Article

# Building Mental Models by Dissecting Physical Models

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## Abstract

When students build physical models from prefabricated components to learn about model systems, there is an implicit trade-off between the physical degrees of freedom in building the model and the intensity of instructor supervision needed. Models that are too flexible, permitting multiple possible constructions require greater supervision to ensure focused learning; models that are too constrained require less supervision, but can be constructed mechanically, with little to no conceptual engagement. We propose "model-dissection" as an alternative to "model-building," whereby instructors could make efficient use of supervisory resources, while simultaneously promoting focused learning. We report empirical results from a study conducted with biology undergraduate students, where we demonstrate that asking them to "dissect" out specific conceptual structures from an already built 3D physical model leads to a significant improvement in performance than asking them to build the 3D model from simpler components. Using questionnaires to measure understanding both before and after model-based interventions for two cohorts of students, we find that both the "builders" and the "dissectors" improve in the post-test, but it is the latter group who show statistically significant improvement. These results, in addition to the intrinsic time-efficiency of "model dissection," suggest that it could be a valuable pedagogical tool. © 2015 by The International Union of Biochemistry and Molecular Biology, 44:7–11, 2016.

**Keywords:** *active learning; assessment of educational activities; contributions from cognitive science and educational psychology to student learning; effective in-class problems; instructor-regulated collective learning; teaching and learning techniques methods and approaches; visual literacy*

## Introduction

A model is a representation of an idea, an object, an event, a concept, a process, or a system [1]. In education, models are particularly used in science classrooms to demonstrate elements of structure and function that are not intuitive. One possible way in which models aid learning is by supporting the process of abstraction [2] and by allowing learners to visualize complex ideas, processes, and systems [3]. Because abstraction and visualization are critical components for learning of concepts, specifically for those concepts that are beyond direct sensory perception (viz. biomolecules) [4, 5], it has ensured that models are not simply show-and-tell devices but the tools with which learners can construct better mental models [6, 7]. This construction is brought about by a dynamic interaction between the learner's prior mental model, which may be formed through verbal or text-based instruction, and the novel representations of the same information presented by the external model.

The ability to abstract and construct an informed mental picture is enhanced when one works with physically manipulable models [8]. For instance, when students work with a three-dimensional physically manipulable model, it is observed that they learn better—exploiting the haptic and proprioceptive resources of the model, rather than following the visual cues of the representation alone [9]. The shared representational bases of perception and cognition likely supply the mechanisms whereby the construction of mental models is affected by the nature of interaction that users have with the model in hand. Thus, existing research

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*[S] Additional Supporting Information may be found in the online version of this article.*

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supports the view that physically manipulating models can facilitate learning by influencing learners' cognitive processes [10, 11].

One of the most common ways in which physically manipulable models are used in science classrooms is by letting learners build complex models from prefabricated simpler components. Model-building, where students build physical models themselves, leads to improved spatial understanding and the ability to translate that understanding from known to unknown problem situations [12]. For these reasons, the use of physical model-building in high school and college-level science education is strongly encouraged with multiple research studies promoting its benefits viz. [13].

A practical concern about model-building as an instructional aid is that one has to trade off degrees of building freedom with the intensity of instructor supervision. Using a completely open-ended kit for building allows for maximum exploration of possibilities, but requires a lot of instructor supervision to ensure everyone builds the right structure. On the other hand, using prefabricated kits with low degrees of building freedom permit instructors to be more hands-off, since very few deviations from the canonical structure are possible, but simultaneously permit students to put components together purely as a mechanical task—with little conceptual engagement. Given logistical constraints in most education settings, instructor time is usually scarce, which predisposes the choice of physical models towards the latter type. This then leads to inefficient use of physical models, wherein students mechanically build models successfully, but don't learn very much by doing so.

We offer a solution to this problem—we suggest that students will learn better by breaking models than building them. To be more precise, we propose that getting students to "dissect" 3D models is a more efficient way of teaching them about related concepts than having them build such models from kits.

