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RESEARCH ARTICLE

An Electronic Engineering Approach for Turning a Lego Brick Piano into a Musical Instrument

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ABSTRACT We demonstrate and reflect on a rebuilding and electronic engineering approach to augment and electrify a Lego brick model. Concretely, we turn the not musically playable Lego Grand Piano into a functioning musical instrument as a MIDI keyboard with 25 keys and a sustain pedal. Our proposed solution is unobtrusive, flexible, and reversible. We only use off-the-shelf components and instead of soldering we take advantage of the bricks' interlocking mechanism together with wires and self-adhesive copper tape, which also keeps the costs and required skills for our approach low. Two live performances evidenced by videos showed the practical and musical applicability. We created and reflected on an extensive step-by-step documentation of the whole transformation process which we offer for potential reuse purposes. Overall, our approach to electrify a brick-built model and turning it into an interactive musical interface was successful, insightful and has the potential to be expanded, but needs further elaboration with other brick-built models and for different application purposes than musical instruments. Thus, we explicitly invite researchers, designers, engineers, tinkerers and makers who engage themselves in electrified and interactive brick-built models to get inspired by our approach, replicate and advance it.

INDEX TERMS Electronic engineering, human–machine systems, interactive systems, Lego brick-built models, digital musical instrument (DMI), MIDI keyboard.

I. INTRODUCTION

Interlocking (toy) bricks, particularly Lego, are diversly and beneficially used for creative thinking, idea finding and solving real-world problems [13], [18], [32] or just to build models for design purposes [3], [14], [34]. In all cases, one of the shared benefits of Lego bricks are their tangible and modular nature that offers a haptic experience and wide-ranging applicability.

Electrified or interactive bricks have a tradition as well. Since decades, Lego offers a series of motors, sensors and embedded systems to motorise models and create robots [19]. In parallel, brick-based interactive systems are continuously used and developed in research, engineering, and education for building complex robots, customised interactive bricks or for engaging children and students in technology [1], [12], [37], [39].

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Although bricks for tangible artefacts and interactive systems share a common track record, they are mostly either used creatively as a tool and to build models, or with an engineering perspective on technical capabilities. Instead, we use a complex, well-designed and playful Lego brick model to find a viable electronic engineering and manufacturing method for turning this model into a functioning interface. We chose the *Lego Grand Piano* [22] as shown in Fig. 1 as a study object which is a brick model of a piano with mechanical functions and a self-playing feature according to the freely available instructions [21]. But the model has a drawback that obviously serves our purpose to transform it into an interactive interface: being primarily a model, the playability is limited to silently pressing the 25 keys and the pedal. The musical capabilities are constrained to a Lego sensor that recognises random key presses to play back a song through a remotely connected smartphone within an official Lego app. However, the working hammer and pedal mechanisms offer a tangible operating experience and a great potential

FIGURE 1. ***The Playel*, a *Lego Grand Piano* turned into a musical instrument, played by the author in a concert. (Photograph: Joseph Krpelan).**

for attempting to turn the piano into a functioning musical instrument.

Further benefits of using this brick-built piano as a study object are: a musical instrument is of practical relevance and can be played and used in a performance to test its applicability; an instrument offers an additional musical perspective to reflect on besides our primary intention of studying the transformation process; finally, a digital musical instrument (DMI) offers both possibilities and requirements to consider for a resulting interactive device such as enabling embodied expressivity and ensuring reliability.

Motivated by the goals of this study, firstly, turning a *Lego Grand Piano* into a fully functioning musical instrument and, secondly, using this resulting electrified brick-built model in practice for a concert, we raise the following research questions:

(1) Are we able to turn the *Lego Grand Piano* with mechanically working but non-interactive hammer and pedal mechanisms into a fully functioning Digital Musical Instrument (DMI) of practical use?
(2) What can we learn from this transformation process about functionality, fabrication techniques and electronic engineering of interactive brick-based models?
(3) How is the practical applicability of a brick-built model turned into a fully functioning DMI?

To answer these questions, we conducted four phases over the course of half a year: Firstly, constructing the original Lego model; secondly, developing a proof-of-concept pilot to be empirically tested in a first public performance; thirdly, transforming the brick model in a fully functioning musical instrument, which we call *The Playel*[1]; and fourthly, a second public performance to test the final prototype in practice.

The medium of this transformation was a detailed photo documentation of the rebuilding and electronic engineering process along with textual notes on the practical experience of all phases and work steps. Firstly, this data body was used for the reflective analysis in the aftermath. Secondly, we followed a conclusion on the importance of documentation for replication especially in DMI design [48]. The performances were video recorded for both the reflective analysis and to produce showcase videos which are available online [16], [42].

We continue this article with a literature review of brick-built models in relation to research, design and engineering. Then we describe our research approach followed by the preparation and first two phases of our study, the proof-of-concept pilot. The core of this article is a detailed description of how to turn the *Lego Grand Piano* into a fully functioning MIDI keyboard being able to use it in a musical concert. Finally, we reflect on the whole transformation process and discuss our learnings to answer our research questions. Moreover, there is a comprehensive documentation available as supplementary material for this article, which allows the reader to follow the rebuilding process step-by-step [15]. Thus, we explicitly invite researchers, designers, engineers, tinkerers and makers to get inspired by our approach, replicate and advance it for their own brick-based projects and interactive brick-built models.

II. LITERATURE REVIEW

A. BRICKS FOR DESIGN PURPOSES

Lego bricks are used for design and creative thinking simply as a tool [13] or as part of the company's self-developed approach *Lego Serious Play* [20] where studies have shown positive effects on flow experience [32] and solving real-world challenges [18]. Other scholars identified the brick's power to aid non-designers in sketching and for generating more original ideas [45] or to use *Lego Serious Play* beneficially for teaching software engineering in a playful and active way [46].

