Using 3D Printing to Illustrate Protein Modularity and Dynamics

Joanna Dinesen and Dr. Jonathon Mauser
Department of Chemistry, **Winona State University, Winona, MN, USA, 55987**

Abstract

Many important enzymes are part of multi-subunit complexes that involve complex movements and interactions that are difficult to visualize via traditional 2-dimensional diagrams or in visualization software. Physical, 3-dimensional models are an especially effective way to illustrate abstract concepts within the curriculum, including about protein dynamics, subunit functions, pathway architectures, and the nature of protein-protein interactions. The usage of physical models in the classroom has been successful when teaching concepts such as enzyme catalysis and protein refolding, quantized by increased exam scores and positive student feedback. Here, we present work done to 3D print publicly available protein structures of the Krebs Cycle enzymes in both rigid and flexible polymers to convey concepts of dynamics in protein structure, as well as aid in teaching the roles of different monomers within the cycle. Structures 3D printed with thermoplastic polyurethane (TPU) are lightweight and flexible, which allows the models to be safe for classroom use while simultaneously teaching dynamics of enzyme motion among subunits and individual chains. Highly regulated enzymes have been coated with a glaze to easily differentiate from the other five enzymes of the pathway. Upon integration with traditional lecture methods, student gains in key learning outcomes will be quantified by polling, comparison of results of a pre- and post-assessment, and performance on standardized test items.

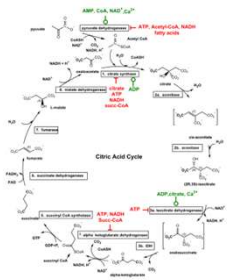
Hypothesis

- Students will learn about allostery, multimeric enzymes, enzyme classes, and regulation better than their control group counterpart through exposure to biologically accurate physical models alongside traditional teaching methods.

Introduction

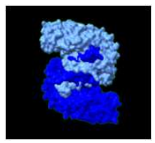
Class	Example	Color
1. Oxidoreductase	• Dehydrogenase • Oxidase	Green
2. Transferase	• Kinase • Transaminase	Blue
3. Hydrolases	• Esterase • Glycosidases	
4. Lyases	• Aldolase • Hydratase	Pink
5. Isomerases	• Epimerase • Mutase	
6. Ligases	• Synthetase • Carboxylase	Purple
7. Translocases	• ATP synthase • ATP-binding cassette (ABC) type transporters	

- Table of enzyme classes with color coded key



- Traditional teaching diagram of Krebs Cycle

Methods



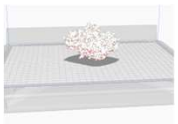
RCSB Protein Data

↓

UCSF ChimeraX surface view

↓

Ultimaker Cura 5 (slice)



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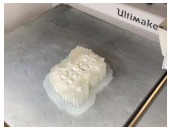
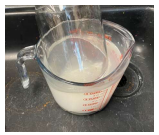
Print using PLA or TPU polymer (13 hours – 5.5 days)
Soak and exchange PVA supports





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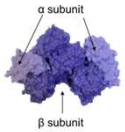
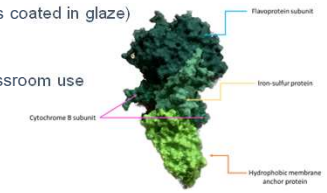
Prime and paint by enzyme class (regulated enzymes coated in glaze)

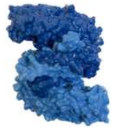
↓

Ready for classroom use

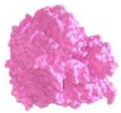




3D Printed Surface Representations



Citrate synthase



Aconitase

Isocitrate dehydrogenase

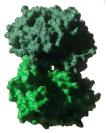
In progress (Print time: 5 days)

α-Ketoglutarate dehydrogenase

Succinyl-CoA synthetase

Succinate dehydrogenase

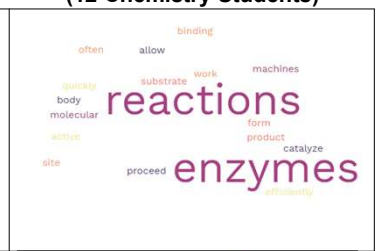
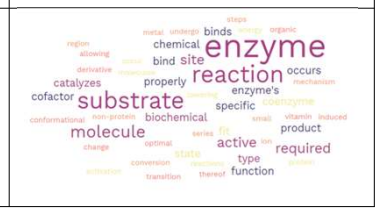
Fumarase (chain A)

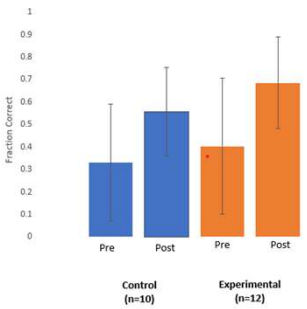


Malate dehydrogenase

Preliminary Results and Discussion

Prompt: Describe how a protein functions to catalyze a biochemical reaction:

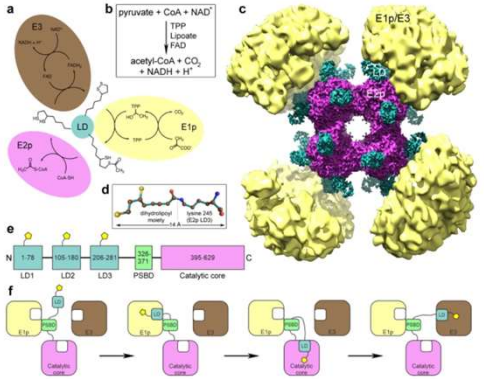
	Control Group (10 Chemistry Students)	Experimental Group (12 Chemistry Students)
Pre-Test		
Post-Test		



We need more background data & students to sample.
Please take our survey!

Future Directions

- Improve Quantification Method
- Print models using molded silicone
- Print models using magnetic connectors
- Print more detailed and accurate dynamic models (point-mutations and wild-type)
- More complicated regulatory models: E. Coli Pyruvate Dehydrogenase Complex



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Acknowledgments

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