Dissection has historically proven to be a very powerful device to understand biological systems, which are inevitably complex, modular, and intricate [14]. How does one element of the system relate to its neighbors? What components connect to this one? How does the structure of this element support its biological function? Observing biological organs *in situ* creates a natural setting for studying such questions, and allows students to figure out many such answers by the simple task of observation. We propose that the benefits of dissection as a study method can also translate to learning-by-doing activities like physical model manipulation, which is particularly relevant for learning biochemistry concepts [15].

With a small empirical study, we explored the relative efficacy of model-building and model dissection in improving students' understanding of the deoxyribonucleic acid (DNA) structure. The DNA molecule is a very popular benchmark for such a comparative study, since it is an important concept that serves as an entry point to vast areas of molecular biology and biochemistry for precollege biology students. It is also particularly apt for studying model-based pedagogical methods, because details of its 3D structure are best understood using models and an understanding of its 3D structure clarifies the biological functions of the DNA molecule, viz. how the complementary orientation of the nitrogenous bases enables the sophisticated process of replication and transcription and, hence, the basis of genetic constancy.

# Method

## Sample

Eighteen biology undergraduate students (6 males; 12 females) responded to a general call for a workshop on understanding DNA structure using a 3D physical model. Students were randomly assigned to two cohorts of "model builders" and "model dissectors." Further, within each cohort, two groups were formed. Thus, in effect, there were two groups who were "building" models and two groups who were "dissecting" models. The two groups, in both cohorts, had five and four students, respectively.

## Study Design

The basic design of the experiment sandwiched model-related activity between a pre- and a post-test, administered using a set of MCQs (4 choices/1 correct) to each student individually. Questions for both pre- and post- sets were common for all students, but differed between themselves. Thus, a total of 32 questions were designed drawing upon the standard Grade 12 biology textbook resource. The complete question bank is given in Supporting Information.

### *Model-building Intervention*

The two groups were given a 2D printed diagram of DNA structure, giving molecular details. Also given were differently colored atomic components of a 3D DNA physical model (Fig. 1). The specific colors were red (oxygen), black (carbon), blue (nitrogen), white (hydrogen), and purple (phosphorus). Students in each group were asked to build the physical model using the components, while referring to the 2D blueprint. Model builders received no explicit feedback from the instructor when they made mistakes; groups either self-corrected through mutual discussion, or were guided by the physical constraints of the model components to converge to the correct form.

### *Model-dissecting Intervention*

These two groups were also given the 2D printed diagram of DNA structure, giving molecular details. They were then given two prefabricated nucleotide base pairs and were asked to successively dissect them to show the instructor, in order, (i) a nucleotide, (ii) a nucleoside, (iii) a deoxyribose sugar molecule, (iv) nitrogenous bases (ATGC), and (v) a phosphate group (Fig. 2). Model dissectors received feedback from the instructor when they made mistakes, in the form of questions probing the misconceptions that caused the error, but no direct advice. For the most part, these groups also

FIG 1 *Photographs depicting nucleotide base pairs (left) built by model builders from component atoms and (right) given as starting element to model dissectors. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]*

self-corrected through mutual discussion. Out of four erroneous dissections across the two groups, three were amended by self-correction without instructor input. In one case feedback was needed.

## Results

### Physical Manipulation Leads to Improved Performance

In line with previous research literature, our results suggest that an opportunity to physically manipulate the 3D model led to improvement in conceptual understanding. Measuring conceptual understanding via response accuracy on a 16 item questionnaire, we found a 25% improvement overall in our study, with the difference between pre- and post-test scores statistically significant $t(34) = -2.5$, $p = 0.017$. While some of this improvement could be attributed to mental priming during the retest, this is unlikely to be a big effect, since the questions used during pre- and post-testing were different.

