



3DP-Jmol: Bridging Structural Bioinformatics and Physical Models for Teaching and Outreach



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<https://github.com/mariusmihasan/3DP-Jmol>



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www.bio.uaic.ro

Founded in 1948

BioActive research group

- Isolation
 - Identification
 - Characterization
 - Biological effects (neurological effects, citotoxicity, oxidative stress, antimicrobial activity)
- of biological active molecules with potential applications in biotechnology.





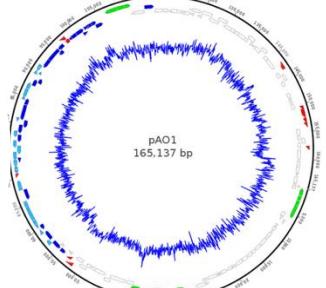
A bit about us and our work in Iași

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Main research subjects:

- molecular biology of pAO1 megaplasmid related to nicotine catabolism, stress induced by nicotine degradation and biotechnological applications.



Latest paper:



Integrated transcriptomic and proteomic analysis of nicotine metabolism in *Paenanthrobacter nictinovorans* ATCC 49919

Amada El-Sabeh, Andreea-Mihela Mlesnita, Marius Mihasan*

Faculty of Biology, Alexandru Ioan Cuza University of Iasi, Romania

ARTICLE INFO

The global tobacco industry produces significant amounts of nicotine-containing wastes, being regarded as a major environmental threat. The appropriate treatment of nicotine-contaminated waste is required for the reuse and toxic abatement before its disposal. In this context, the nicotine-degrading microorganisms have been extensively applied as potential tools for降解和removal of nicotine wastes. Here, by combining long-read direct RNA sequencing data and novel LC-MS/MS proteomic data, we focused on the metabolic pathways involved in the nicotine degradation in *Paenanthrobacter nictinovorans* ATCC 49919. The nicotine-related expression of 25 annotated ncRNAs and proteins was confirmed, eight of these genes were found to be involved in the nicotine degradation pathway. The results showed that *P. nictinovorans* was first at having nicotine-related expression. Insights regarding the active mechanisms involved in integrating the nicotine catabolic pathway with the general metabolism of the bacterial cell and the defense systems employed against the toxic effects of nicotine were also obtained. This study is the first report on the metabolic pathway of the first multistep investigation of *P. nictinovorans* ATCC 49919 and, moreover, the first multistep assessment of a bacterial nicotine catabolic pathway.

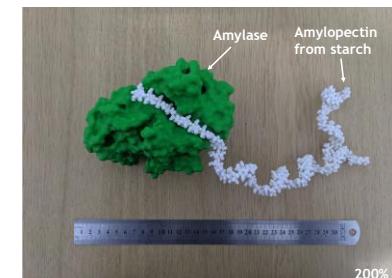
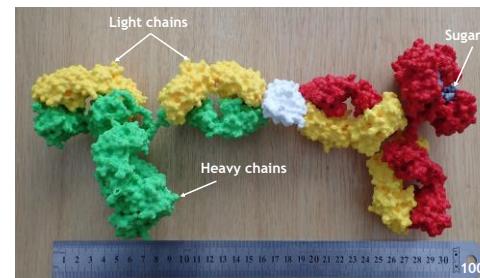
[10.1016/j.biob.2025.106017](https://doi.org/10.1016/j.biob.2025.106017)

ICMB2025

Wed 05.11, 18:10
Tiberius Iustin Munteanu
Thu 6.11, 9:55 - 10:15
Andreea Mihaela Mlesnita

Received: 18 November 2024 | Revised: 17 March 2025 | Accepted: 31 March 2025
DOI: 10.1016/j.biob.2025.106017

- using 3D printing for creating teaching materials to support molecular bioscience education.



