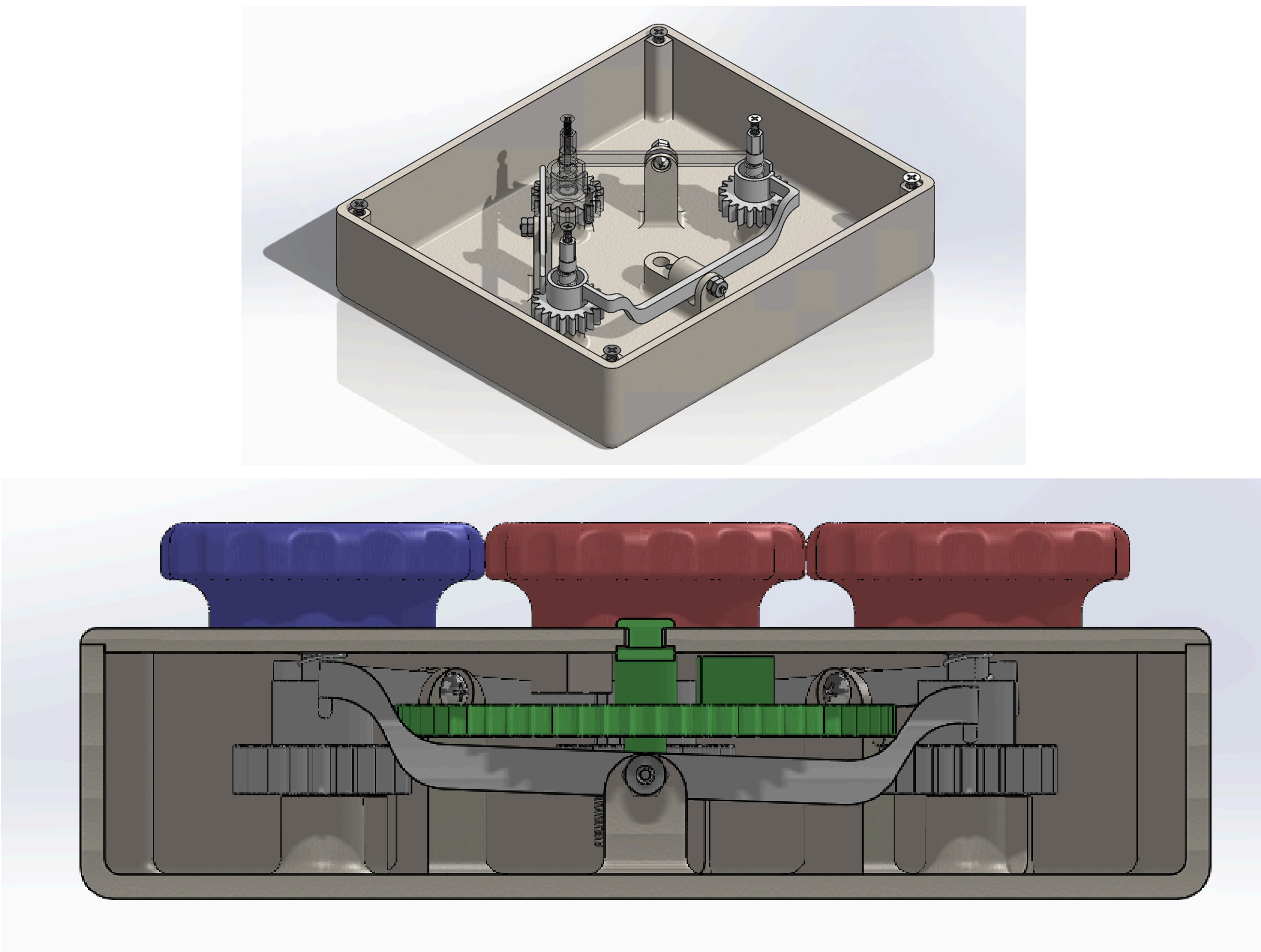

Fig 5. *Lever mechanism exposed.*

5.4 Shafts and holes for number alignment

Pins extending from the underside of the knobs mate with holes in the top cover to ensure that, once engaged, a knob can only be released and disengaged when aligned with a whole number. This allows only discreet rotations, eliminating ambiguity of output and internal gear alignment. Alignment is further facilitated by chamfers that help the pins self-align with nearby holes when released. If a knob is released while not aligned, it will remain engaged such that the mechanism in 5.3 prevents rotation of any other knob until this condition is corrected by the user.

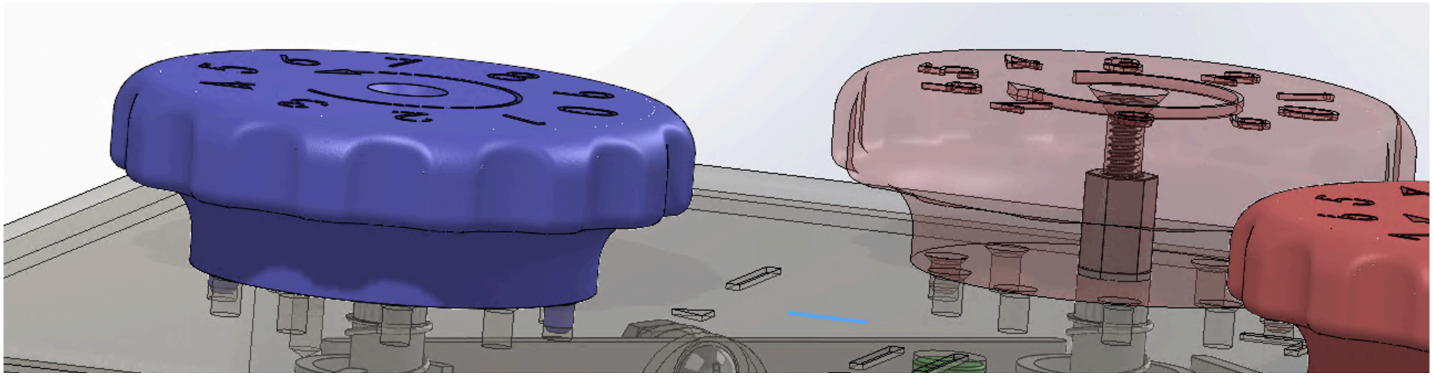

Fig 6. *Pin holes for number alignment*.