In a study by Tseng and Kawahara [34], Lego bricks are used for urban planning as a physical 3D tool to engage "low-tech users in designing high-tech solutions such as AR systems" [34, p. 251]. Similarly, bricks were used for urban planning and augmented with projections to provide more interactive and dynamic models [14]. *Lego Projected Play* [3] used visually augmented bricks as well to serve as a tool for tangible 3D tabletops in a study about design spaces and design processes.

Besides visual augmentation, Lego bricks were also physically combined with other material for design and learning purposes: K-12 students used tape and hot glue to connect electronic wires to attach electronics to Lego among other physical materials without soldering, which was "deemed unsafe for young children" [36, p. 2]. In another study, researchers combined Lego with *Makey Makey*[2] and other materials to let children build musical instruments and to study open-ended and constructive play [30].

Turning images or 3D objects into brick models has also been subject to research. Park et al. [1] developed a "reinforcement learning-based framework for generating a 2D Lego-compatible puzzle from a pixel art image." In a similar

[1] An homage to the traditional French piano manufacturer Pleyel.

[2] https://makeymakey.com (Accessed: Apr. 2, 2024)

direction but to create actual Lego models, Lee et al. [4] developed a genetic algorithm to convert 3D objects into Lego brick-built models.

B. ELECTRIFIED AND INTERACTIVE BRICKS

Reviewing the liaison of analogue bricks and digital technology starts immediately with three official Lego themes: *Technic*, *Mindstorms,* and *Boost* [19]. These official themes and kits include interactive bricks as motors, cables, lights, sensors and embedded systems to build vehicles, robots or other multifunctional models. Some of these themes and their elements are novel, others exist since decades.

Research has also a tradition on interactive bricks. In the 1990s the first generation of *Lego Mindstorms* was used to teach engineering from kindergarten to graduate school [12]. Other scholars successfully used *Lego Mindstorms* to teach undergraduate engineering students [37], found ''Lego robotics'' to be a useful problem-solving tool in the classroom [7] or developed an obstacle avoiding robot [17].

Some researcher used Lego bricks for a bendable handheld controller to let children animate a flying drone swarm and learn to interact with programmable matter [44]. Others did not only use Lego products but merged *Lego Mindstorms* and *Arduino* to take advantage of both platforms and to circumvent the high prices of Lego components to comparably cheaper ones for *Arduino* [26]. Another example is *BRIX*, which are hollowed out and modified bricks to put electronics inside [39] or the more recent *BRIX2* that uses 3D-printed cases instead of original Lego bricks [38].

C. BRICK-BASED MUSIC AND MUSICAL INSTRUMENTS

In recent years, several brick-based approaches in relation to music were studied for interdisciplinary teaching with a focus on children. Baratè et al. [2] studied a new concept to teach computational thinking when mixing musical notation and computer programming facilitated with Lego bricks in a web application. Jakobsen et al. [6] developed a platform called *Hitmachine* where children build their own musical instruments with bricks and *Lego Mindstorms* sensors and perform with them on stage. Oestermeier et al. [28] used bricks as physical representations for musical notes in a musical composition learning environment. Finally, Smarkusky and Toman [35] studied *Lego Mindstorms* among other technologies in a themed learning environment focusing on music and technology.

In terms of actual Lego musical instruments, there are lots of different models found on the internet designed or created by fans or professionals. These instruments range from less to more elaborated ones and from sole display models to fully playable instruments made partly of completely out of bricks [9], [27]. One approach needs to be mentioned, as it also makes the *Lego Grand Piano* musically playable using sensors mounted on the bricks with special 3D-printed parts [8]. This approach, however, seems quite complex, is not meant to be replicated and the resulting functioning piano was not used in practice to our knowledge.

D. FROM AUGMENTED TO TOY PIANOS

Real pianos have been augmented physically with sensors in different ways. The *Magnetic Resonator Piano* is a portable and reversible approach for grand pianos to electronically control the strings using magnets [24]. In a more recent version, the author presents a ''portable optical measurement system for capturing continuous key motion on any piano [..] to provide MIDI from a conventional acoustic instrument'' [25, p. 152]. Other researchers approached piano augmentation using motion tracking [5], microphones and speaker placement [10], an optical sensor mounted in the piano pedal bearing block for pedalling gesture measurement [23] or augmented reality interfaces [11], [33].

Finally, we consider it relevant in relation to Lego to mention toy pianos. These pianos are small of size, musically playable and although primarily targeting children, there are ''dedicated musicians specialising in toy piano performance all over the world'' [29, p. 27].

III. RESEARCH APPROACH

For our goal to transform a Lego brick-built model of a piano into a fully functioning musical instrument, we combined electronic engineering and design methods as well as performing arts for evaluation. Answering the first research question to check whether we can achieve our goal, relied primarily on electronic engineering. This involved basic tinkering, using electronic components and microcontroller technology.

To learn from this transformation process and answering the second research question on functionality, fabrication techniques and electronic engineering of interactive brick-based models, we followed a Research through Design (RtD) approach. Concretely, we created and reflected on a step-by-step documentation of rebuilding and augmenting the brick-built model using engineering methods and physical computing. For answering the third research question and assessing the practical applicability of our prototype, we used *The Playel*, our fully functioning brick-built piano model in two concerts including rehearsing to reflect on its musical and practical applicability.

The whole study was conducted solely by the author of this article who is a computer scientist, engineer and musician. The autobiographical approach to reflect on the subjective performance experience has its methodological limitations [41]. Nevertheless, using an early prototype immediately and straightforward in a concert offered valuable first insights into the practical applicability and complemented the primarily data-driven reflection on the step-by-step documentation of the transformation process. Also, this study is a proof-of-concept for turning a brick-built model into a functioning musical instrument without claiming generalisation for other models.

