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# Component-based Building Instructions for Block Assembly

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**ABSTRACT**

A LEGO sculpture with fragile constructions of blocks might easily fall to pieces during assembly, making a well-designed set of instructions crucial. A simple layer-by-layer, bottom-up assembly does not work well, especially when over-hanging regions exist. We propose a method for generating component-based building instructions aiming at supporting users to assemble fragile block models efficiently. Our method contains two independent segmentations: segmentation at weakly-connected blocks and segmentation for avoiding *floating blocks*. Based on these segmentations, the whole model is divided into components. A set of building instructions is generated by deciding the assembly order of the components. The effectiveness of our method is demonstrated through a user study.

**Keywords:** LEGO®, block assembly, building instructions, segmentation.

## 1 INTRODUCTION

Playing LEGO®, i.e., assembling 3D sculptures with blocks, is fun for people of all generations. A less breakable LEGO sculpture hopes for thickness throughout the model. To ensure enough thickness at thin part, a LEGO sculpture is prone to be designed in high resolution. However, recently, block products designed in low resolution are increasing. Examples of them can be found in the "Nanoblock mini collection" [10]. Each design is assembled with approximately 200 blocks. In such a low-resolution design, it is easy to be fragile at some spots because only a small number of blocks can be used.

A LEGO sculpture with fragile constructions of blocks might easily fall to pieces during assembly. For an enjoyable assembly time, a well-designed set of building instructions is crucial. Although several studies related to LEGO exist, most of them are focusing on designing block structures [5-6],[9],[11-12]. In this paper, we focus on the assembling order of blocks without adding any modification to the structures of target model.

To avoid fragmentation during assembly, a smart approach is to segment a model into solid components, assemble each of them separately, and finally combine them together. This is a common strategy for assembling articulated objects, as investigated by Heiser et al. [4] and Agrawala et al. [1-2]. However, most block models do not have apparent articulations. For user-friendly building instructions, a block model should be divided at weakly-connected blocks, and segmented into as few and as large components as possible to avoid over-segmentation. Also, the preferred assembly orders among LEGO fans seem to be "layer-by-layer and from bottom to top" [8], as these are natural orders for building architecture. "Block-by-block or top-down orders" [7],[12] are sometimes also employed, if necessary. However, if building instructions are not carefully designed, some blocks might have neither upward nor downward connections during assembly, and seem as if they were floating in the air (Fig. 1). This is physically impossible, but such floating blocks are not rare in the instructions generated by existing LEGO design systems [9-10],[12].

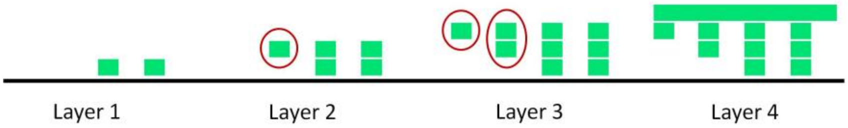



Fig. 1: Blocks floating in the air (red circles) in naive layer-by-layer building.

In line with the principles stated above, we propose a method for automatically generating building instructions for fragile block models. Our method first detects weakly-connected blocks and incoherent spots identified by *floating blocks* in a bottom-up assembly, to segment a model into solid components. The term *floating blocks* here means blocks without upward or downward connections during assembly. The segmentation might generate small components, and thus, our method merges them to obtain fewer components of reasonably large size. During this merging, it is ensured that no *floating block* exists in each component. Finally, our method generates a set of building instructions by deciding the assembly order of the components based on our criteria for easy assembly. We also provide a graphical step-by-step guide for making a user-friendly instruction set. The effectiveness of our method is demonstrated through a quantitative comparison with other tools as well as a user study that proves users can assemble block models more efficiently using our instructions.

## 2 RELATED WORK

Through cognitive psychology experiments, Heiser et al. [4] and Agrawala et al. [1-2] have laid the theoretical cornerstone of producing visually comprehensible and accessible instructions for different assembly tasks (e.g., block assembly, furniture assembly).

