Improving Accessibility to Molecular Case Studies by Using 3D printed Models of Protein Structures

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Abstract

Visualizing the structures of biological macromolecules can provide insights into its functions and help design new properties and function. However, engaging students in the exploration of protein structure and function can be challenging. To address this challenge, we developed a molecular case study, "The Many Faces of Heme". This case study builds on the Nobel prize winning work of Francis Arnold on directed evolution of enzymes, focusing on engineering an oxygen binding protein, myoglobin, into a catalytic enzyme. It guides students through an engaging and interactive set of activities where they visualize the structure of myoglobin and compare the structures to mutated forms of the protein that create room for binding a substrate and function as enzymes. In the original version of the case study students use of a molecular visualization program (Mol*) for viewing the molecular details of the heme-binding site in myoglobin and its engineered (enzyme) forms. To enhance the accessibility of this case for neurodivergent students, we have developed instructions for creating case-specific 3D protein models to provide a tactile representation of the proteins. These physical models can be used for discussions alongside the Mol* molecular visualization activities. They provide a more accessible and immediate option to discover and demonstrate the differences between the active sites of proteins targeted allowing focus on the actual learning goals of the case study by removing barriers that can come from learning the commands of a new software tool. Once produced, 3D models produced with polylactic acid (PLA) plastic are durable and easily stored for repeated use. Guidance for producing the models using a 3D printer, the required files and references to relevant protein structures from the Protein Data Bank will be included as a module for the case study along with teaching notes directing model use to supplement case activities.

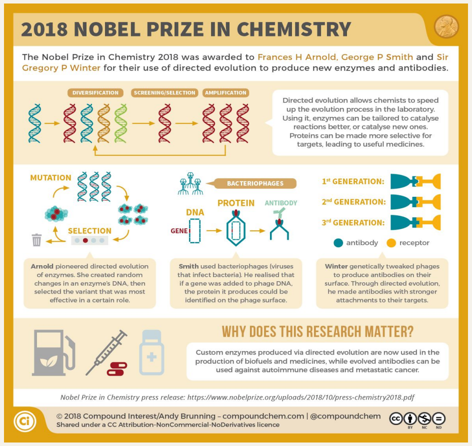


Fig. 1 Infographic summarizing the work on directed evolution to produce new enzymes that resulted in the Nobel Prize in Chemistry for 2018.

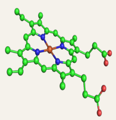


Fig. 2. Heme prosthetic group bound to myoglobin

Many Faces of Heme Case Study

Overall goal: engage students to witness the contribution of a protein's 3D structure to the chemical and physical environment required its specific function.

Rationale: Myoglobin is an excellent example since it is a heme-binding protein commonly used to to illustrate how a protein folds into a tertiary structure and binds a cofactor, in this case, for the purpose of reversibly binding oxygen. However, heme groups serve different functions in the context of other proteins, much like a machine cog whose function changes depending on its environment.

Design: Five modules facilitate implementation and adaptation for a wide range of student levels and activities from introductory to upper-level biochemistry.

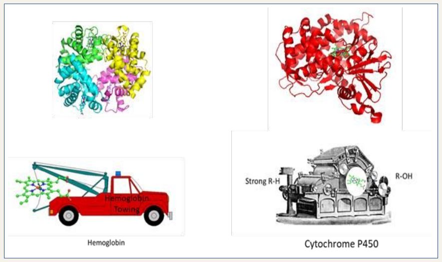
- **Parts 1-2:** introduce students to the basic concepts of chirality and stereospecificity in enzyme reactions that produce single enantiomer drugs. Directed evolution of enzymes is described as an approach to developing new drugs.
- **Parts 3-5:** direct students to explore the 3D structure and active site of myoglobin and compare it to an engineered myoglobin with carbene transferase activity. By visualizing and manipulating the structures of these proteins with digital tools such as Mol*, students gain insights into how subtle amino acid changes alter the active site's physical shape and chemical environment, transforming it from an oxygen storage protein into an enzyme capable of stereochemical reactions.
- **Part 5** serves as an assessment with fewer guided instructions to complete the activity analyzing the double-mutant with an additional non-canonical amino acid in the place of the proximal His 94 and bound to a carbene ligand.