IV. PREPARATION

The preparation comprises the first two phases of our study: First, to build the original model of the *Lego Grand Piano* and second, to develop and test an early proof-of-concept pilot.

A. DESIGN RATIONALE

The rationale to guide our design process follows the original idea of Lego bricks that everybody can build and rebuild brick models with their own parts, skills and imagination. Thus, our final prototype should use as many standard components as possible and as little extra parts as possible (e.g., Lego bricks, electronic components) to keep costs and effort low.

The original appearance of the model and its single parts should ideally not be modified or machined. This means not destroying bricks and keeping the original aesthetics as much as possible. The intention of this design rationale was also allowing the replication of our proposed interactive brick solution by others as simply and effectively as possible.

B. BUILDING THE MODEL AND INITIAL IDEAS

Before the actual transformation process, we had to construct the original *Lego Grand Piano* model, which is made of 3662 individual bricks [22] and features 25 keys, a working hammer mechanism and a working sustain pedal to raise 25 dampers. The original idea behind the model was by the fan designer Donny Chen and was turned into an official Lego product by the Woon Tze Chee and Steen Sig Anderson [21]. Some first ideas to electrify the model and to make it musically playable arose during the construction process of the brick model already: Where to guide wires along and inside bricks; how to ground the keyboard and the keys; and which parts inside the model can be removed (e.g., the self-playing mechanism) to make space for other electronic components.

In a second step, the model was taken to a one-day music hack-a-thon for further elaborating the initial ideas on how to design the interactive parts of the model. The hack-a-thon also culminated in a planned but rather unrehearsed public performance in the evening to demonstrate all finished and playable music hacks. This was a welcome chance to play and test the electrified *Lego Grand Piano* for the first time. The performance lasted around 30 minutes, was streamed online and is available as a live recorded video [42].

The material and time constraints of the hack-a-thon only allowed an early proof-of-concept pilot using the available material and electronic components. We only had an *Arduino Duemilanove*,[3] one kind of wire and aluminium foil available. The *Arduino Duemilanove* has 14 digital input/output (I/O) pins, thus from the beginning we knew that this *Arduino* model was not good enough to sense the input of 25 keys and the pedal.

For wiring the keys, the only available wire was a bit too thick for laying it easily through the inside of bricks and for using the interlocking mechanism of bricks to fix stripped wires firmly enough. The wires did not properly fit inside the bricks and spread them slightly apart, which caused adjacent keys to block occasionally while pressed.

The aluminium foil worked well during construction for using it as a ground to electrify the keys. But during the concert the aluminium foil turned out to be not tearproof enough. The repeating friction of pressing keys scratched and ripped the thin foil that served as the ground which caused dropouts when the electronic circuits did not close.

Nevertheless, at the end of the hack-a-thon, one octave (12 keys) was electrified using the available material and we performed in a concert with our early prototype. Most important, we knew about the necessary improvements in terms of additional components and material.

[3] https://docs.arduino.cc/retired/boards/arduino-duemilanove (Accessed: Apr. 2, 2024)

TABLE 1. Additional electronic components required.

#	Description	Specifications	Fig.
1	Copper tape	2.5 cm width x 50 cm length	2
38	Jumper wires (connected)	20 cm long each (terminated as male to female pins)	2
1	Wire (hooked up stranded)	625 cm long (25 cm x 25 keys), max. outer diameter 0.8 mm², cross section 0.05 mm²	3a
34	Header pins	25 for keys, 9 to turn female to male for breadboard wiring	3b
1	Small breadboard	3,5 cm height x 4,7 cm width	7a
1	Arduino Mega	including a USB cable of 1 m length	7a
2	Resistors	220 ohms	7a
1	MIDI connector	including a MIDI cable of 1 m length	7a

C. ADDITIONAL COMPONENTS

Following our early proof-of-concept pilot experience, we compiled a list of additional components we needed for the final prototype. Note, we did not know the exact list of all required additional components before the end of the transformation process. But for a better understanding of the subsequent rebuilding and electronic engineering process description, we already present the complete list here in Table 1, which lists all additional electronic components required. We consider the number and specifications of consumables (e.g., jumper wires, header pins) as a minimum recommendation.

The only mandatory additional *Lego Technic* parts needed were 25 *Technic pins 1/2* to fix the wires on each of the 25 keys (see the blue *Lego Technic pins 1/2* in Fig. 3b and Fig. 4a). Two *Technic bricks* with 1 × 16 studs (i.e., 15 holes) or other lengths and combinations of shorter and longer *Technic* bricks are recommended for cable routing, but not required (see the white *Technic bricks* at the bottom of

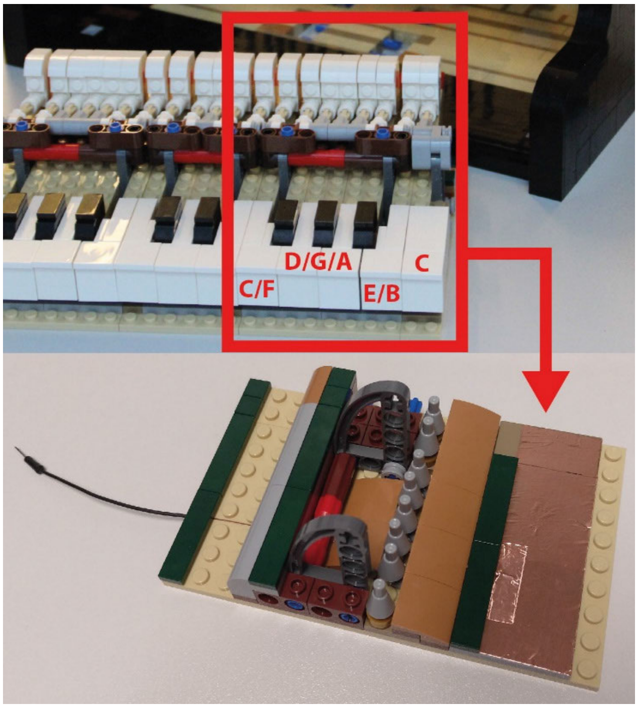


FIGURE 2. The whole keyboard block disassembled from the piano and one of the four keyboard blocks without keys, hammers and mounts but with copper tape and a jumper wire for the ground.