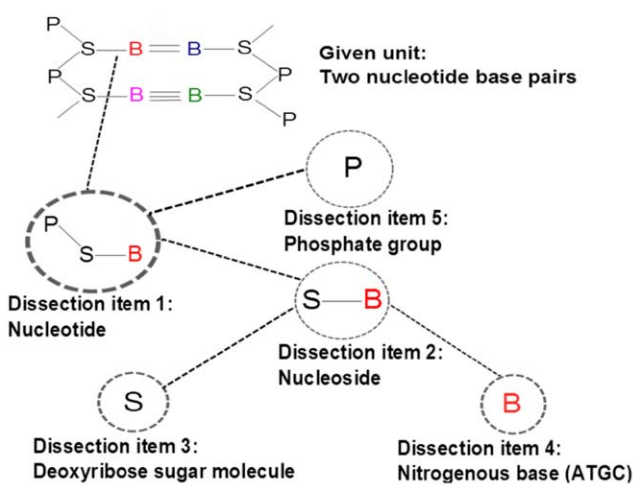


FIG 2 *Representational image depicting the general protocol followed for model. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]*

### Model Dissection Leads to Significantly Improved Performance than Model Building

While the overall sample showed improvement in test scores, this increase was larger for the dissector group, as illustrated in Figs. 3 and 4. The difference between the performance of the two groups on the post test was statistically significant, $t(16) = -2.9$, $p = 0.01$. In contrast, the pre-test performance difference between the two groups was statistically insignificant, $t(16) = -1.26$, $p = 0.22$. These observations together demonstrate that, *ceteris paribus,* model dissection promotes performance to a greater degree than model building.

## Discussion

The primary contribution of this article is proposing model dissection as a potentially valuable pedagogical tool. In our study sample, it quantitatively outperforms model building in improving performance in the context of understanding a complex molecular structure. Crucially, the benefit of the model-dissecting intervention is not restricted to only those concepts that are explicitly probed in the dissection intervention. A more generalized benefit is also seen, (improvement in scores for concepts not directly probed in the dissection task) so our results cannot be explained by the difference that model-building does not target specific concepts while dissection does.

Also, model dissection naturally takes less time per student than building, although building requires less interactivity and so can be performed in parallel for multiple students. Overall, the greater efficiency of the dissection method in promoting understanding suggests that it is a viable alternative to model-building as an instructional aid.

In our study design, we comparatively evaluated the efficacy of model-dissection vis-a-vis model building as a pedagogical tool. We do not claim that model dissection leads to better "conceptual understanding" than model building for measuring performance using MCQs ignores factoring other known facets of conceptual understanding [16]. Incorporating such factors (viz. various cognitive skills

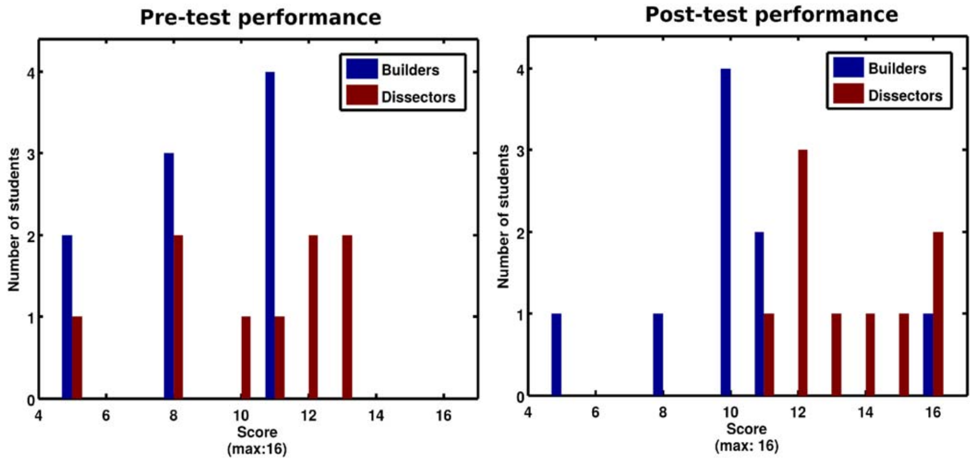


**FIG 3** *Comparing pre- vs. post-test performance for both our cohorts as measured by the number of questions (out of 16) each student got correct. While both groups showed improvement on the post-test, the "dissector" group showed greater improvements than the "builder" group, with nearly all students in the dissector group scoring above 75% on the post-test. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]*

employed in a task) in future experiment designs could help further studies probe the precise nature of knowledge improvements occurring through model dissection better.

