Bioanalogous Mechanical Joints for Authorized Disassembly

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Abstract
This paper describes bioanalogous, or biomimetic, lock-and-key mechanical joints that enable disassembly that is easy but only by those authorized. The problem is motivated by the increasing need for economical disassembly of products by original equipment manufacturers (OEMs) while protecting high-value components from theft and third-party recyclers. The joints must be easy to disengage with the 'key' but difficult to disengage without it. They also must be easy to manufacture, assemble and provide sufficient stiffness. An analogous biological phenomenon involving enzyme-substrate interaction was used to inspire the development of a heat-reversible snap-locator joint system.

Keywords:
Disassembly, Joining, Biologically inspired design

1 INTRODUCTION

Recent legislative and social pressures have driven product manufacturers to reduce the amount of material that enter the waste stream at product retirement. For example, in the European Union, the WEEE (Waste Electrical and Electronic Equipment) directive mandates minimum reuse/recycle proportions of retired consumer electrical appliances for their manufacturers. Therefore, products are designed with increased emphasis on effective reuse and recycling at the end of product life. Since both part reuse and material recycling require the disassembly of products, Design for Disassembly (DFD) has become a key design strategy for product manufacturers.

Despite the possibility of incurring additional costs during design and manufacturing, pursuing the ease of product disassembly can benefit manufacturers by reducing disassembly cost and thus increasing the net profit from reuse and recycling. To sustain reuse/recycle infrastructures, it is crucial that OEMs can retrieve easily parts with high reuse/recycle values. Such high-valued parts, however, would also attract third-party entities, authorized or not, to start reuse and recycling operations independent of OEMs. For example, if a product contains relatively new microchips and memory components, or large amounts of indium, platinum, and gold, the value of these parts and materials can well offset the cost of independent collection, disassembly, refurbishing, shredding and sorting, and purifying and processing. Such third-party operations would be the unintended beneficiaries of additional OEM investment during design and manufacture to enable the ease of product disassembly. To discourage such third-party activities, OEMs may desire high-valued components to be very difficult to retrieve without authorized means (e.g., a disassembly 'key').

This paper describes the biomimetic, or bioanalogous, design [1,2] of 'lock and key' mechanical joints that enable disassembly that is easy but only by those authorized. Relevant biological phenomena identified using keyword searches are summarized, followed by the description of a heat-reversible snap-locator system concept that was inspired by biological phenomena.

2 RELATED AND PREVIOUS WORK

2.1 Related work

Design for disassembly encompasses design methods and guidelines that enhance the ease of disassembly for product maintenance and/or end-of-life (EOL) treatments such as recycling and reuse [3-6]. As is the case in design for assembly, the estimation of disassembly difficulty has been a focus of DFD research [7,8], since it is a major driver of disassembly cost [9]. Desai et al. [10] developed a scoring system that considers factors associated with disassembly time such as disassembly force, the requirement of tools and the accessibility of fasteners. Sodhi et al. [11] focused on the effect of unfastening actions on disassembly cost and constructed a 'U-effort' model that helps designers select fasteners for easy disassembly. Perhaps most related to the present work is the concept of active disassembly using smart materials (ADSM) that relies on self-disengaging fasteners and compression springs by Chiodo et al. [12]. Although effective in the specific cases presented, the concept may have shortcomings in general applications, as it requires the use of special and costly materials.

2.2 Previous Work

A biomimetic design method was developed that identifies biological phenomena relevant to engineering problems by conducting keyword searches on natural-language biological text. Previous applications include those in design for remanufacture [1] and microassembly [2]. A simple keyword search on electronic text, with no special indexing/clustering of the contents, is employed since the purpose is to inspire, not to provide solutions to given engineering problems. For example, the keyword 'center' was searched in an introductory biology text [13], which led to the development of concepts for centering microscale objects during assembly [2].

3 BIOMIMETIC 'LOCK-AND-KEY' CONCEPT

3.1 Problem Statement

Mechanical joints are required that enable disassembly that is easy but only by those authorized (i.e., OEMs and

their contractors). Analogous to a 'lock-and-key', such joints must be easy to disengage with the 'key' but fairly difficult to disengage without it. They must also be easy to manufacture, assemble and provide sufficient stiffness. Most importantly, the design should add negligible cost compared to conventional means of joining, such as welds, fasteners, and snap fits. Therefore, designs that use, for example, complex mechanisms, unconventional materials, actuators and microprocessors, are highly undesirable.

3.2 Biological Lock-and-Key Phenomena

We were curious what analogous lock-and-key phenomena existed in biology. By simply performing a search for 'lock and key', three matches were found in Purves et al. [13]. The first two matches describe how substrates and enzymes interact as lock and key. The third match describes how olfactory receptor proteins are specific for particular odorant molecules that also fit together like a lock and key. This section will describe the substrate-enzyme analogy as well as non-competitive enzyme inhibition and the effect of acidity on enzyme function.