For block assembly, the mainstream of automatic guiding systems seems to use either the *layer-by-layer* assembly or the *block-by-block* assembly. On the one hand, in the *layer-by-layer* assembly, blocks are prone to be grouped inside one layer. Automatically generated block groups seem layer-like ones to facilitate the assembly *layer-by-layer*. This layer-like block group is very common, and can be found in most open-source systems (e.g., LEGO Instruction Creator [8], Testuz et al. [11]). On the other hand, in the *block-by-block* assembly, blocks are prone to be grouped in a more free way. LEGO Digital Designer [7] is the most representative tool of this type. It seems that blocks are grouped one-by-one in a particular order. In such an order, each step ensures the connection of an upcoming block to earlier-built blocks.

For manually generated instructions, tools basically support a manual editing of ordered block groups. Generation of a user-friendly building instruction might require interactions among several tools for many subtasks, e.g., MLCAD for modeling, LDView for displaying model, and LPub for page layout in building instructions.

In particular, Gupta et al. [3] proposed a Kinect®-based augmented system for guiding block assembly. Unlike conventional systems using a block model as input, this augmented system requires the troublesome tracking of a designer's real-time modeling to generate a building guide.

In this paper, we propose a novel automatic building instructions generation method to group blocks by merely allowing segmentation at fragile spots and spots showing incoherence in assembly.

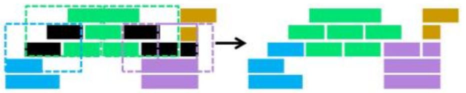
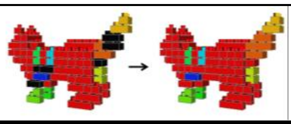
## 3 PROPOSED METHOD

We aim at the user-friendly assembly of fragile block models, i.e., block models with weakly-connected blocks. The input of our method is an assembled shape of a block model, which can be easily obtained using existing LEGO design software. All blocks are assumed to be rectangular solids having the same height, similarly to the previous methods, e.g., [11]. The output of our method is a step-by-step set of 3D instructions which can be viewed from any angle. Firstly, we will introduce a method for dividing a model into components in Section 3.1. Then we will introduce a method for generating building instructions by deciding the assembly order of the components in Section 3.2.

## 3.1 Generation of Components

We define a *block segment* as a set of blocks treated as a basic element for generating component. To facilitate operations (e.g., intersection, union) among basic elements, each basic element requires blocks inside to be interconnected as one. Our basic approach for generating components is to initially segment the input model into *block segments* deliberately and then make components by merging some unnecessarily-small *block segments*. For the segmentation, our aim is twofold: to separate the input model at weakly-connected blocks; and to separate the input model to eliminate *floating blocks*. These two types of segmentation are implemented independently, and are described in Section 3.1.1 and 3.1.2 respectively. In Section 3.1.3, we describe how the *block segments* generated by both segmentations are merged into components.

### *3.1.1 Segmentation at Weakly-Connected Blocks*

| | *Operation* | *2D Illustration* | *3D Illustration* |
|---|---|---|---|
| Step 1 | Detect weakly-connected blocks $W$ in input model $M$. |  |  |
| Step 2 | Divide $M$ into several *block segments* by subtracting $W$ from $M$. |  |  |
| Step 3 | Merge each block $w \in W$ into a *block segment* that has the largest number of connections to $w$. |  |  |

Tab. 1: Algorithm and illustrations for segmentation at weakly-connected blocks (black blocks).

We detect weakly-connected blocks as blocks corresponding to the previously defined "weak articulation points" [11]. Note that a block model can be abstracted as a graph, where the vertices represent individual blocks and the edges indicate brick linkage by studs. An articulation point in graph theory is such a vertex that when removing it the graph generates more than one disconnected subgraph. For a block model, to identify important articulation points, Testuz et al. [11] define a "weak articulation point" as an articulation point that connects each subgraph owning a size (number of edges in subgraph) greater than one.

When designing a block model, previous research [11] detected "weak articulation points" for reducing them in optimized model; however, not all "weak articulation points" can be avoided when thin part exists. In this paper, we find "weak articulation points" as weakly-connected blocks to help us to divide a model into *block segments*. Definition of "weak articulation point" [11] decides that, by removing each weakly-connected block, the model can be separated into multiple disconnected parts, with each part containing more than one block. Inspired by this property, in our segmentation (see algorithm in Tab. 1), all the weakly-connected blocks detected in Step 1 are removed from the initial model in Step 2. Then in Step 3, each weakly-connected block is merged into a *block segment* that has the largest number of connections to the block.