Latest paper:

Received: 18 November 2024 | Revised: 17 March 2025 | Accepted: 31 March 2025
DOI: 10.1016/j.biob.2025.106017

ARTICLE

Impact of 3D-printed molecular models on student understanding of macromolecular structures: a compensatory research study

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Funding information
Ministry of Research, Innovation and Higher Education, Romania, Grant/Award Number: PN-III-P2-1.2-PED-2024-0340

Abstract
A strong understanding of molecular structure is key for mastering structure-function concepts in life sciences and is based on the visualization of biomolecules. Therefore, new approaches to help students translate between the 2D representation of a molecule and its 3D form as a molecular model have been used. Object-based learning is an approach that gives students a tangible way to view and manipulate physical structures in three dimensions, strengthening learning and challenging students to engage with and interrogate the object. In this work, atomically accurate 3D-printed models of macromolecules have been fabricated using consumer-grade 3D printers intended from non-medical use. The impact of the models on students' ability to overcome common misconceptions related to protein and DNA structures was evaluated in a randomized controlled experiment using a compensatory research design. To our knowledge, this is the first time such an approach has been used in each of the two groups of students who also used the models as a control and as an intervention. The results have been used to evaluate the impact of physical models on learning gains. Presenting the physical molecular models in the class and allowing students 3–5 min to handle them was enough to convert low-gain lectures into medium-gain lectures. The students' responses helped them to stay on-task and increase their on-task engagement, enhancing their focus and engage their visual memory. Despite some identified drawbacks, using physical models of molecules fabricated using 3D printing is a great way of improving bio-molecular education with low costs.

Keywords
3D printing, learning gains, molecular models, object-based learning, teaching

Developed educational resources:

EXPLOREAZĂ UNIVERSUL MOLECULAR CU AUTORUL MODELELOR IMPRIMATE 3D

Despre noi | Noutăți | Cum obținem modele | Modele noi | Modele gratuite

Heavy chain

Modelle fizice ale moleculelor pentru o mai bună educație în științele vieții

Un concept de bază în științele vieții este legătura dintre structura unei molecule și funcția acesteia. Formulele chimice nu pot reda eficient complexitatea structurală a moleculelor biologice și sunt cel mai frecvent recopiate de studenți și elevi ca simple imagine. Această aplicație face posibilă să vizualizăm moleculele și să le manipulăm, oferind un mijloc de învățare interactivă și interactivă.

Multe modele fizice precum dimensiunile atomilor, unghiiile dinții și legăturile chimice și relații dimensionale dintre diverse molecule.

<https://modelelemolculare.ro/>

The plan for today



Theoretical part - This presentation

- Why are 3D printed molecular models needed?
- Are these models efficient?
- How and from where can I get 3D printed models ?