Background

Enzymes are complex proteins that act as catalysts in biochemical reactions. Their catalytic activity is activated upon binding to substrates, which forms enzyme-substrate complexes, as illustrated in Figure 1.

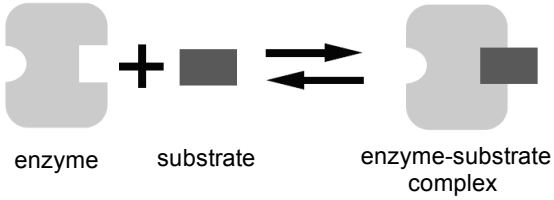

Figure 1: Binding of enzyme to substrate.

Enzymes bind only to specific substrates at particular locations called active sites. The specificity of binding is realized by the 3D geometric complementarities of the active site of an enzyme and that of a substrate. This fit between an enzyme and its substrate has been compared to a lock and key mechanism as early as 1894. This analogy was only indirectly supported until 1965, when X-ray crystallography was used to observe a pocket in the enzyme lysozyme that neatly fits its substrate. The lock-and-key model was further supported by studies to determine whether molecules similar to a substrate could fit into an active site on an enzyme and prevent the real substrate from binding. These studies showed that mimic substrates bound to the enzyme, but did not react; much like the wrong key may fit into a lock, but not turn the lock [13].

Enzyme inhibition

Inhibitors are molecules that decrease the activity of specific enzymes. Inhibitors bind to particular locations of enzymes much like substrates. Competitive inhibitors bind at the active site, physically blocking the binding of the substrate. Non-competitive inhibitors bind to enzymes at sites other than the active sites, hence not competing with substrates. The binding causes an intermolecular force imbalance in enzymes and in turn a conformational change at the active site, which prevents enzymes from binding to substrates, as shown in Figure 2. Since inhibitors work by binding, the lock and key analogy also applies here.

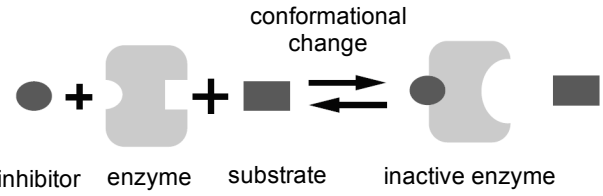

Figure 2: Non-competitive enzyme inhibition.

The lock-and-key model begins to break down when enzyme inhibitors that are much larger than the real substrate were found to be effective, i.e., a key much larger than the real one fits into the lock. Unlike stiff physical locks, enzymes are flexible and their active sites can expand to fit substrates in a phenomenon termed induced fit [13]. Figure 3 shows how the enzyme hexokinase changes shape after the binding of its substrates, glucose and ATP (adenosine triphosphate).

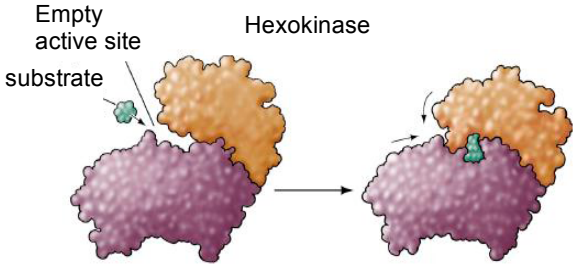

Figure 3: Enzyme shape-change on substrate bind [13, with permission].

A consequence of the shape change is the improved catalytic ability of the enzyme, which exposes the parts of the enzyme that react with the substrate. In addition, the induced fit of the enzyme around the substrate may exclude substances, e.g., water, that adversely affect the catalytic reaction.

Effect of acidity on enzyme function

Enzymes function best within certain pH or acidity ranges of the environment. For example, pepsin, an enzyme found in stomachs, works best in a strongly acidic environment, and lipase, an enzyme found in small intestines, works best in a basic environment. The changes of pH beyond certain ranges can alter or totally inhibit enzymes from catalyzing biochemical reactions; the proton atoms in the environment affect the polar and non-polar intra-molecular attractive and repulsive forces, and in turn alter the conformation of the active sites to the point where the substrates could no longer fit, as shown in Figure 4.

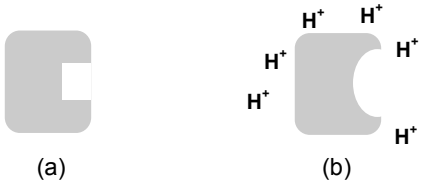

Figure 4: Effect of acidity on enzyme function: (a) normal, and (b) altered at a higher pH level.

3.3 Engineered Lock-and-Key Joint Concept

This section will describe a joint concept inspired by the biological phenomenon of the lock-and-key mechanism observed in enzyme-substrate interaction.

