Barbed-Spring Locks of the Museum: The Integrated Applications of Research, Exhibition and Science Education

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***Abstract*—No matter in ancient China or other ancient civilizations, locks and keys have been used for thousands of years. With the progressive development of the society and the advance of technology, the function and the safety of locks are getting more and more complete. Since the development of mechanical locks has a long history all over the world, the interiors of locks cover different kinds of mechanical members. The barbed-spring lock was the most typical type of ancient lock and was widely used in ancient China. Certain changes in the topological structures are involved in padlock operation. Therefore, they are reconfigurable mechanisms and can be illustrated with variable chains. Based on the concept of variable chains with the representation of joints developed by the authors, the topological variability of padlock operation is analyzed and presented. Several feasible designs of the barbed-spring locks are made as physical models. Furthermore, the corresponding animation of the padlocks is also successfully designed, produced, and used for exhibition purpose at the National Science and Technology Museum since 2012. Through the process of science popularization, the maker activities related to the mechanical locks are developed to promote the education of science and technology. The teaching DIY kits and the cultural and creative products of locks are developed further. This work provides an example of how ancient machinery researches can be a dependable result for transforming basic research into novel applications in science and technology museums.**

***Keywords*—barbed-spring lock, maker, exhibition, science education, mechanism design**

I. Introduction

Locks have been widely used in our daily life for thousands of years. The development of locks arises due to people's psychological needs for safety. With the progressive development of the society and the technology, the function of locks is getting complete. Not only is the design of locks greatly improved, but the manufacturing of locks is also more precise. Furthermore, the usage of locks has been extended from doors, chests, and boxes to desks, safes, vehicles, etc. [1]. In recent decades, the studies regarding ancient Chinese locks have started to appear. Needham presented the historical development of Chinese and Western locks, discussed their reciprocal affections, and described the characteristics of ancient locks [2]. Yan started to collect and study ancient locks since 1990 [1] and presented a procedure to design ancient Chinese barbed-spring locks [3–5]. Shi *et al.* [6] analyzed three existing ancient Chinese maze locks and provided the features of the structures of maze locks. Hsiao investigated the open-keyhole and hidden-keyhole puzzle locks and provided a procedure to describe their mechanism structures [7, 8]. Hsiao *et al.* [9–11] investigated ancient Chinese puzzle locks and discussed their topological structures. Shi et al. studied the existing ancient Chinese wooden locks and provided a procedure to analyze them [12].

According to the unearthed objects and the related documents, there were two major types of locks in ancient China: fixed and portable locks [1]. The fixed locks were always made of wood and assembled on the door. The barbed-spring lock was the most typical type of portable lock in ancient China and can be dated back to 200 BC. In addition to the cultural relics that can be found in China, barbed-spring locks have been used in India and Europe more than 2,000 years ago, and the appearance, type, and function of locks in various regions are very similar. The locks started to be used massively around the 2nd century. After the 9th century, the craftsmanship of lock manufacturing was already quite advanced, and the types, shapes, and carvings were increasingly numerous. It was no later than the 16th century that locks which needed specific processes to open were widely manufactured and used. These kinds of locks can be named as puzzle locks. They are difficult to open within a short period of time even if the correct keys are in place.

However, when people are used to the convenience and security of using locks, the historical development of locks, the relationship among society, culture and locks, in addition to the science principle and the artistic values of locks are usually ignored. Therefore, this work focuses on the study of the ancient Chinese barbed-spring locks and the applications in museum. First, the brief historical development and the structural analysis of locks are discussed. Then, the lock exhibition and the maker activities related to locks in museum are described. Finally, the science education programs and the cultural and creative products of locks are presented.