### *3.1.2 Segmentation Avoiding Floating Blocks*

We first extract the blocks that will be in the floating state during a layer-by-layer, bottom-up assembly. Such *floating blocks* are easily detected as follows. As shown in Fig. 2(a), we visit connected blocks from each bottommost block to the top. The allowed visiting direction is only upward, because in a LEGO model two blocks are directly connected to each other only if they overlap each other. The blocks that have not been visited by the end are *floating blocks*. Fig. 2(a) illustrates a simple LEGO model in 2D with *floating blocks* (colored in red).

This process for detecting *floating blocks* uses basically a breath-first search algorithm. By default, as shown in Fig. 2a, there is only one bottom, hence the search starts from all the bottommost blocks (i.e., initial search keys) and travels through the whole model. If allowing one more bottom, as shown in Fig. 2b, the original model is segmented, causing an independent search inside each *block segment*.

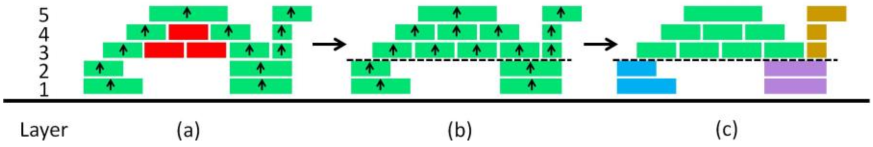


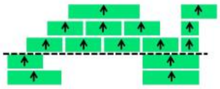
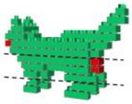
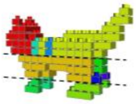
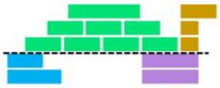

Fig. 2: Segmentation avoiding *floating blocks*. (a) Detecting *floating blocks* (red blocks) along arrows. (b) A *pseudo floor* is inserted between the 2nd and 3rd layers. (c) The model is divided into four *block segments*.

Our final target is to ensure that there are no *floating blocks* in each component generated. Here, we introduce two strategies to achieve this goal. One is a direct way, the other indirect. The direct way is to explicitly separate the *floating blocks* as components. Note that, in Fig. 2(a), if we treat the *floating blocks* (colored in red) and the rest (colored in green) as two different components, each component contains no *floating blocks* inside. On the contrary, the indirect way is separating the model by horizontal planes until no *floating block* exists as illustrated in Fig. 2(b). The dashed line shows the horizontal plane used to separate the model into components. This separation works as if we had inserted a working floor between the 2nd and 3rd layers. We call this separating plane a *pseudo floor*. In Fig. 2(c), due to the separation by the *pseudo floor*, four independent components are obtained, and each can be assembled from the bottom to the top without any *floating block*. So we know that we have eliminated the *floating blocks* by inserting a *pseudo floor* at an appropriate location. In Fig. 2, such a location is between the 2nd and 3rd layers. However, sometimes one *pseudo floor* might be not enough to eliminate all the *floating blocks*; we might require more, or in an extreme case, one *pseudo floor* under each layer.

Now we have two strategies to generate components with no *floating blocks* inside. We further combine both strategies to reduce the amount of *block segments*, which will benefit a more precise instruction. We do so by applying indirect way first, however, not for eliminating all *floating blocks*, but for reducing *floating blocks* reasonably by inserting a few effective *pseudo floors*. After that, we use the direct way to handle the unreduced *floating blocks*.

The problem now becomes how to select effective *pseudo floors*. We find that inserting a *pseudo floor* at an appropriate location (e.g., between the 2nd and 3rd layers in Fig. 2) is important. This location is important because if a *pseudo floor* is inserted elsewhere, *floating blocks* below the *pseudo floor* cannot be eliminated. To find such an appropriate location, we introduce an index $C_{floating}(l)$, which equals the number of *floating blocks* had by inserting a *pseudo layer* between the $l$-th and ($l$+1)-th layers for $l = 0, 1, 2, \ldots$ ($l = 0$ means the ground floor). By evaluating the value of $C_{floating}$ for all possible $l$, we choose to insert *pseudo floors* where the value of $C_{floating}$ takes on local-minima. We do so because each local-minimum of $C_{floating}$ indicates a horizontal separation which can better reduce *floating blocks* in the local area around the *pseudo floor*. By applying all these separations at the same time, the initial model is segmented into several *block segments*. The algorithm described above is summarized in Tab. 2 with 2D and 3D illustrations. Note that all *floating blocks* are not eliminated always by Step 1. The red blocks in the top row of 3D illustration are *floating blocks* when the model is separated by two *pseudo floors* (illustrated by dashed lines). On the other hand, no *floating blocks* exist in the example illustrated in 2D after inserting a *pseudo floor*. Therefore, there are no differences between middle and bottom rows of 2D illustrations.