Figure 5 shows a locator-snap system [14] along a parting line of a box-like product enclosure (Figure 5a) and bottom cover (Figure 5b). Three L-shaped locators (L_1, L_2 and L_3) and the snap (S) on the bottom cover engage complementary features on internal surfaces of the enclosure. Figure 6 shows the engagement steps. The enclosure is first added from the top onto a stationary bottom cover, such that locators L_1 and L_3 are aligned with the vertical slots inside the enclosure (Figure 6a). Next, the enclosure is pushed down and then slid in the negative x direction, as shown in Figure 6b. Finally, joining is established when the locators and snap are locked in corresponding features on the enclosure through a snapping action realized by snap geometry and elasticity of the bottom cover (Figure 6c).

Figure 7 illustrates the heat-enabled disengagement steps, where the right sides of Figures 7a-c show cross-sectional views in the y-z plane just behind the enclosure wall contacting the snap. First, a part of the bottom cover near the snap is heated from the outside (Figure 7a). In-plane (x-y) thermal expansion of the bottom cover constrained by locators, as well as the temperature gradient along the plate thickness, result in out-of-plane (negative z direction) bulging of the cover that releases the snap (Figure 7b). Once the snap is released due to thermal deformation, the joint can be disengaged with the reverse motions of engagement, by sliding the enclosure in the positive x direction and moving it up in the positive z direction.

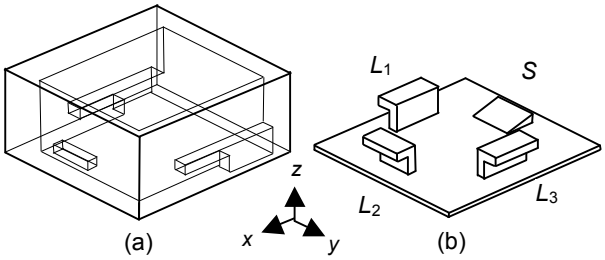

Figure 5: Heat-reversible snap-locator system concept: (a) product enclosure with internal slots and (b) bottom cover with three locators L_1, L_2, and L_3 and one snap S.

While Figures 5-7 illustrate a simple embodiment for the purpose of explanation, the concept will be valid with an arbitrary number of locators and snaps as well as partition lines with arbitrary geometry. Since snap locations are not visible from the outside, it would not be obvious to unauthorized disassemblers how much heat should be applied at which locations, especially with multiple snaps. Furthermore, complex 3D parting lines with curvatures and lips can be employed, in order to prevent tool access to pry open the snap.

Figure 8 shows a more complex example – a conceptual DVD player case with a planar T-shaped partition line. Although the working principle is the same, the locators and snaps are configured slightly differently from Figure 5, in order to accommodate motion constraint imposed by the internal component (not shown). To unlock the joint, it is necessary to heat two locations simultaneously as shown in Figure 9. Simulation has confirmed that heating only one of two locations will not unlock the joint.

Since many materials expand at elevated temperatures, the heat-reversible snap-locator system does not require special materials. It is therefore no more difficult to manufacture and assemble than conventional snap fits. In addition, the locators can be made stiff enough to meet the joints' structural requirements, since the snapping action does not rely on the elasticity of the locators.

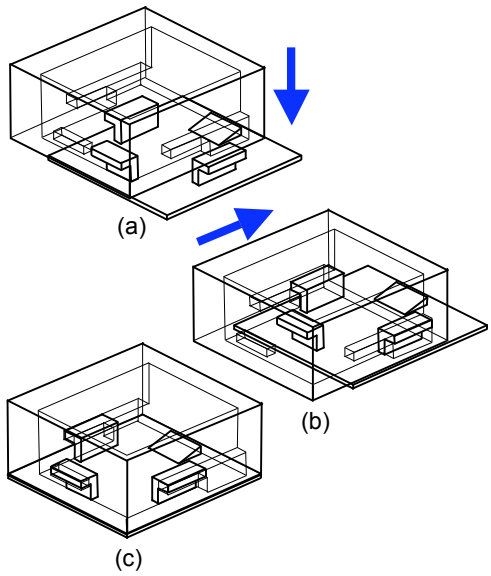

Figure 6: Engagement: (a) push (b) slide, and (c) lock.