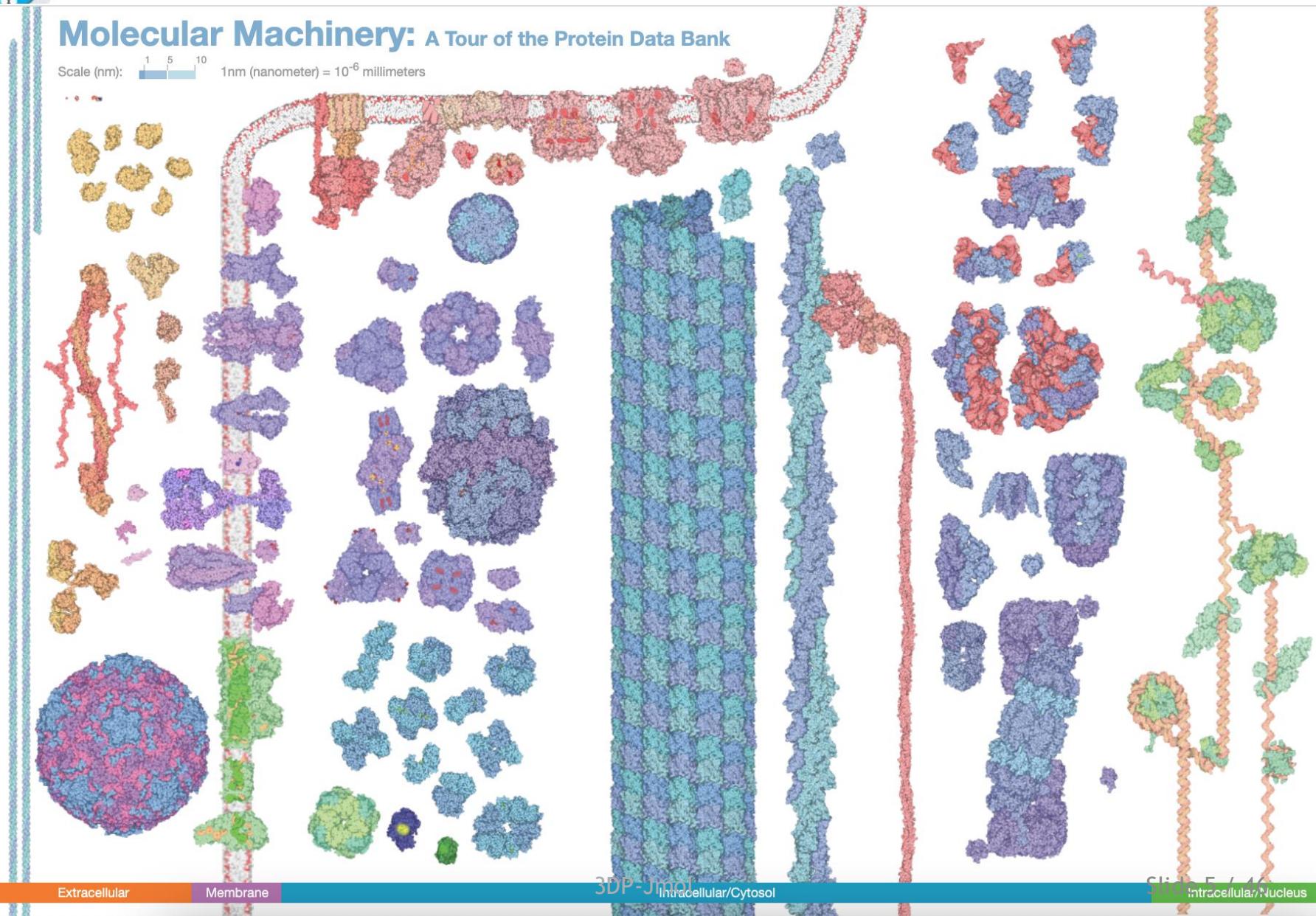
Hands-on part - the workshop

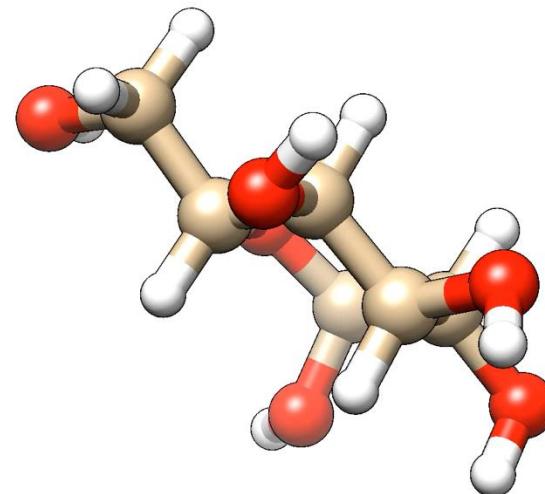
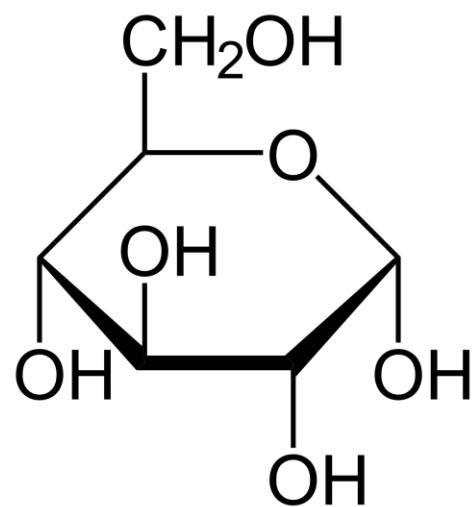
- .PDB to .STL files - software and steps
- Practical considerations when 3D printing molecular models