While a quantitative advantage for model dissection is seen in our sample, it would be inappropriate to interpret this as evidence for the inefficiency of model-building, since the information provided to students in both protocols differs both in representation and quantity. However, the qualitative advantages conferred by model dissection over model building are less ambiguous to infer. First, model dissection encourages focused interaction with the model. This, we believe, is enabled by the inherent nature of the process of "dissection" which asks for undivided attention to the points of attachment of the concerned component. Model dissectors pay special attention to the zone in which the component-to-be-dissected is situated so that they neither pull out an irrelevant piece from the neighbor nor leave out essential portion from the relevant component. This forces the dissectors to focus their attention on both the spatial organization of the component as well as on the individual elements of the component. Greater attentional focus on specific characteristics of the component leads to sustained learning via the formation of richer mental

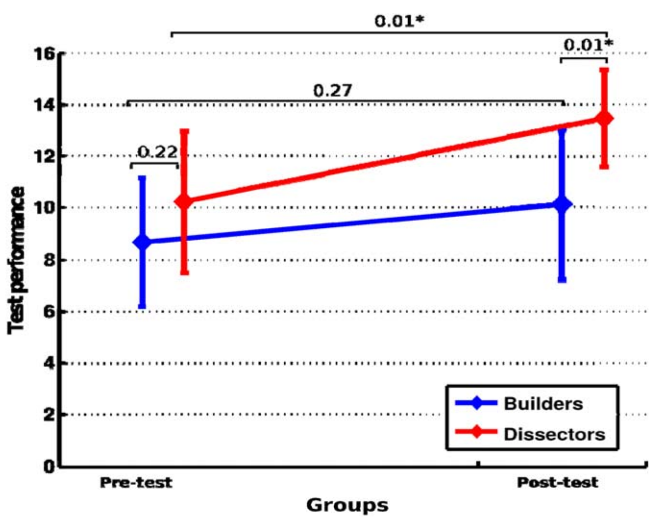


**FIG 4** *Illustrating performance improvement in pre- vs. post-tests of knowledge about DNA structure. All results are sample averages. Error bars represent ±1 SD. p values are derived from two sample T tests in all cases. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]*

**TABLE I** *A few other concepts that could be dissected* AQ8

| *S.No.* | *The 3D modeled concept* | *Components that could be dissected* |
|---|---|---|
| 1. | Cell (animal/plant) | Membrane and various organelles |
| 2. | Individual organelles like the chloroplast | Membrane/granal/stromal thylakoids/globules |
| 3. | Eye | Components like the iris, lens, retina, the different nerves and others |
| 4. | Hemoglobin (and other protein models) | Hydrophobic/Hydrophilic regions/element binding region |
| 5. | Antibody (Immunoglobulin) | Variable/constant region/light/heavy chain |

representations. A second feature concerns efficient use of supervisory resources. Numerous studies suggest that instructors, especially in science classrooms, are hard-pressed for time and find it difficult to allow learners to constructively engage in conceptual understanding. Model dissection can prove valuable to such instructors as a hybrid between teacher-driven instruction and student-driven exploration, balancing the logistics of classroom instruction with the fundamental requirements of allowing students to figure things out on their own.

In this study, instructors can also let the two groups of builders and dissectors come together to stack their dinucleotide pairs to form a 10 nucleotide pair long DNA helix. This would help learners visualize the overall structure of the DNA molecule along with appreciating the specific features, viz. planarity of the bases, of the DNA molecule.

We note that indiscriminate use of model dissection is unlikely to yield learning advantages. Learners will benefit from dissecting models of systems wherein the structural organization of the system's components hold the key to its overall function. The DNA molecule is one of the paradigmatic examples of such a system. We list some other model systems here (Table 1), all of which share this common thread—their function is naturally constrained by the structure and, hence, understanding of their function is strongly informed by understanding their structure. In cases such as these, we expect model dissection to be a valuable pedagogical tool.

The instructor's choice of dissection concepts would scale the protocol up feasibly to small classroom settings and the basic nature of the dissection task would eliminate the possibility of students mechanically manipulating the physical model.

In summary, we have proposed physical model dissection as a novel classroom study tool, and shown that it promotes enhanced understanding of DNA structure and function for undergraduate students. We expect such improvements to generalize to other fields of study, and to be particularly apt for biochemistry and molecular biology education, wherein subtle insights frequently lie buried within molecular structures.

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