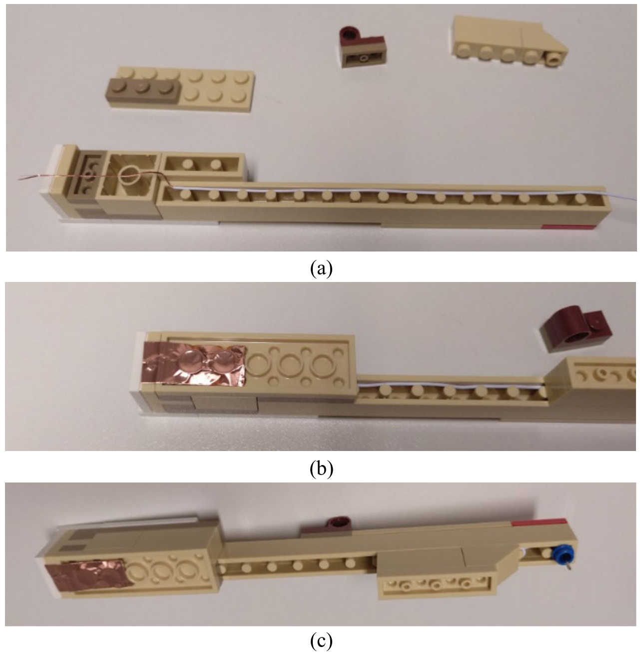


FIGURE 3. (a) A single key with disassembled parts to lay a partly stripped wire inside the brick. (b) The nearly reassembled key with copper tape to fix the stripped wire. (c) The header pin on the right fixed with a blue *Lego Technic pin 1/2* inside the brick.

Fig. 5b). For these additional Lego parts, the colours do not matter as all parts are hidden inside the model in the end.

V. REBUILDING AND ELECTRONIC ENGINEERING

In this section, we describe all necessary steps to rebuild and electrify the *Lego Grand Piano* for turning it into a MIDI keyboard. Although this article covers all steps, there is an even more detailed step-by-step building instructions available as supplementary material online [15].

A. GROUNDING THE KEYBOARD BLOCK

In the first step, we prepare the mounting of the keyboard block to serve as a ground for all keys, which are electrified afterwards. We remove the whole keyboard block from the piano (see the original Lego instructions [21, p. 546]). The keyboard block can be separated into four blocks to handle each of them separately which makes it easier when electrifying all 25 keys (see Fig. 2).

After disassembling the hammers including their mounts and all keys from a keyboard block, we apply self-adhesive copper tape on the *Lego tiles* and fix the stripped end of the jumper wire with a smaller piece of copper tape on top (see Fig. 2). Then we reassemble only the mounts of the keys again to fix the loose stripped wire underneath the bricks (see Fig. 2).

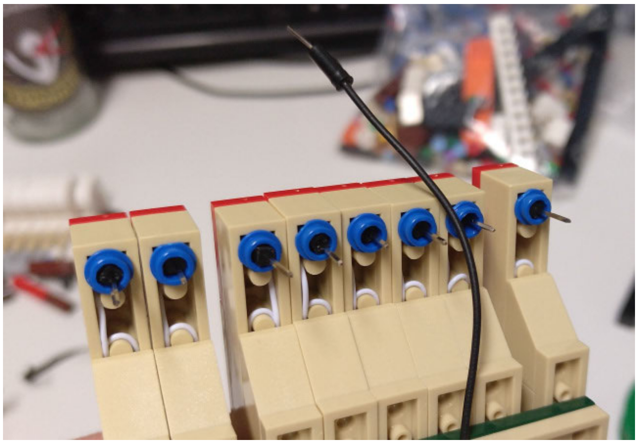
B. WIRING THE KEYS

There are five types of keys in two colours throughout the two octaves: One type of black keys and four types of white keys (C/F, D/G/A, E/B and rightmost C) as shown in Fig. 2. The wiring of the keys is similar for all types. We use the *rightmost C* to explain the wiring in detail and describe the differences to the other key types afterwards.

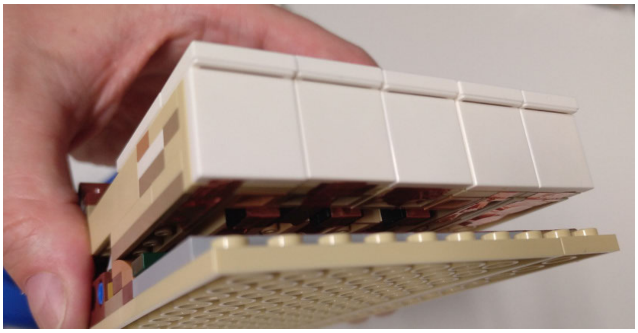
To wire a key, we need to remove some small parts on its top and bottom side. Then we place a wire about 25 cm long with 10 cm stripped along the bottom of the key with the insulated part inside the long brick (see Fig. 3a). We reassemble the *Lego plates* on the front to fix most of the stripped part of the wire. Then we fix the small overhanging piece of the wire with copper tape (see Fig. 3b).