Molecular Machinery: A Tour of the Protein Data Bank

Scale (nm): 1 5 10 1nm (nanometer) = 10^{-6} millimeters





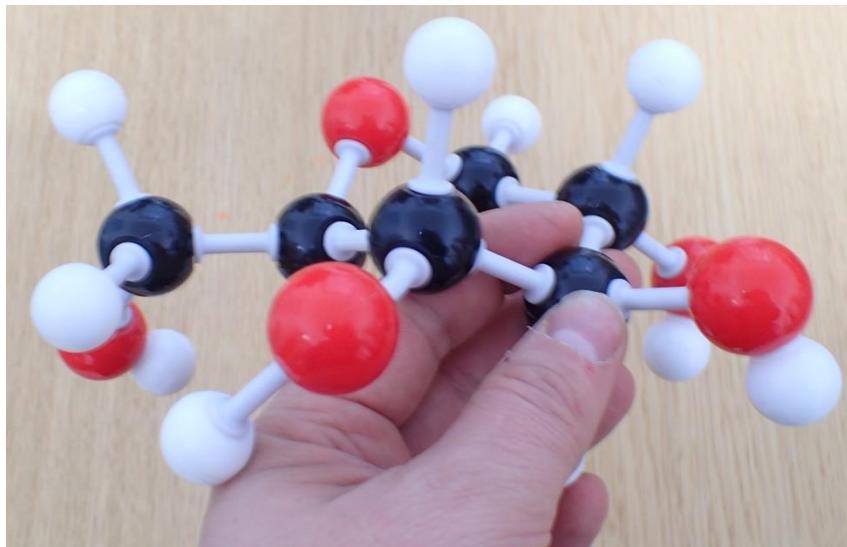
α-D-glucopyranose

Molecular models to aid teaching - Molymod



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http://www.molymod.com/MMS-004_Inorganic__Organic_Teacher_Set.jpg

molymod®

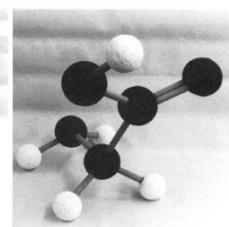
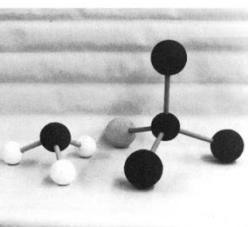
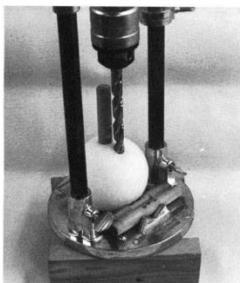
The *original* dual-scale system of molecular models

Molecular models to aid teaching - DIY



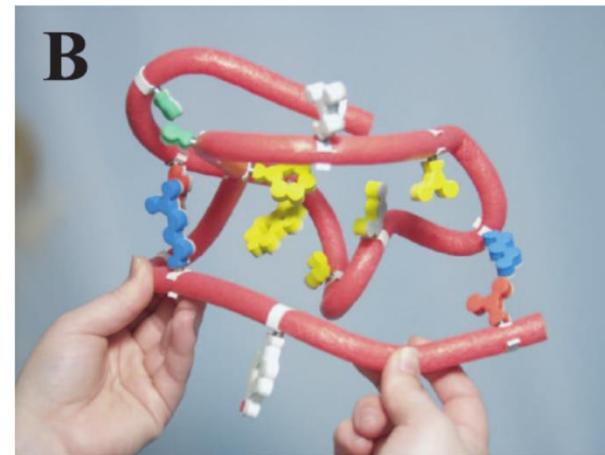
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Styrofoam balls and copper wires