These separations caused by this algorithm result in unnecessarily-small *block segments* (e.g., the brown and the purple *block segments* in 2D illustration in Tab. 2, these *block segments* can be combined without generating any *floating block*). In next subsection, we will describe a strategy to adjust these over-segmentations.

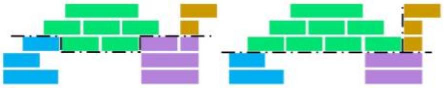
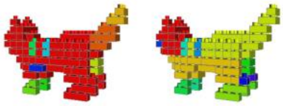
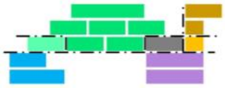
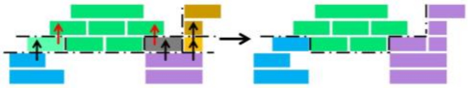
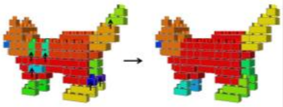
| | *Operation* | *2D Illustration* | *3D Illustration* |
|---|---|---|---|
| Step 1 | For each $l$, calculate a $C_{floating}(l)$ by pre-inserting one horizontal *pseudo floor* between the $l$-th and $(l+1)$-th layers. Then insert *pseudo floors* where $C_{floating}(l)$ takes on local-minima. |  |  |
| Step 2 | Indirect segmentation: Divide the input model by the inserted *pseudo floors*. |  |  |
| Step 3 | Direct segmentation: detect *floating blocks*, and then explicitly separate them as new *block segments*. |  |  |

Tab. 2: Algorithm and illustrations for segmentation avoiding *floating blocks*.

### 3.1.3 *Making Components*

The initial model is segmented using the two approaches mentioned above. Based on these segmentations, the components are generated. As described in the algorithm in Tab. 3, we first apply the two segmentations to the model (Step 1). Then we generate components by dividing the model along the boundaries of the segmentations (Step 2). If *floating blocks* remain, we separate them as individual components. Because this generates tiny components, we merge them to reduce the number of components (Step 3). This step is divided into following four sub-steps.

i) Find a component "A" which touches a *pseudo floor*, or contains only one or two blocks;
ii) Find a component "B" which connects component "A";
iii) Merge component "A" and "B" only if the merged component does not generate additional *floating blocks*;
iv) Repeat i) to iii) until all possible merge operations are done.

| | *Operation* | *2D Illustration* | *3D Illustration* |
|---|---|---|---|
| Step 1 | Apply the two segmentation algorithms to the model: driven by weakly-connected blocks (left), and avoiding *floating blocks* (right). |  |  |
| Step 2 | Generate components by dividing the model along the boundaries in both segmentations generated by Step 1. |  |  |
| Step 3 | Merge components as much as possible, ensuring no *floating block* is generated. |  |  |

Tab. 3: Algorithm and illustrations for making components from *block segments*. In Step 3, black arrows upward indicate successful merging. We also show some failed merging indicated by red arrows in 2D illustration.

Tab. 3 illustrates our way to obtain components containing no *floating block*. However, theoretically, other results for components (see Fig. 3) can achieve the same goal if other features (e.g., recognizability of a component, equilibrium of a component) are not considered. In the future, improvements can be made to satisfy more beneficial features in a component.

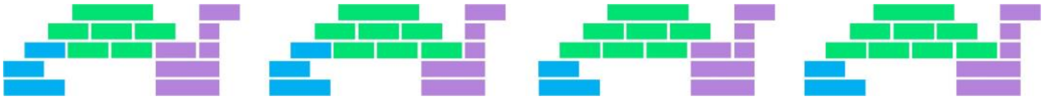


Fig. 3: Different results for components containing no *floating block*.