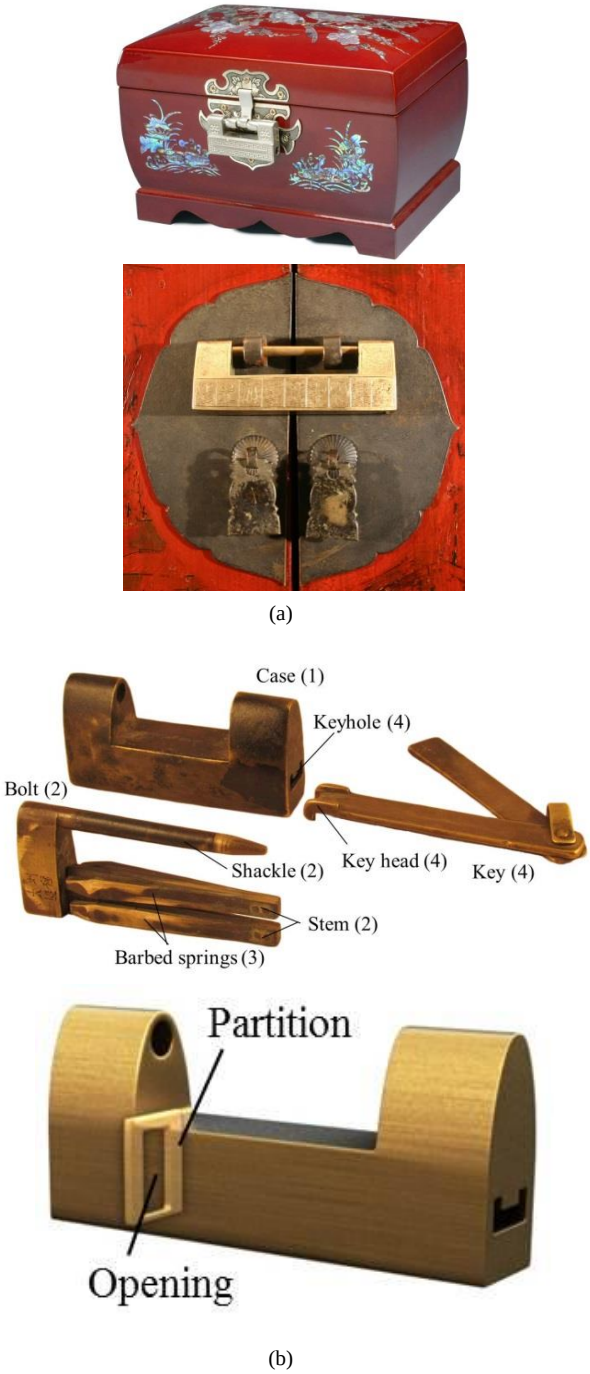
II. Mechanism Structure of Barbed-Spring Lock

In general, a barbed-spring lock has a long shackle used for penetrating and fixing the two rings on a door or a box to prevent the door or box from being opened, as shown in Fig. 1(a). The barbed-spring lock that can be opened with a key, can be further divided into two kinds: open-keyhole lock and hidden-keyhole puzzle lock, depending on the visible features of the keyhole(s). Fig. 1(b) shows a simple open-keyhole lock, which consists of four members: case, bolt, barbed springs, and key. In this case, there is a keyhole for inserting the key to enable the action of the bolt. Since there is no relative motion between the bolt, the shackle, and

the stem, they can be considered as one member. The barbed springs are connected to the stem on one end, and make contact with the partition of the case on the other, to complete the locking function by preventing the partition from being removed from the case. The four pieces of barbed springs of equal lengh can be considered as one member. The key head is designed according to the position and shape of the keyhole, and also the configuration of the barbed springs. The lock can be opened by inserting the key. When the key head presses the springs and forces them to be separated from the partition, the bolt can then be slided out of the case to free the shackle and open the lock.

The topological structure of a mechanism is defined by its types and numbers of links and joints, and the incidences between them [13, 14]. A mechanism that meets certain changes in its topological structure during operation is called a reconfigurable mechanism [15]. Since barbed-spring locks have different topological structures in the opening process, they are deemed reconfigurable mechanisms. A mechanism consists of different types of members and joints that can be presented as the form of variable chains with only generalized links and joints [16]. A generalized link is a link with generalized joints; it can be a single link, binary link, ternary link, etc., as shown in Fig. 2. A generalized joint is a joint that can be a revolute joint, prismatic joint, or others. Through apointing specific types of members and joints in the generalized chains, the variation process of barbed-spring locks can be described. The form of variable chains is a useful tool to present the topological structure of barbed-spring locks in each opening step. The rectangular coordinate system is used to illustrate the opening process. In the case, a maze lock is provided as an example. In general, the positive x-axis can be set as the direction of sliding out the bolt, the y-axis is perpendicular to the horizontal plane, and the z-axis is based on the right-hand rule.