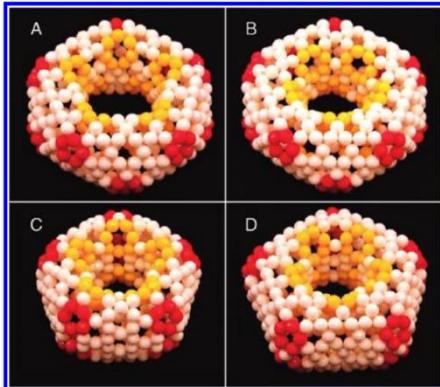
[10.1021/ed066p1015](https://doi.org/10.1021/ed066p1015)



B

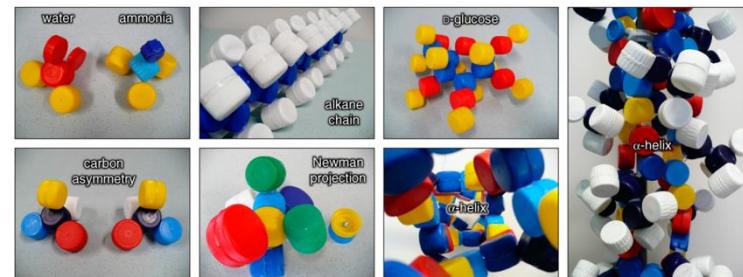
Flexible foam, wires and foam cut-outs

[10.1002/bmb.2006.494034042649](https://doi.org/10.1002/bmb.2006.494034042649)



Glass Beads

[10.1021/ED200142G](https://doi.org/10.1021/ED200142G)



Screw-on bottle caps

[10.1021/ed400126p](https://doi.org/10.1021/ed400126p)

Molecular models to aid teaching - Paper models



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Antibody
(Paper Model)



DNA
(Paper Model)



Dengue Virus
(Paper Model)



Green and Red
Fluorescent Proteins
(Paper Model)

PDB-101
pdb101.rcsb.org

Build a Paper Model of DNA

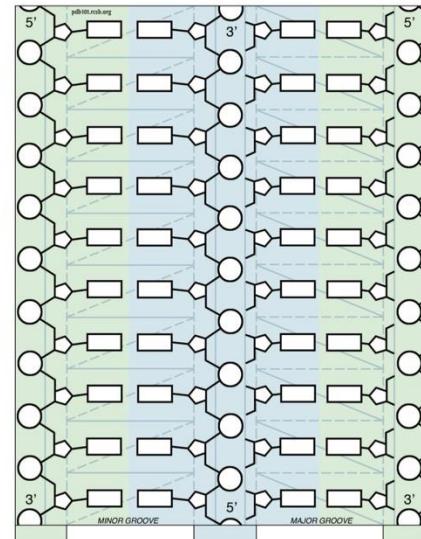
Fill in the names of the bases on the model shown to the right, or use the detailed model that shows all the atoms in each nucleotide (back side of paper).



About DNA
DNA is perfect for the storage and readout of genetic information, which is stored in the way the bases pair one another on opposite sides of the double helix. Adenine (A) pairs with thymine (T) and cytosine (C) with guanine (G), with each pair forming a set of complementary hydrogen bonds. The all atom model (shown on the second side) has the sequence C-C-T-T-A-A-G-C-G. Notice that this sequence is palindromic. If you turn one end of it around, it will form the same base pair as another copy of the chain. Adenine overhangs one end of the model to the right... but be sure to tuck them up properly! The edges of the base pairs are exposed in the two grooves of the double helix; the wider major groove and the narrower minor groove. These can also be used to carry information that is read by proteins that interact with the double helix.

Go to pdb101.rcsb.org:

- READ the Molecule of the Month on DNA
- DOWNLOAD additional copies of the model, and WATCH a video demonstration of how to build it (Learn > Paper models)



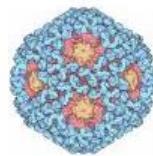
PDB-101 is the educational portal of RCSB Protein Data Bank (rcsb.org)



G Protein-Coupled
Receptor (GPCR)
(Paper Model)



HIV Capsid
(Paper Model)



Human Papillomavirus
(HPV)
(Paper Model)



Insulin
(Paper Model)