### 3.2 Making a Component-Driven Instruction

After the LEGO model has been divided into components, we start to make an instruction guide for assembly. By now it is ensured that no *floating blocks* exist in any component. Hence, we can simply assemble each component in bottom-to-top order, and focus only on the order of combining components. Among the components, we define a *joint component* as one connecting two or more other components. The assembly order of components is decided according to the following priorities:

i) the number of connected components
ii) the number of blocks contained in the component
iii) the number of connected *joint components*
iv) the distance from the bottommost block (smaller has higher priority).

If value i) is the same for each component, value ii) is used to decide the priority. Furthermore, if value ii) is the same for each component, value iii) is used, and so on. Finally, if symmetrical components-pairs exist, the order of components is further adjusted to ensure successive assembly of such symmetric component-pairs.

After deciding the assembly order of the components, we generate a graphical instruction guide. To prepare the user for the assembly flow, the guide firstly switches from the original LEGO model (Fig. 4(a)) to the completed model showing colors assigned from blue to red to the components according to their priority (Fig. 4(b)). After that, the user begins assembling the first component (the red one in Fig. 4(b)). The assembly procedure of each component is displayed in an interactive 3D view (Fig. 4(c)) and a static top-view (Fig. 4(d)). Both views are simultaneously updated step-by-step. In both views, blocks in the active component (the component being assembled) are rendered in the original color, but already assembled components are rendered in a customized color (beige in Fig. 4(c, d)). Showing the already assembled components with the active component helps users to understand their relative positions. Visibility of blocks during assembling process is important. Because each component generated in our method can be assembled layer-by-layer, a 2D view which shows blocks in current assembling layer (Fig. 4(d)) always ensures the visibility of all blocks, even though these blocks might be occluded in 3D view.

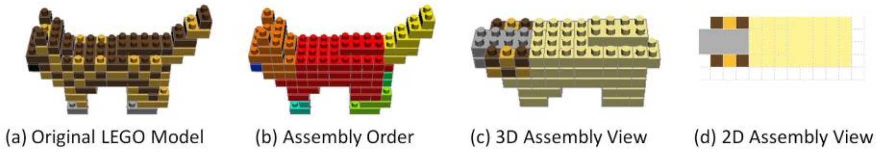



Fig. 4: Our graphical instruction guide.

## 4 RESULTS AND DISCUSSION

We developed a prototype system to evaluate our method. It was implemented using C++ and tested on a laptop with a 2.40-GHz Intel Core (TM) i5-2430M processor, 8 GB RAM, and NVIDIA NVS 4200M GPU.

As far as we know, benchmark containing different block models (e.g., block models designed in different resolutions, block models fragile to varying degrees) has not been discussed before. To build such a benchmark is not easy. In this paper, our proposed method is mainly designed for fragile block models. Because the fragile structure is normally found in block models designed in low resolution, low-resolution block models are used to evaluate our proposed method. We prepared seven low-resolution block models (see Fig. 5) created by a mini block artwork design system [12]. These test examples are fragile to varying degrees, i.e., weakly-connected blocks in these block models are counted differently (see Tab. 4).

### 4.1 Generation and Ordering of Components

| | *Segmentation at weakly-connected blocks* | | *Segmentation avoiding floating blocks* | | *Making components* | |
|---|---|---|---|---|---|---|
| *Test model* | *# of weakly-connected blocks* | *# of block segments generated (Fig. 5(a))* | *# of pseudo floors (local-minima)* | *# of block segments generated (Fig. 5(b))* | *# of components by overlapping block segments* | *# of components after merging (Fig. 5(c))* |
| sunglasses | 14 | 7 | 1 | 5 | 11 | 7 |
| flower | 12 | 4 | 1 | 4 | 6 | 6 |
| dolphin | 1 | 2 | 1 | 5 | 6 | 5 |
| cat | 7 | 12 | 2 | 16 | 20 | 10 |
| headphones | 10 | 3 | 2 | 11 | 13 | 11 |
| legoman | 5 | 4 | 3 | 6 | 8 | 6 |
| camera | 0 | 1 | 1 | 3 | 3 | 3 |

Tab. 4: Statistics of test models.