Case Study Components

Part 1: **The Importance of Chirality**
Engage students with background investigation highlighting the important of stereochemistry illustrated by the teratogenic birth defects caused by thalidomide, a drug with two enantiomers. This example showcases the need to synthesize enantiomerically pure compounds, which enzymes are capable of doing efficiently

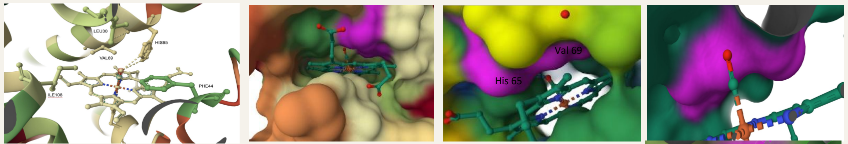
Part 2: **Making Single Enantiomers of Drugs**
Introduce the development of highly effective enzymes through evolution and the efforts of researchers to produce new enzymes using directed evolution. Students us the infographic in Fig. 1 to answer questions designed to define proteins and enzymes and connect their production to DNA

Part 3: Exploring Heme Proteins
The heme molecule bound to these proteins acts like a cog. When put into different protein scaffolds (3D molecular machines) it results in proteins with very different functions ((below, diagram illustrates different heme proteins).

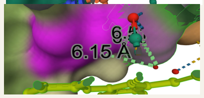


Students use the molecular visualization tool, Mol*, to explore the heme binding pocket for wild type myoglobin (1JW8) starting with the identifying features of the protein structure in the PDB entry. Student provided instructions and examples that lead them in using Mol* functions to alter the molecule display, highlight important amino acids (distal His 65 and Val69) with color (magenta below) and examine the area of the protein around the heme. They are asked to identify interactions of the heme with nearby residues and to describe how their presence affects the space in the active site.

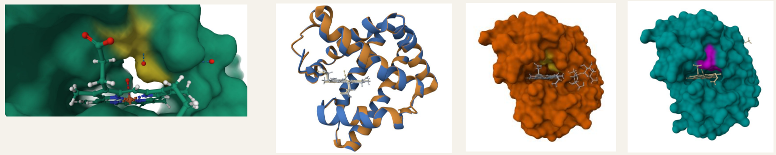
Students described a "dome" created above the heme iron by the wild-type protein His65 and Val69 residues and hydrophobicity surroundings.



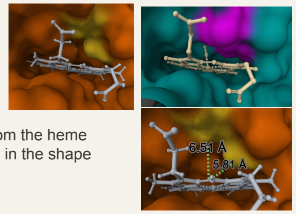
Optional Activity (advanced students or time flexibility: Measure the distance between the heme iron and Val 69



Part 4: Mutating a Protein to Create an Enzyme
Since students now familiar with the wild-type myoglobin active site, they are now guided to explore the effects of mutations at His65 and Val69 that confers stereospecific catalytic activity on the double mutant mutant (PDB 6M8F). Note: the residues numbers slightly differ in this protein model (His64 and Val 68).

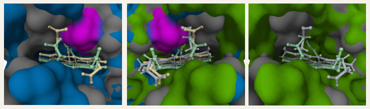


Through questions and guided instructions, students identify residues that interact with the heme, overlap the wild-type and mutant structures and observe the different shape and space present in the heme-binding cavity resulting from the two mutations. The catalytically active mutant has more open space above the heme.



An option is included for students to use Mol* tools to measure distances from the heme iron to the mutated residues forming the roof of the cavity to see differences in the shape and cavity size compared to wild-type.