On the other side of the wire, we remove 1-2 cm of the insulation, wind this stripped end around a header pin and use a *Lego Technic pin 1/2* to cover and fix the wired part of the header pin (see Fig. 3c). To finish the wiring of a key, put the *Lego Technic pin 1/2* inside the last space of the brick's inside and reassemble the bricks at this end of the key again to fix the insulated wire inside the brick. Ensure that the unwired side of the header pin sticks out as in Fig. 3c and that the *Lego Technic pin 1/2* sits firmly inside the brick's bottom. Optionally, we could solder the wire on the header pin to fix it firmly, but it still works well without soldering.

The wiring of all other white keys works similar, but with some variations as they are constructed differently on their front side having less space to lay and apply the stripped wire inside the bricks. Thus, the wiring of the stripped part and applying the copper tape must be done particularly careful to avoid overhanging parts which can create short circuits with adjacent keys. For the black keys, we also remove some parts

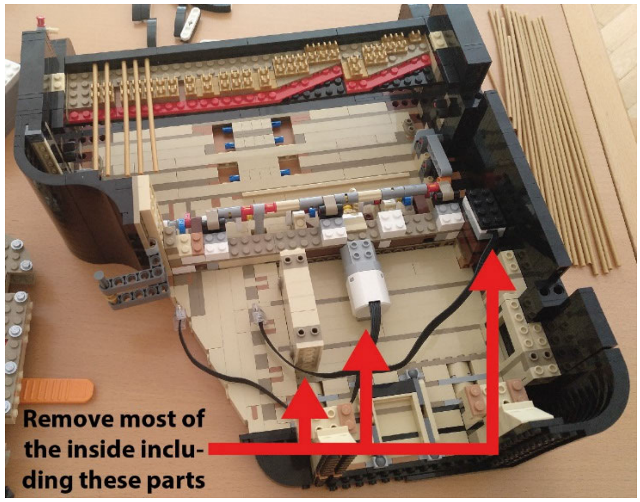


(a)



(b)

FIGURE 4. (a) One of the four keyboard blocks with header pins mounted inside the brick using blue *Lego Technic pins 1/2* and the black ground jumper wire. (b) Barely visible copper tape at the bottom of each key's front.



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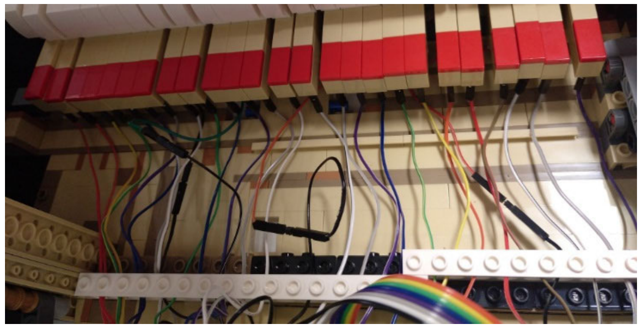


(b)

FIGURE 5. (a) The nearly emptied interior of the piano. (b) The reassembled keyboard with 29 jumper wires connected to the key's header pin.

from the front of the key to fix the stripped wire between the *black tile* 1 × 1 and the *black curved slope* 2 × 1 on the front.

C. REASSEMBLING OF THE KEYBOARD BLOCK

When the wiring of all 25 keys is finished, we put each key one by one back on the respective keyboard block. On the back of each keyboard block, you should only see the loose ground jumper wire and the fixed visible header pins (see Fig. 4a). On the front you should barely see the copper tape on each key's bottom side and the keyboard block's plate (see Fig. 4b). Finally, we reassemble the four separated keyboard blocks.

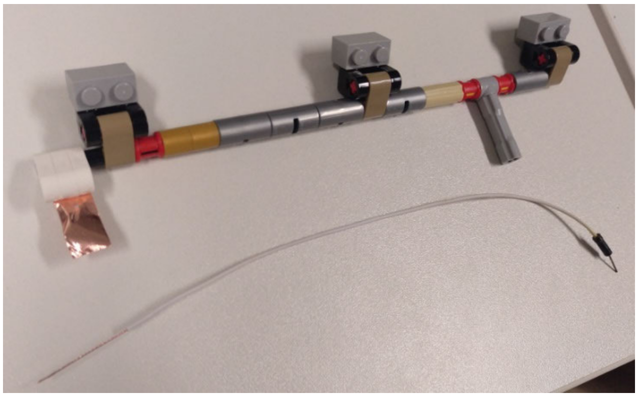
D. MODEL REBUILDING AND KEYBOARD WIRING

For wiring the whole keyboard, we disassemble most of the interior of the piano model. We only leave the pedal bar, but completely remove the existing electronic components and the self-play mechanism (see Fig. 5a and the steps 78-118 of the original Lego instructions [21, pp. 68-89]).

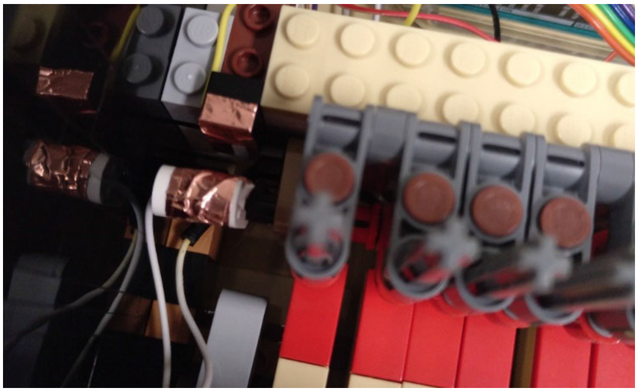
We apply any kind of our own spare *Lego Technic bricks* of variable length on the same level where the self-play mechanism was earlier to better guide the 29 jumper wires for connecting the 25 keys and 4 grounds. Then we take 29 jumper wires, lay them through the *Lego Technic brick's* holes, connect 25 of them to the header pins of the keys and 4 of them to the ground wires of the keyboard block. When all keys and grounds are wired, we sort and arrange the jumper wires straight but not too tight (see Fig. 5b).