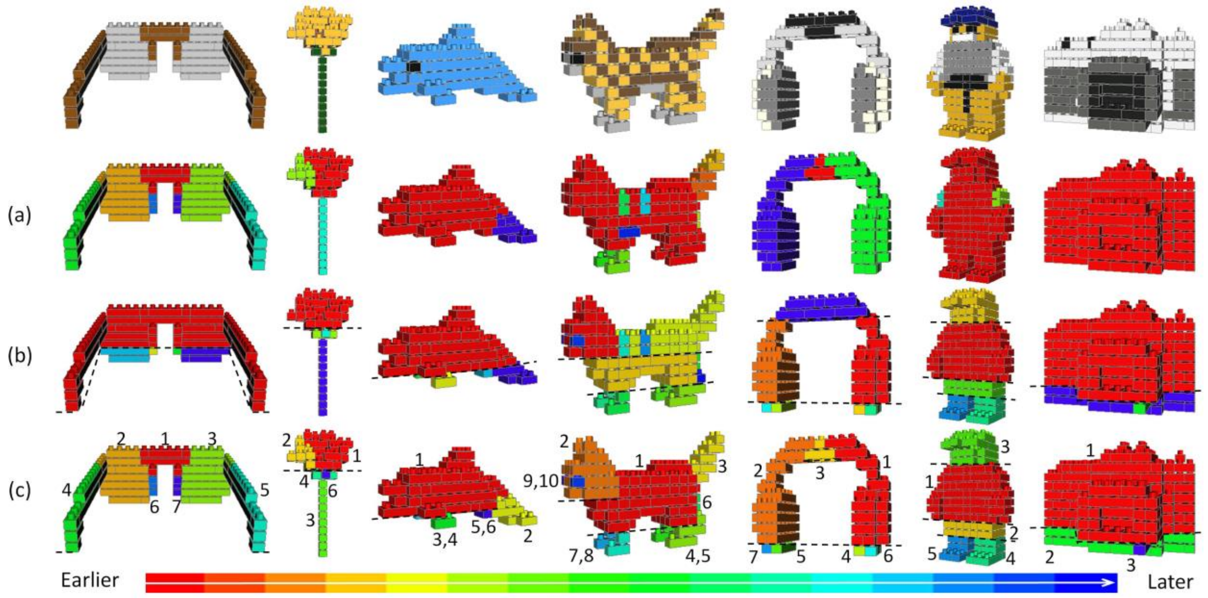



Fig. 5: Generation and ordering of components in different test models (top row). (a) *Block segments* separated at weakly-connected blocks. (b) *Block segments* avoiding *floating blocks.* (c) Final components generated. Assembly order of final components, as marked by numbers, is associated with a specific color in a color map varying from red (built first) to blue (built last).

Segmentation in our method is driven by weakly-connected blocks and *pseudo floors* found in input model. As shown in Tab. 4, the number of weakly-connected blocks ranged from 0 (camera) to 14 (sunglasses) in our test models. After the segmentation at weakly-connected blocks, the number of *block segments* ranged from 1 (camera) to 12 (cat). Fig. 6 shows the graph of $R_{floating}(l)$, which is the normalized value of $C_{floating}(l)$ divided by total number of blocks in the model so that it takes between 0 to 1. For example, if no *floating block* exists when a *pseudo floor* is inserted between $l$-th and ($l$+1)-th layers, $R_{floating}$

($l$) takes zero; if half of all blocks are floating, $R_{floating}(l)$ takes 0.5. By observing the graph, we can find that most test models (except for legoman) have only one local-minimum or two local-minima. Detailed information is shown in middle column of Tab. 4. Although both segmentation steps result in unnecessarily tiny components (Fig. 5(a, b)), our merging strategy successfully combines tiny components into large ones for better results (Fig. 5(c)). Details can be found in right column of Tab. 4.

Note that Fig. 5 reveals an important feature of our component generation method: segmentation along the horizontal *pseudo floor/floors* might be locally unwise sometimes (see sunglasses, dolphin and cat in Fig. 5b); however, segmentation along horizontal *pseudo floor/floors* is able to be revised locally, because a wise remerging is possible due to a wise segmentation of existing *block segments* at local disjunctions. Currently, local disjunctions are identified by weakly-connected blocks in fragile block model. In the future, for a block model being not fragile, other efficient segmentation methods can also be easily integrated into our current method.