Quasisymmetry in
Icosahedral Viruses
(Activity Page)



tRNA
(Paper Model)



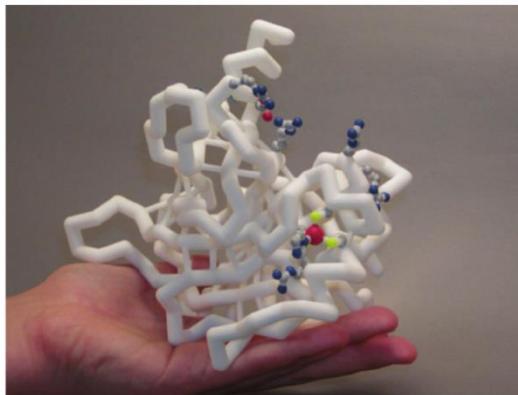
Zika Virus with and
without antibodies
(Paper Model)

Molecular models to aid teaching - 3D printed models



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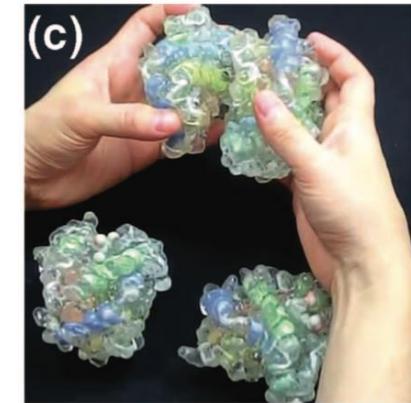
p53 tumor suppressor protein

[10.1002/bmb.2006.494034042649](https://doi.org/10.1002/bmb.2006.494034042649)



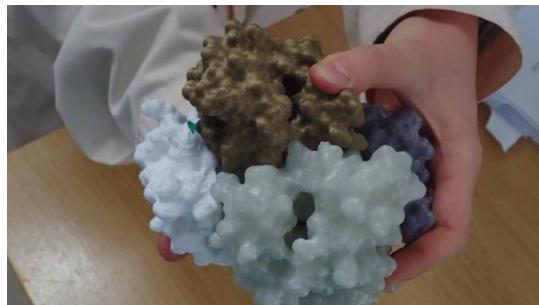
Leucine zipper

[10.1021/acs.jchemed.5b00207](https://doi.org/10.1021/acs.jchemed.5b00207)

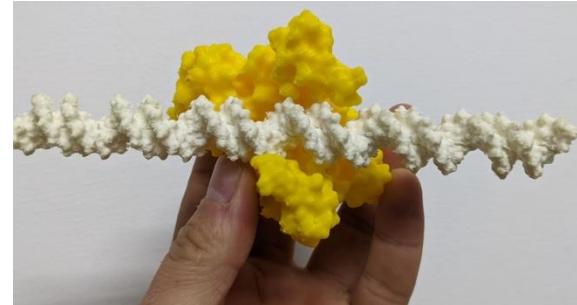


Human haemoglobin

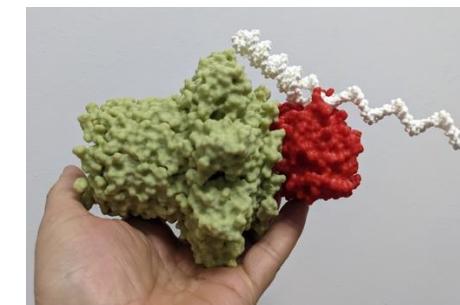
[10.1063/1.4739961](https://doi.org/10.1063/1.4739961)