E. WIRING THE PEDAL MECHANISM

For electrifying the pedal mechanism, we take out the pedal bar from the inside of the piano. We replace the *yellow axle* on the pedal bar's left with a slightly longer *black axle* to fix three white *Technic beams* 1 × 2 (all taken from spare parts removed earlier). Then we take a jumper wire slightly longer than the pedal bar and strip the end. We add a piece of copper tape to the previously extended end of the pedal bar to fix the stripped part of the wire (see Fig. 6a) and reassemble the pedal bar to its original position. Finally, we use another stripped jumper wire and some of the remaining spare bricks removed earlier to build the ground for the pedal switch. There is no need to make an exact copy of the illustration in Fig. 6b but ensure that the height is similar, the stripped wire is firmly copper taped and that the coppered areas connect, when the piano pedal is pressed. Eventually, we use more spare bricks or remove bricks to adjust the height of the ground.

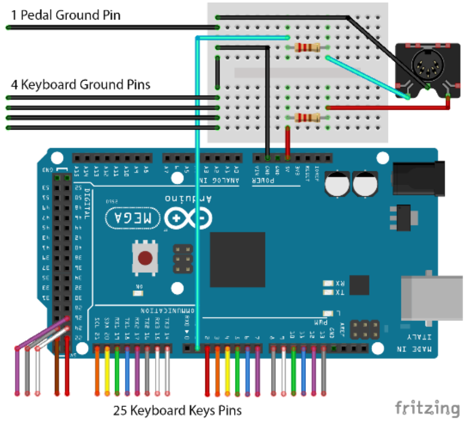


(a)

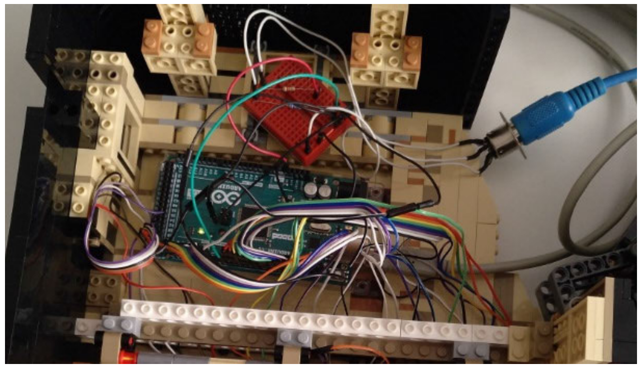


(b)

FIGURE 6. (a) The pedal bar taken out from the inside with additional bricks on the left and copper tape to fix the stripped wire. (b) The pedal bar reassembled again with the additional parts for the ground.



(a)



(b)

FIGURE 7. (a) The circuit diagram for connecting electronic components. (b) The inside of the piano with the additional electric components before reassembling the strings and lids of the brick model.

F. CONNECTING ARDUINO AND REASSEMBLE MODEL

In the last step, we take an *Arduino Mega* and the small breadboard to assemble all remaining electronic components listed in Tab. 1 according to the circuit diagram shown in Fig. 7a. We put two resistors on the breadboard, wire the MIDI connector and connect three jumper wires to the *Arduino* pins 5V, GND and TX (pin 1). Depending on the type of the MIDI connector, it might be necessary to solder the wires for the three pins of the MIDI connector. Similarly, all components can be soldered instead of using the small breadboard.

We put the *Arduino Mega* and the small breadboard in the emptied space of the piano and connect the 25 key jumper cables from right to left (starting from the *rightmost C*) to the input pins from 2 to 26. Then connect the 4 ground jumper cables from the keyboard and the one from the pedal according to Fig. 7a. Then we connect the *Arduino* to a computer, (eventually install and) use the *Arduino IDE* [43], download the provided open-source sketch [15] and upload it to the *Arduino*. For a first test, we connect the MIDI connector to a MIDI interface and check if (technically) everything works (see Fig. 7b). Finally, we can reassemble all remaining and previously removed parts of the piano (e.g., the strings, the lids).

VI. FINAL PROTOTYPE AND PERFORMANCE

The final prototype of this electrified *Lego Grand Piano* as shown in Fig. 8 is a fully MIDI-compliant keyboard with 25 polyphonically playable keys sending note on/off events and a sustain pedal on/off commands. The piano looks like the original model apart from the USB and MIDI cables coming from the inside of the piano (see Fig. 8). We named our musically playable *Lego Grand Piano* "*The Playel*" as a reference and homage to the French piano manufacturer Pleyel [31].

The fourth and last phase of our study was a public open-air concert on the campus of the University of Vienna. The concert was part of a science communication event and not primarily intended to showcase *The Playel*. In fact, the performance could have been played with any other keyboard. However, this science communication event was a good occasion to test the practical and musical applicability of our prototype somehow safely in an actual performance. See Fig. 1 at the beginning of this article with a photograph of *The Playel* as it was played during this concert.

The preparation and rehearsing of the piece to be played with *The Playel* happened frictionless under the same circumstances and with the same musician (a drummer) as the other pieces for this concert. The final performance with

FIGURE 8. The fully functioning Lego Grand Piano, called The Playel, which looks like the original model apart from the USB and MIDI cables coming from the inside of the piano.