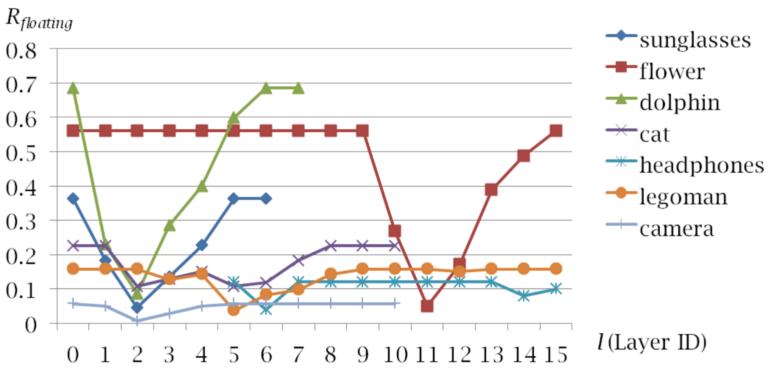



Fig. 6: Graph of $R_{floating}(l)$, which takes ratio of *floating blocks* in whole blocks.

Assembly order of components determined by our method is illustrated in Fig. 5(c) as well. As expected, *joint components* are to be built earlier (in a warmer color), and symmetric component-pairs to be built successively are in similar colors. This demonstrates the effectiveness of our ordering.

### 4.2 Auto-generation of Instruction Guide

| | *# of components* | *Max/Min # of blocks in component* | *Instructions steps for component* | *With first block for* |
|---|---|---|---|---|
| Our system | 10 (see Fig. 5) | 53/1 | layer-by-layer | body |
| LEGO Digital Designer | 2 (body & tail) | 89/4 | block-by-block | foot |
| LEGO Instruction Creator | 1 (whole) | 93 | layer-by-layer | foot |

Tab. 5: Step-by-step instructions created by three systems.

Tab. 5 compares the instruction guide generated by our method with those generated by LEGO Digital Designer [7] and LEGO Instruction Creator [8]. We used in our test the cat model shown in Fig. 5, which consists of 93 blocks and 7 weakly-connected blocks in total. On the one hand, we found that the instruction guide generated by LEGO Instruction Creator showed some steps with *floating blocks*, while our layer-by-layer assembly inside each component avoided *floating blocks*. On the other hand, we found in the test that the assembly starting from the feet was breakable, because earlier-built weak parts of the feet interfered with the smooth assembly of the rest. However, unlike the other two systems which did not generate separate components for the feet, in our instruction guide, the assembly of the separate foot components was near the end, and thus, it seldom affected the assembly of other components.

We recruited four undergraduate volunteers to test the time efficiency of the instruction guides generated by our system and LEGO Digital Designer. The results showed that all subjects completed the cat model in much less time when using our instructions. The average time needed to complete the model with our instructions was 17 min, which is about 60% of the time needed with LEGO Digital Designer's instructions.

## 5 CONCLUSIONS AND FUTURE WORK

To help the efficient assembly of fragile LEGO models, we proposed a method for automatic generation of component-based building instructions. We divide up a model into components by considering segmentation at both the weakly-connected blocks and the incoherent spots identified by *floating blocks*. We implemented our method and evaluated the efficiency of the instructions it generated for several models. We also compared the instruction guide generated by our prototype system with those generated by the well-known LEGO Digital Designer, and another software tool called LEGO Instruction Creator.

In this paper, we mainly focus on low-resolution block models, which are usually small enough to be assembled inside our hands. It seems that our assembly efficiency has not been greatly troubled by the equilibrium of components. However, to make our proposed method more compatible with various kinds of block models, we can evolve our component generation to satisfy more requirements, e.g., components with more perceivable shapes, the static equilibrium of component during assembly. Moreover, a benchmark of block models is expected to be built to facilitate the evaluation of a LEGO-related method all-around. Finally, to make the automatically generated instructions more user-friendly, diverse notations shown in manually drawn instructions might be considered.

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