Human deoxyhaemoglobin



EcoRI endonuclease and DNA



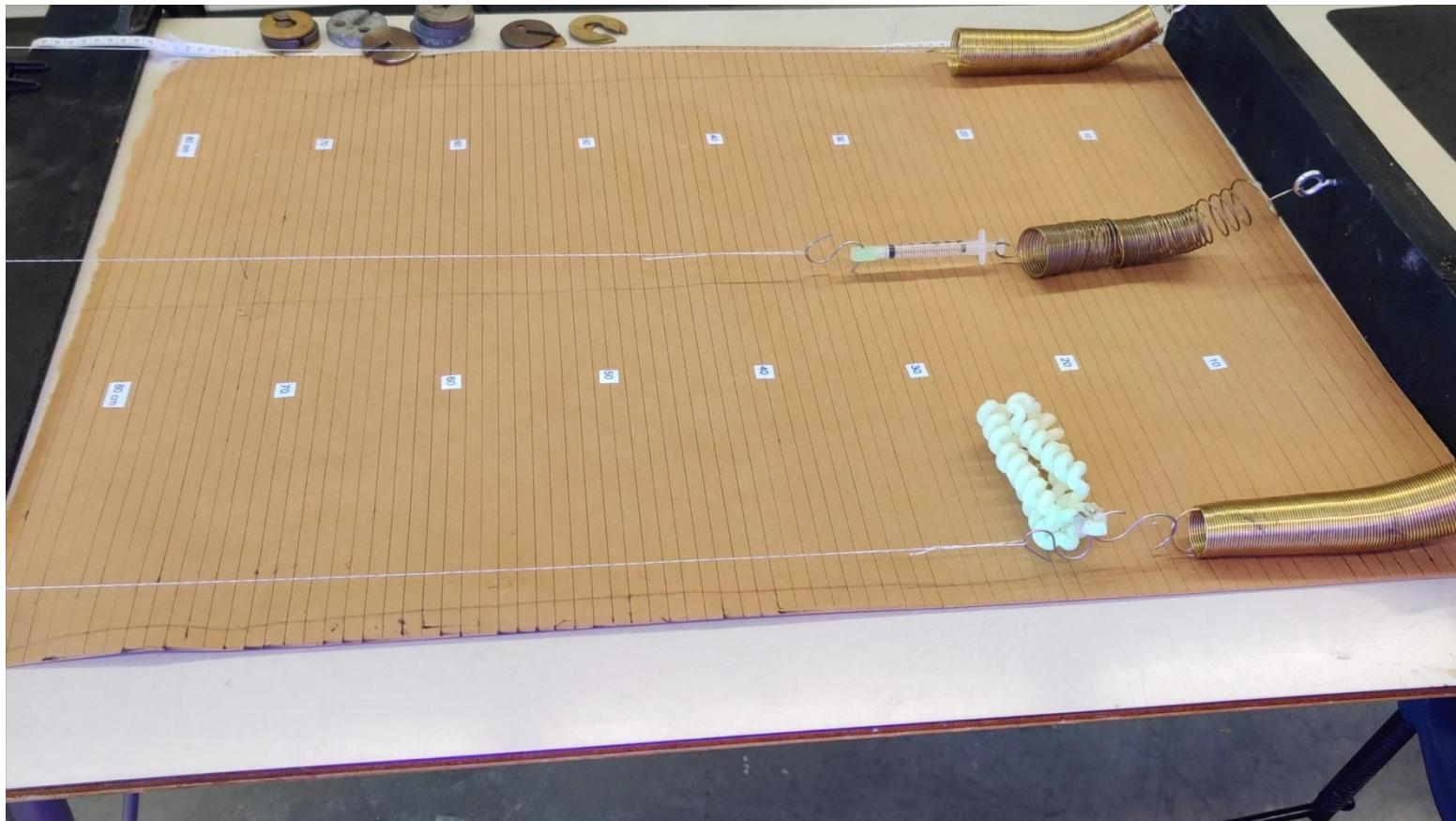
Nanopore sequencing complex

Molecular models to aid teaching - 3D printed models



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[10.1021/acs.jchemed.2c00231](https://doi.org/10.1021/acs.jchemed.2c00231)

Custom macromolecular models, adapted to the teacher's/demonstrator's requirements are needed !!!