The Playel had a duration of 4'15''. A live video recording of this performance is available online [16].

During the performance itself, we had only one brick-related connectivity problem which we did not experience earlier during rehearsing. Two times during the concert the conductivity was not given when a key was first pressed too weakly (see 0'35'' and 4'03'' in the performance video [16]). After immediately repressing the key more firmly, the clips of the connected bricks got loose. This problem concerns only D/G/A key types (see Fig. 2) which have a specific construction technique using clips to connect bricks on the front side of the key (see step 404 of the original Lego instructions [21, p. 300]). When these D/G/A key types are (accidentally) pressed too far on the front edge, the clips are not strong enough and get easily loose. During the performance, this mechanical issue could be easily fixed while playing but caused an unwanted musical effect due to a short audible delay.

VII. REFLECTION AND DISCUSSION

A. THE ROLE OF THE EARLY PROOF-OF-CONCEPT

The initial construction of the original *Lego Grand Piano* was obviously necessary to have a model ready to work with. However, to simply construct the complex model following the instructions step-by-step was insofar relevant to the transformation process from the beginning, that it gave important insights and helped to understand the already available functions of the model (e.g., the hammer mechanism), how they work and how they might be combined with electronic components.

The first ideas on how to use the *Lego base plates* for grounds (Fig. 2) and how to guide the wires through bricks (Fig. 3a-c) arose during the initial construction of the model. These first design ideas were then elaborated with the early proof-of-concept pilot at a hack-a-thon, which turned out to be indeed important. During this phase, we could empirically exclude unsuited material such as the fragile and non-tearproof aluminium foil which caused connectivity problems, too thick wires which did not properly fit inside the bricks and the *Arduino Duemilanove* with not enough I/O pins for 25 keys and the pedal. Only through this early prototype experience, we knew that we need an *Arduino Mega*, which has 54 I/O pins,[4] a wire with a maximum cross section of 0.05 mm^2 and self-adhesive copper tape instead of aluminium foil. Thus, the principal strategy for the transformation and most of the necessary components for the final prototype were clear after the empirical trials with the early proof-of-concept pilot.

B. ENGINEERING AND FABRICATION TECHNIQUES

We could limit our solution to three fabrication techniques for combining bricks with electronic components: the interlocking mechanism of the model's existing bricks to fix wires (Fig. 3); self-adhesive copper tape (Fig. 2, 3 and 6); and a few additional Lego parts (Fig. 5b). To guide wires through the inside of bricks (Fig. 3a) and to fix wires between two bricks (Fig. 3b), a thin wire with both a small cross section and outer diameter is crucial to not spread apart bricks.

From our experience, the interlocking mechanism of bricks is strong enough to fix wires. This aligns with the findings of the creators of the *BRIX* [39] who preferred the "optimized friction type" of Lego bricks over "3D-printing or CNC milling"[5] [39, p. 819]. The main problem with the aluminium foil for our proof-of-concept pilot was the fragility and not being tearproof. We did not encounter similar problems with the copper tape. However, we do not have long-term experience so far. Overall, we could limit fabrication techniques to basic tinkering. Even one step, where components could be soldered is optional and can be avoided (Fig. 3b).

For the final prototype, we could consequently follow our design rationale and only used off-the-shelf components. We avoided physical brick modification and other special techniques that would have required computer-aided design (CAD) or 3D-printing such as the other known solution to make the Lego piano musically playable [8]; or it would have required higher engineering skills and effort as with *BRIX* [39]. Overall, we could keep the use of different technologies and the technical effort low. In fact, we even removed the original Lego sensor and the Bluetooth battery box from the model's inside because they had no

[4] https://store.arduino.cc/products/arduino-mega-2560-rev3 (Accessed: Apr. 2, 2024)

[5] CNC stands for Computerized Numerical Control.

use anymore. Using these electronic Lego elements in combination with an *Arduino* might be possible [26], but we would have needed more than one sensor for each of the 25 keys and the pedal anyway. The only real argument for using sensors for the keys would be an increased expressivity, which we will reflect on later from the musical perspective.

In general, the costs for turning a brick model into an interactive system by using our engineering and fabrication technique is relatively cheap as only basic electronic components are required. Although, in our case of the *Lego Grand Piano*, the costs are a two-edged sword. The original Lego product costs 350 Euro [22] which is considerable high. For the additional components needed, we estimate a lump sum of 100 Euro. Considering the total costs of 450 Euro to get a two-octave MIDI keyboard you even must build by yourself, is far from being cost-effective. You can get an off-the-shelf keyboard much cheaper. However, if you already have the brick model, our solution to make it musically playable still might be easier and cheaper than the only known alternative [8], which we assume to cost more due to complex electronic components and additional manufacturing techniques (e.g., 3D-printing, soldering).

C. THE FINAL PROTOTYPE

We were able to make use of the existing hammer and pedal mechanisms to turn the brick model piano into a fully MIDI-compliant interface with 25 keys and a pedal. In relation to appearance, we did not modify or destroy any bricks as already mentioned and kept the original model's exterior as much as possible apart from two cables (see Fig. 8). Thus, from an aesthetical point of view, we can consider our solution to turn a brick-based piano model into a musical instrument achieved in a (highly) unobtrusive way. There is not even any copper visible from the outside as with other rather simple Lego musical instruments [30, p. 156]. We could even avoid the two cables if wanted. There is still enough empty space inside the piano for using a battery to power the *Arduino Mega*. The MIDI cable can be replaced with a wireless solution, which has been demonstrated as a viable solution for musical interfaces [47].

Theoretically, our approach is also fully reversible, apart from cleanable adhesive residues and potential small scratches, which used bricks can have anyway. Thus, our solution to make the piano model interactive, keeps the original idea of brick models to be disassembled and to reuse these parts.