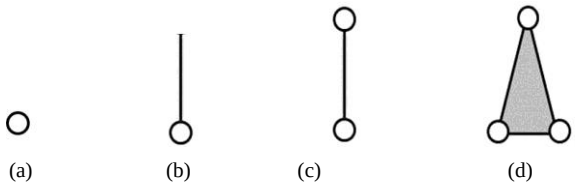
In order to open a maze lock, the key head must be held in an clumsy position, and then inserted in a unexpected path. Figuring out how to insert the key head is like steering through the maze, so we call it “maze” lock. Figure 3 shows a maze lock with four members including the case, the bolt, the barbed springs, and the key. There are three steps to open the lock, incluing inserting the key into the keyhole, pressing the barbed springs, and sliding the bolt. In the first step, the barbed springs and the bolt are temporarily immovable. The key head is placed horizontally over the keyhole and rotated about the negative z-axis with respect to the case. The key head is connected to the keyhole with a revolute joint R-z. Then, the relative motion between the key head and the keyhole is rotated about the negative y-axis and translated along the negative z and the positive x axes, denoted as R-y P-z P+x. Finally, the key head is translated along the positive z and x axes with respect to the case, denoted as a prismatic joint P+z P+x, as shown in Fig. 3(b). And, the corresponding simulation is shown in Fig. 4(a). In the second step, the key is connected to both the case and the barbed springs with prismatic joints P+x. The barbed springs are connected to the bolt and the case with a spring joint SRy and a prismatic joint Pz, respectively. The bolt is connected to the case with a fixed joint X, as shown in Fig. 3(c). And, the corresponding simulation is shown in Fig. 4(b). In the last step, the squeezed barbed springs are separated from the partition of the case, and the bolt is moved by pushing the key. The bolt, the barbed springs, and the key have no relative motion and can be considered as the same member. It is connected to the case with a prismatic joint P+x, as shown in Fig. 3(d). And, the corresponding simulation is shown in Fig. 4(c).



(a)

(b)

Fig. 1. Barbed-spring locks.



(a) (b) (c) (d)

Fig. 2. Generalized links and joints: (a) joint; (b) single link; (c) binary link; (d) ternary link.

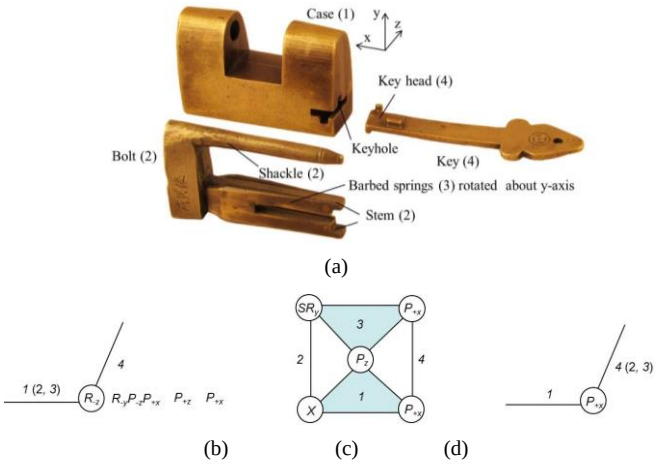


Fig. 3. A maze lock.