Part 5: Ligand Binding to Mutated Myoglobin (Assessment)
This section can serve to assess what students have learned in the case by using the Mol* tools to explore and analyze the wild-type and mutant forms of myoglobin and to draw conclusions about their activity based on structural features of the active site. Less guidance is provided to complete the activity and reach conclusions



1JW8 w/ 6G5B 1JW8 w/ 6G5B w/ 6M8F 6G5B w/ 6M8F

Conclusion and adaption to include 3D models

- This case study has been implemented with variations for different student sets and levels of experience with molecular visualization and background in biochemistry.
- Due to its modular design, it can easily be adapted by minimizing or expanding different parts for student level or time requirements. Qualitative student feedback related that the digital simulations were effective in promoting active learning to understand the connections between subtle changes in protein structure conferred by mutations that dramatically alter their activity.
- The inclusion of 3D printed physical models will lower barriers and extend access to students who
  - May be limited in initial usage of molecular visualization tools due to the cognitive load of learning new software.
  - Are engaged by physically holding, rotating and directly observing/comparing the wild-type and mutant myoglobin proteins alongside case study activities
  - Need spatial perspective on the protein structure and physical location of referenced residues in case study activities, i.e. "whole to part" and "part to whole" or "concrete"
  - Can benefit from using low-technology options (i.e. cell phone) to create images or compare protein features such as active-site size.
  - Have trouble following directions or collecting data that is tangential to the main learning goal of studying protein structure and function
  - Feel frustration with being unable to show what they know about topics without software mastery or disabilities such as dyslexia.

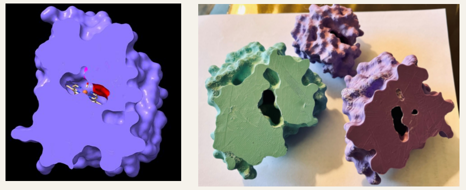
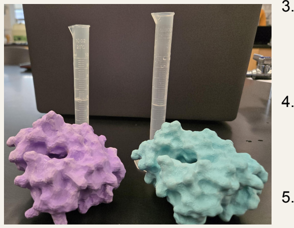


Fig. 3 (Left) rendering of wild type myoglobin highlighting active site residues that are mutated in 6M8F mutant. The structure was cut in half to give students a better view of the active site. (Right) 3D printed models of the mutated (PDB 6M8F) and wild-type myoglobin (PDB 1JW8).

Suggestions for using 3D models in the case study

1. Place 3D models on-loan at a library or secure location for easy student access to preview or while working on the case study.
2. Introduce the case study to students using physical models they can hold and see to preview exploring deeper in the case study.



3. Use water and pipettes and graduated cylinders to measure the volume different between wild-type and mutant proteins (printed at the same scale) (left).
4. Use the models to flip the classroom by enabling students to develop ideas from protein structures prior to analysis via molecular visualization.
5. Use the models for reference alongside case study activities and to foster group discussion.

Additional details for the case study worksheet, keys, teaching notes and 3D printing instructions for the protein models to accompany this case are available. Email jvillema@iup.edu.

References

- Data, P., & Data, P. (2024). RCSB PDB - 3D View. Rcsb.org. https://www.rcsb.org/3d-view
- Tinoco, A., Wei, Y., Bacik, J-P, Carminati, D.M., Moore, E.J., Ando, N., Zhang, Y, Fasan, R. (2019) Origin of high stereocontrol in olefin cyclopropanation catalyzed by an engineered carbene transferase. *ACS Catal. 9,* 1514-1524.
- Herman, T., Morris, J. Colton, S., Batiza, A., Patrick, M. Franzen, M., and Goodsell, D.S. (2006). Tactile teaching: Exploring Protein Structure/Function Using Physical Models. *BAMBED 34,* 247-254.
- Villemain, J. (2025) "Myoglobinphysicalmodel_howto3Dprint". Available on BioQuest

Acknowledgements

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