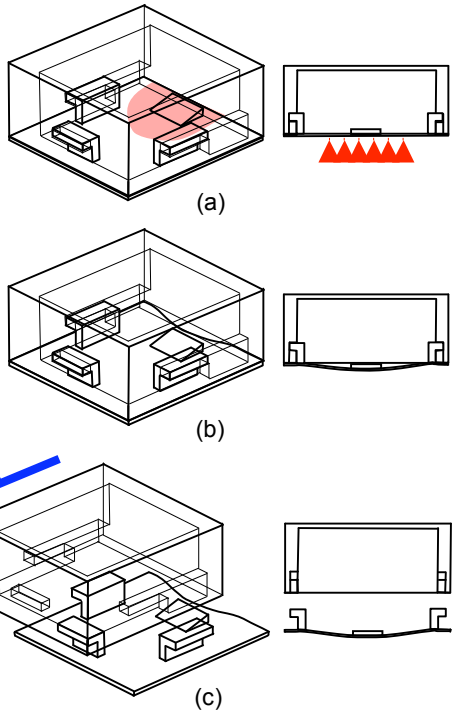

Figure 7: Disengagement of heat-reversible snap locator system: (a) heat, (b) unlock, (c) slide + remove.

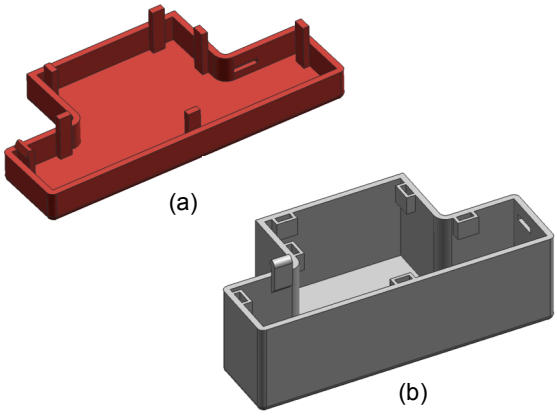

Figure 8: Conceptual DVD player case with heat-reversible snap locator system:
(a) upper part, and (b) lower part.

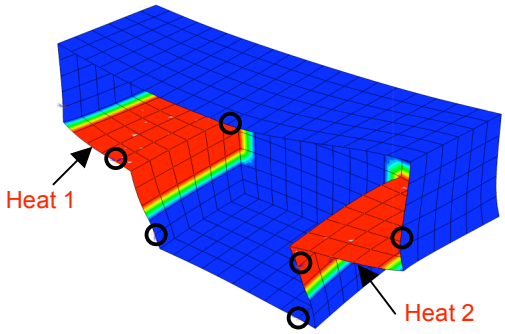

Figure 9: Thermal deformation of DVD player case lower part by heating two locations simultaneously. Circles indicate locations of the locators.

3.4 Analogical Similarities and Mapping

While design by analogy is subjective by nature, similarities between the biological lock-and-key model of enzyme-substrate interaction and that of the heat-reversible snap-locator system are numerous.

While we began with a more abstract interpretation of lock-and-key, where only OEM and authorized disassemblers have access to the 'key' to unlock or disassemble products, many physical similarities are also notable. The active sites of the enzymes map to the recessed features of the mechanical fastening system. Clearly only geometrically complementary parts will fit and snap together, much like specific substrates will bind to specific enzymes. Similar to induced fit, the mating parts fit together due to compliance during assembly, and disassemble due to a greater amount of compliance through the application of heat. Other advantages of induced fit in biology may be explored further for incorporation in the engineered system, e.g., exposure of active features that further facilitate assembly and/or disassembly, as well as the exclusion of substances, e.g., formation of a watertight seal.

The concept is related to the effect of acidity on enzyme function, where enzyme-substrate binding is disabled by the shape change of the binding site induced by a factor in the environment. Instead of change in proton concentration, the concept uses the concentration of heat to induce shape change, thereby disabling the joint.

Returning to the more abstract interpretation, the 'key' also corresponds to the precise knowledge of where to apply heat to disengage the lock. This is especially evident in the DVD player example, where the simultaneous heating of two locations is necessary. Simply applying heat will also cause part deformation, but not in a manner that results in disassembly. Furthermore, the parts could be configured such that inappropriate attempts at disassembly would cause irreversible damage to the part, preventing its reuse and acting as an inhibitor to unauthorized disassembly.

4 SUMMARY AND CONCLUSIONS

This work was motivated by the desire of OEMs for joints that are easy to disassemble, but only by those authorized. To comply with legislative and consumer pressures, OEMs have invested resources to design products for ease of disassembly, as well as set up infrastructure to process products at the end of life. However, products that are easy to disassemble also entice theft, as well as unauthorized disassemblers who may be unintended beneficiaries of design for disassembly. In addition to ease of authorized disassembly, other requirements of such joints include sufficient stiffness as well as ease of manufacture and assembly.

By performing a search on biological knowledge in natural-language format, phenomena described as 'lock-and-key' mechanisms in biology were easily located. The phenomena involved in enzyme-substrate interaction led to the development of a heat-reversible snap-locator joint system. More detailed examination of similarities between the biological and engineered systems could reveal further enhancements of the engineered system to satisfy the lock-and-key requirements of the joint.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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