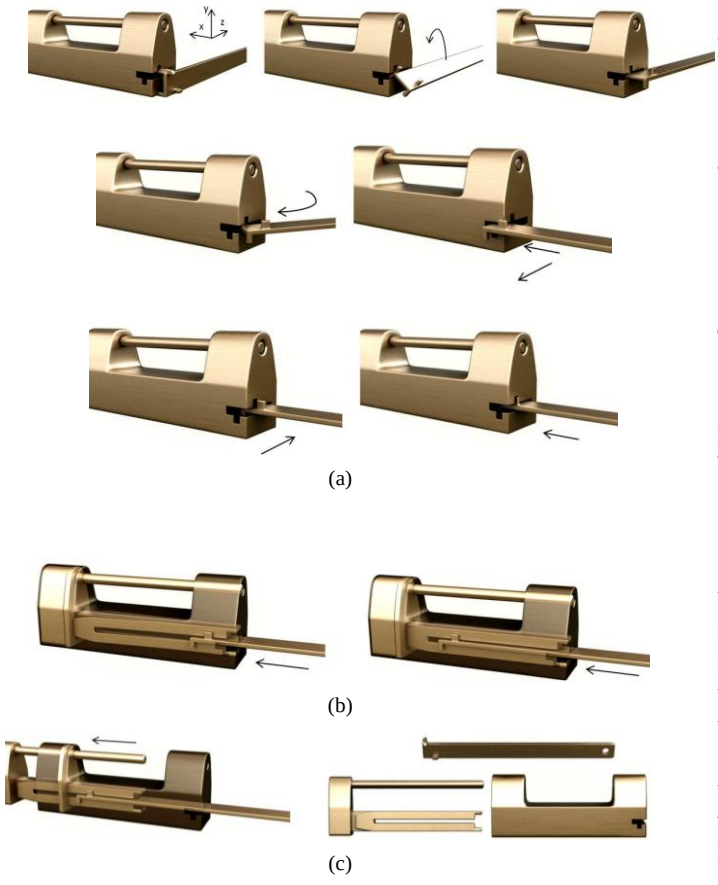


Fig. 4. Animation of maze lock: (a) Inserting the key head into the keyhole; (b) Pressing the barbed springs; (c) Sliding the bolt.

III. Application in Museum Exhibition

The museum has been defined by the International Council of Museums (ICOM) as "a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment" [17]. It's museum's mission to integrate the functions of collection, research, exhibition, and education to convey information about precious heritage of humanity to the public. The National Science and Technology Museum (NSTM), the largest national museum of applied science in Taiwan, has dedicated to the application of collection in all aspects of the museum functions. Ancient Chinese lock is one of the collection highlights in the museum, and barbed-spring locks account for a significant part. After basic study of the mechanical structure and the historical development of barbed-spring locks, the physical models and corresponding animations have been applied in exhibition and education in the museum.

The Lock Area is located in the "Power and Machines" Exhibition. This area introduces the history of locks, structures and types of ancient Chinese locks, ancient foreign locks and modern locks, in addition to the lock industry development in Taiwan. All of which are enriched with films, displays of objects and collections, in addition to interactives. Regarding the barbed-spring locks, as shown in Fig. 5(a), texts, images and figures are incorporated to present general information which enables visitors to gain insight into culture and stories. As shown in Fig. 5(b), abundant collections of different types of barbed-spring locks are also displayed to help visitors to appreciate the beauty of ancient locks and observe the differences from characteristics of appearance, such as key holes, surface carvings, keys, etc.

In order to enhance visitors' understanding of barbed-spring locks, corresponding animations and hands-on experience of operating a lock using a model are also arranged in the exhibition area. Since the topological structures of locks have different arrangements during operation, the approaches of opening locks vary accordingly. Thus, opening different types of barbed-spring locks can be as fun as solving puzzles.

Two kinds of physical models are made based on basic research regarding barbed-spring locks- enlarged basic-structured lock and true-sized sophisticated locks. The enlarged basic-structured model installed in the exhibition area, as shown in Fig. 6, is made of metal, similar to the original material of a barded-spring lock, to allow the visitors to experience the texture of a real ancient lock. The enlarged model consists of a case, a bolt, springs, and a key. The middle part of the case surface is replaced with clear acrylic to facilitate visitors' view of all the members and motions of them during operation.

For those visitors who are machine enthusiasts can refer to the animations and the sophisticated models. Some locks are very interesting in the opening processes. However, if the locks can only be seen from the display case, the ingenious designs and superlative workmanship of locks cannot be revealed. Two animations regarding the movement processes of inner mechanisms of "Hidden-keyhole puzzle lock" and "pull-back lock", are shown in the exhibition area. Hidden-keyhole puzzle locks have many variations, such as a front push button, a bottom push button, and an end push button. A puzzle lock with an end push button is presented in the animation as shown in Fig. 7. There are two buttons attached to the end plates, one at each end. One is fixed and the other is movable. The lock consists of seven members, including the case (1), the bolt (2), the end button with barbed spring 1 (3), barbed springs 2 (4), the end plate (5), the bottom plate (6), and the key (7). There are seven steps to open this lock, including pushing the end button, sliding the bolt a little bit, rotating the end plate, sliding the bottom plate, inserting the key, pressing the barbed springs, and sliding out

the bolt as shown in Fig. 8.

(a)

(b)

Fig. 5. Barbed-spring locks in the Lock Area: (a) Graphic panels of barbed-spring locks; (b) Display of barbed-spring locks.