5.5 Stoppers against over-rotation and counterrotation

All knobs are guarded against both over-rotation (past 9) and counterrotation (attempting to rotate directly from 0 to 9 or into negatives) using physical stoppers. The output gear is also guarded against going to negative numbers with another hard stop. Due to the lack of room on the input gear, a plastic molded stop would have been very small, and finite element analysis (FEA) results showed insufficient strength. Thus we instead use a screw to provide the necessary strength in this confined space.

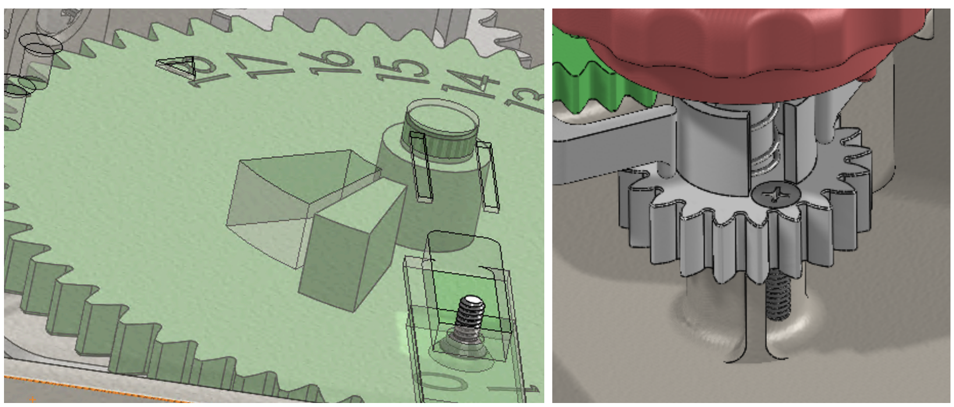

Fig 7. *Hard stops on input and output gears.*

5.6 Output override

In the unlikely case that the gears become misaligned and the output is displayed incorrectly, the parent can manually adjust the output gear to the correct orientation using a common flathead screwdriver through a small access hole at the bottom of the toy. This should not in general ever be necessary during normal operation of the toy as the mechanisms described above prevent user-induced misalignment; furthermore, the shaft of the output gear is preloaded with a UHMW friction pin to prevent free rotation under inertial or vibrational forces, guarding against accidental misalignment when uncoupled from the inputs.

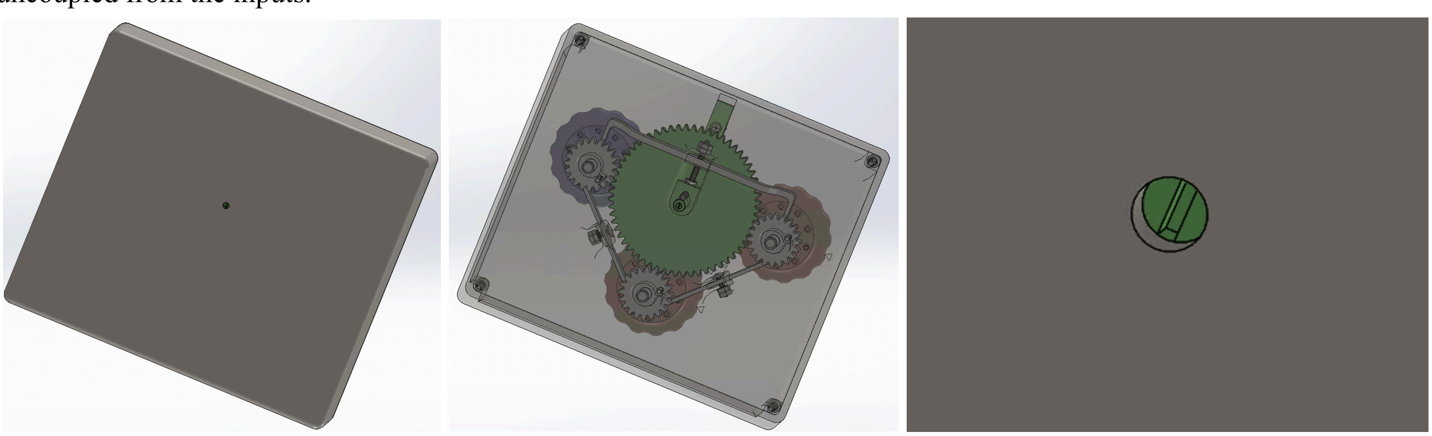

Fig 8. *Output overriding slot.*

6 Conclusion

Our toy provides a robust design that, unlike other toys on the market, provides all the following aspects that parents may find desirable in a toy: educational, portable, durable, lightweight, purely mechanical (no need to charge), and non-hazardous. It accounts for all reasonably conceivable failure modes and addresses them seamlessly.

References

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