D. PRACTICAL APPLICABILITY

We tested the practical applicability of our interactive brick-built model by using it as a MIDI interface in two musical performances. From the experience of these performances, we can say that the practical applicability of *The Playel* to serve as a playful brick-built interface was principally given. In this regard, we mainly consider the performance with final prototype. The earlier performance with the proof-of-concept version was successful as well, albeit with some drawbacks on material issues with aluminium foil and wire thickness, which served the purpose to learn from as discussed already.

The main issue we encountered in both performances was brick-related fragility, which is somehow obvious when parts can get lose in a brick-built model. Being aware of that, handling the model carefully is a must – especially when it is moved around. However, during the actual performance, we did not experience instability issues in general apart from the one problem with loosening brick clips on the front side of the D/G/A key types. This mechanical weakness can be quickly fixed when it happens, even while playing, but it still disturbs playing the piano. Using a small piece of clear adhesive tape on the top of the key's front would easily solve this problem. To literally play safe and if full reversibility of the model is not necessary, gluing (some) bricks together would be a solution too for overcoming problems with the fragility of a brick-built model and potential weak spots.

E. MUSICAL CAPABILITIES

Related to the practical applicability is the musical dimension. *The Playel* offers 25 polyphonically playable keys and a sustain pedal which allows the typical embodied expressivity for a MIDI keyboard of this kind. We did not encounter general musical problems during the performance apart from the loosening brick clips of D/G/A key types. As just discussed, fixing the clips with glue or adhesive tape could help here to be also musically fail-safe. The keystroke to play the instrument is smooth-running for all keys with a slight but not disturbing rattling sound.

The musical expressivity is limited insofar as our rather simple non-sensor-based solution does not allow touch-sensitivity of keys. Apart from these musical drawbacks, we could rely on *The Playel's* capabilities to serve as a musical instrument with another added value: Immediately after the final performance, audience members came to the stage and expressed their interest in how this small brick piano works. This observation supports a statement on toy pianos and how they ''break the ice with audiences'' when used in musical performances [29, p. 27]. If *The Playel* can be ''entertaining yet also effective in teaching core musical concepts'' as the *Augmented Reality Piano* [11, p. 511], points to further potential studies using bricks for interactive devices in music and beyond to merge creative work approaches and engineering.

As an augmented piano with added MIDI capabilities, *The Playel* shares similarities with another approach to augment real pianos and to ''provide MIDI from a conventional acoustic instrument'' [25, p. 152]. We also provide a flexible and reversible solution, but apart from the different technical approach, the fundamental difference is that we augmented a non-musically playable and brick-built piano.

F. REPLICABILITY AND LIMITATIONS

We carefully documented the rebuilding and electronic engineering process to allow both, a data-driven reflection and potential replication of our approach by others. Still, we needed to take two additional and missing photographs afterwards when documenting the step-by-step transformation which underlines the importance of a detailed documentation for RtD in general as discussed by Bardzell et al. [40] and for DMIs in particular as raised by Calegario et al. [48]. In our case, five photographs were only taken once and from different angles, which required us to annotate the rotation explicitly for a better understanding. Reproducing these photographs afterwards would have meant to dis- and reassemble the whole model again with a considerable high effort. For our reflection on the process, all available photographs were good enough. But for the documentation to be best possibly replicable and reusable, more photographs would have been useful. A fixed time lapse camera focusing on and recording the work progress would be even better. However, to what extent our approach can be transferred to other brick-based instruments or other brick models in general, needs further investigation.

Similarly, we cannot draw conclusions on how someone else than the author may replicate this approach. The actual effort and required skills to electrify the *Lego Grand Piano* is hard to gauge. Building a complex brick model of this size usually takes a couple of hours depending on the experience of the builder. But brick building is a welcome leisure activity for many and pays off the hours-long effort at least for the model construction. Assembling the additional electronic components depends on the skills (and age) of the builder. In this regard, we were able to use only basic electronic components (e.g., jumper wires), off-the-shelf devices (e.g., *Arduino*) and tinkering techniques that do not even require soldering. Since Lego bricks are standardised and are used for all kinds of models within imagination, we consider our approach in principle to be flexible and transferable enough to electrify other models. Our approach also complements other research where conductive materials with Lego were used to study constructive play with children [30], [36] as we present a functioning electrified brick model. However, the full replicability of our approach by others than the author and its suitability for creating different interactive brick-based models needs to be further investigated.

VIII. CONCLUSION

We successfully transformed the *Lego Grand Piano* into a fully MIDI-compliant keyboard with 25 keys and a pedal for musical expression. Thus, we can positively answer our first research question whether if we are able to electrify the mechanically working but non-interactive hammer and pedal mechanisms for turning the *Lego Grand Piano* into a functioning musical instrument.

The second research question focused on learning from the transformation process. We can conclude that our solution is unobtrusive and keeps the original aesthetics of the original brick-built model. The approach is reversible using only off-the-shelf components and basic tinkering, which also keeps costs low. The fabrication techniques we propose are in principle flexible enough to turn any brick model into an interactive system without soldering, but instead use the brick's interlocking mechanism and self-adhesive copper tape.

The practical applicability of the electrified brick-built model as a musical instrument was the subject of the third research question. Two successful concerts without major problems showed the practical and musical applicability of *The Playel* which even attracted the audience in an entertaining way to take a proactive interest in the electrified brick model. Also, the inherent fragility of brick-built models where not a particular problem during our performances.

Finally, while the rebuilding and electronic engineering process in our present case study was successful, further studies are needed to assess the suitability and the required effort and skills of others to reuse and replicate our approach with the piano model or other brick models.

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