(a)

(b)

Fig. 6. The enlarged basic-structured model of barbed-spring lock in the Lock Area: (a) The enlarged model with operational instruction; (b) Visitors can operate the model on their own.

For ordinary ancient Chinese locks, the key is pushed forwards to squeeze the springs and slide the bolt to open. However, opening the lock in Fig. 9 is to pull back the key to press the barbed springs to open. The key is a curved piece of thin metal with a rectangular hole, and it is used to pull the bolt out of the case instead of pushing it out. The keyhole is a small slit, hidden in plain sight. To open this kind of lock, one must insert the key into the keyhole under the bolt's end piece and push the key forward. A clicking sound indicates that the key hole has engaged with a pair of barbed springs. Then one pulls the key back to press the springs and release the bolt, which slides out along with the key as shown in Fig. 10.

The sophisticated models, which include "pull-back locks" and "maze locks", require detailed explanation and instruction regarding lock opening from a well-trained interpreter. So they are displayed in the Open Storage where is the first museum storage room open to the public in Taiwan and well-trained volunteers are ready to serve during opening hours of the museum. Visitors are allowed to operate these locks under the assistance and guidance of the volunteers, as shown in Fig. 11.

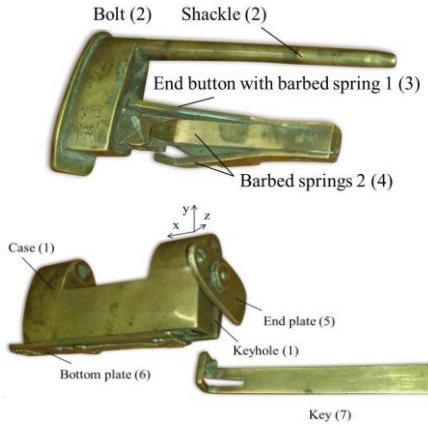
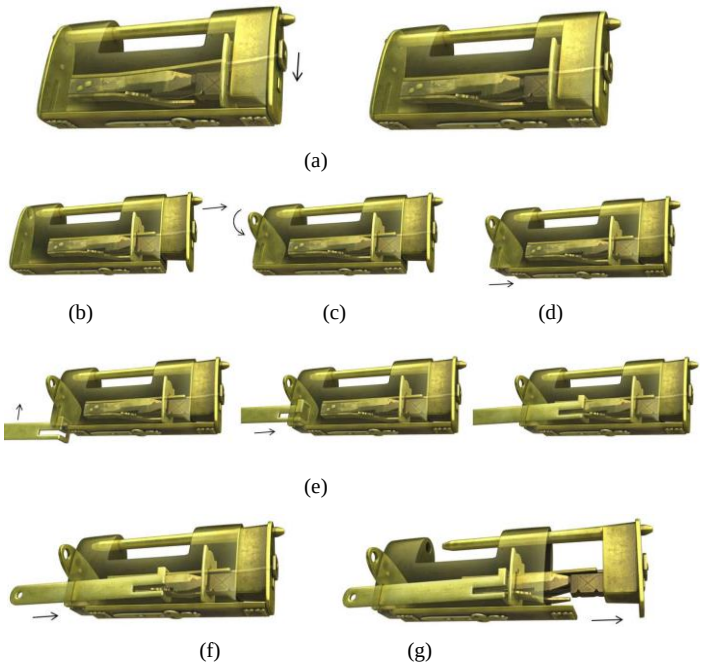


Fig. 7. Hidden-keyhole puzzle lock with an end push button.



(a)

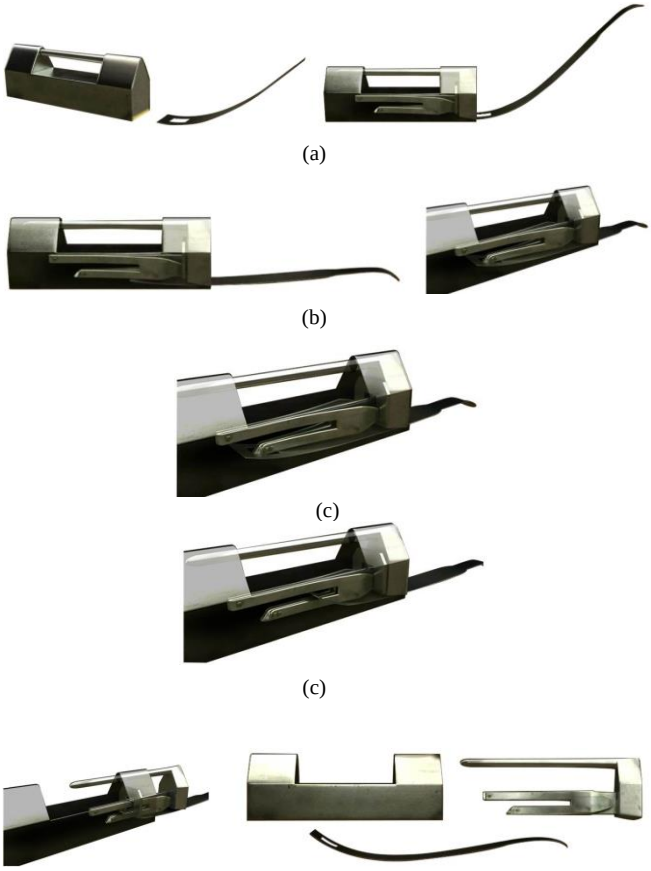
(b) (c) (d)

(e)

(f) (g)

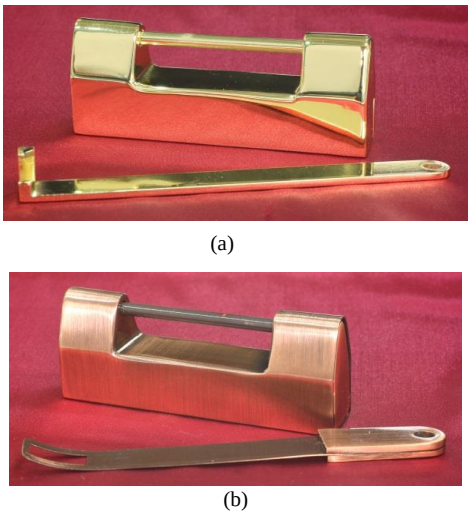
Fig. 8. Animation of hidden-keyhole puzzle lock: (a) Pushing the end button; (b) Sliding the bolt a little bit; (c) Rotating the end plate; (d) Sliding the bottom plate; (e) Inserting the key; (f) Pressing the barbed springs; (g) Sliding out the bolt.

Fig. 9. Pull-back lock.



(a) (b) (c) (c) (d) (d)

Fig. 10. Animation of pull-back lock: (a) Inserting the key into the keyhole; (b) Pushing the key forward; (c) A clicking sound, Pulling the key back and pressing the springs; (d) Sliding the bolt; (d) Opening the lcok



(a) (b)

(c)

Fig. 11. True-sized sophisticated models and the application in exhibition: (a) Model of maze lock; (b) Model of pull-back lock; (c) Visitors can operate the models under volunteer's instruction.

IV. Teaching Activities and Cultural and Creative Products

The combination of locks and keys is a brilliant invention in the historical development of human culture. This invention involves considerable knowledge of science and techniques. Especially for the barbed-spring locks and the corresponding keys, the mechanism design that determines the category, the opening way, and the opening procedure of locks is the core of the investigation. Simultaneously, it should be discussed if the standard of manufacturing techniques and the material characteristics are consistent with the contemporaneous level of workmanship. As described above, the barbed-spring locks has numerous types. The NSTM has gradually developed related educational activities and cultural and creative products based on the educational concept of the color palette model [18]. Also, the contents of locks and keys in teaching strategies are the same as the spirit of Science, Technology, Engineering, Art, and Mathematics (STEAM) [19]. In what follows, the teaching activities and the cultural and creative products about barbed-spring locks are introduced.

A. Teaching Activities for Barbed-Spring Locks

The spring design is a professional issue regarding the stress analysis of a flat plate considering material characteristics. However, such issue is unnecessary for general public education. As for popular science education, the teaching activities should be more inclined to focus on understanding the structure of the mechanical devices. Here, the NSTM has integrated with the Maker concept to present the design of educational activities for mechancials locks as follows:

1) Stage of introduction

It's a good way to begin the activity by asking the participants how many locks and keys they have used as a

reminder of the importance of locks and keys in daily life. Then the origin and the historical development of the locks and keys in both Western and Eastern cultures are introduced in this stage. The focus is the introduction of the ancient Chinese locks based on the exterior and observable characteristics, such as the shapes, the carving techniques, materials, keys and keyholes.

2) Stage of structural analysis

Exploring the lock's interior mechanism is the core of the structural analysis. The locking function of the ancient Chinese locks is activated by the motion of barbed springs. According to the mechanism design, the ancient Chinese locks are basically divided into combination locks and barbed-spring locks. The barbed-spring locks are further categorized according to the configurations of springs. The numbers, the positions, and the lengths of springs all affect the opening procedure. The barbed-spring locks must correspond to the design of the key. The shape of the key is related to the compression of the spring for unlocking.

3) Stage of visiting exhibition

The collection and exhibition are the features of the museum's educational activities. By observing and operating the objects or physical models of locks and keys, the students can be much more impressed. The NSTM has built the digital archives in the online museum for the purpose of e-learning. Browsing the digital archives which display the pictures and the animations of lock collections is an alternative way of visiting exhibition. This stage can be done by either way, field or virtual visiting.

4) Stage of experience and practice

Experience and practice are essential in the teaching activities by integrating the educational concept of Maker. The NSTM has reconstructed several physical models as teaching aids to allow the students to experience the unlocking mission. After the previous structural analysis stage, the students are arranged to operate the teaching aids of the pull-back lock, the maze lock, and the hidden-keyhole puzzle lock. The interesting experience can provide more substantial learning effects. In addition, the NSTM has developed some DIY lock kits for educational activities according to student's age and the ability of tool and machine operation. Figure 12 is the activity records of experiencing the teaching aids of mechanical locks and assembling an integrated lock of combination lock and wooden pin lock. During the assembly process, the students can investigate the structure and mechanical elements' design of a lock, like the interference fit, the elastic of materials for preloading. The assembly of the DIY kit is the beginning of manufacturing locks. Afterwards, by learning other manufacturing techniques such as 3D printing and laser machine, the students can further improve the locks.

Besides, the teaching activities are good experiments to evaluate the teaching design, including the knowledge content and and the experiential activies from the feedback of students. By applying the Generic Learning Outcome model (GLOs) [20], the NSTM researcher customizes a questionnaire using Likert scale questions to quantitatively analyze the students' learning results which are categorized into five categories. The statistic analysis can further improve the design of teaching content and the DIY kits.

(a)

(b)

Fig. 12. The records of lock teaching activities: (a) Experience of the teaching aid of mechanical locks; (b) Teaching activity of assembling an intergrated lock (DIY kit).

B. Cultural and Creative Products of Mechanical Locks

Based on the research results of locks, the NSTM has developed several cultural and creative products of mechanical locks. These products include DIY kits for teaching and exquisite locks for souvenirs or presents. The design of DIY lock kits for teaching is wholly related to the Maker educational activities. Also, the design of DIY kits follows mechanical engineering principles which the design of mechanical elements, the manufacturing process, the interference fit, and the assembly tolerance are all taken into consideration. Besides, the development of cultural and

creative products can be regarded as the extension of the museum's education and exhibition missions. Fig. 13 shows a cultural and creative product developed based on the research results of the hidden-keyhole puzzle lock with an end push button.

Fig. 13. Product of hidden-keyhole puzzle lock developed by the NSTM.

V. Conclusion

The barbed-spring lock was widely used after the 2nd century in ancient China. It was the most representative type of lock and had been used for more than two thousand years. Based on the basic research results of locks, the historical development and the mechanism structure of the barbed-spring locks are comprehended in the first place. Then, the animations of locks that can show the movement processes of inner mechanisms are made. Besides, the interactive lock exhibition area is organized and the science education activities of locks are also planned and held. And, according to the results of the structural analyses, the models of the locks for visitors' hands-on experience and cultural and creative products for sale are made or developed. The lock exhibition and the series science education courses of locks allow more and more people to get access to the insights of locks that are closely related to daily life. As a result, this work presents a solid example of how academic studies can be a reliable source for transforming basic research into innovative applications in science museums.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jian-Liang Lin, Hsin-Te Wang and Kuo-Hung Hsiao analyezd the research of lock structure, the development of locks' teaching models, and the practice of locks. Ching-Ching Pu contributed to the guide of locks exhibitions and the polish of the paper. Chin-Fei Huang developed the teaching plans focusing on the locks. All authors had approved the final version.

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