Custom macromolecular models for teaching are need it



The custom macromolecular models should be:

Based on real scientific data;



Depicted using standardized representations;

Easy to edit and adapt to the outcomes of a specific lesson;

Cheap to fabricate and reproduce;

Easy to distribute

224 572 structures
1 068 577 CSM freely available

molecular visualization software
Chimera, Jmol, PyMol



3D printing can do that





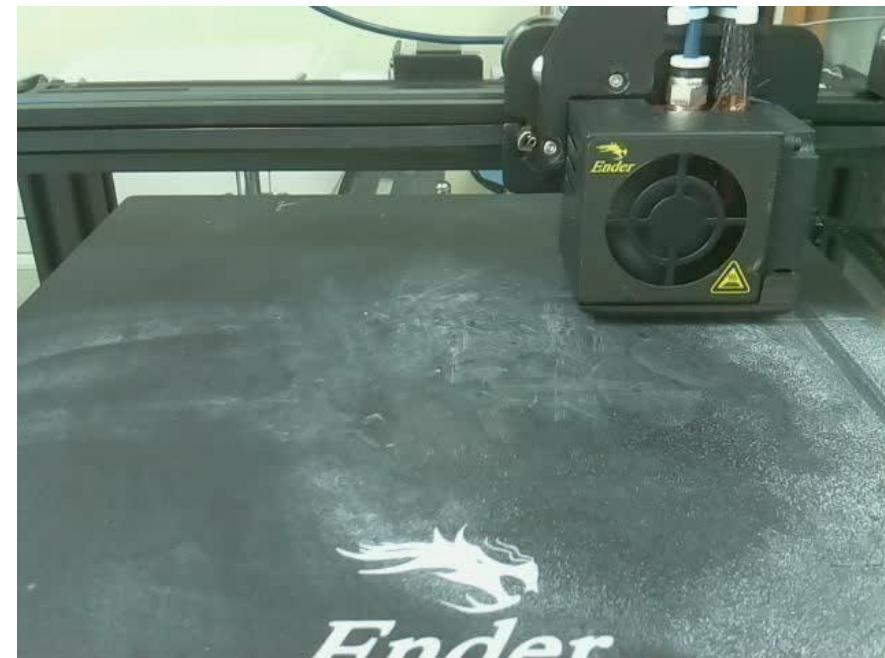
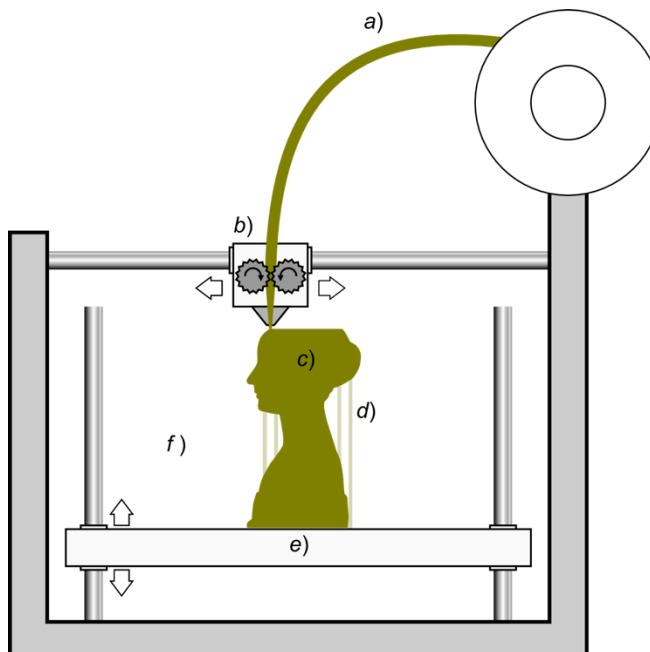
What is 3D printing?

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3D printing - construction of a three-dimensional object from a digital 3D model.
Also termed **additive manufacturing**.

Material extrusion / Fused filament fabrication (FFF) / fused deposition modeling (FDM)



Scopigno R et al. (2017). "Digital Fabrication Techniques for Cultural Heritage: A Survey". Computer Graphics Forum 36 (1): 6-21

3D printing using FFF is accessible



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Under 500\$ printers



20\$ - 40\$ Kg of plastic

Amazon Deliver to Iasi 700400 All pla

1-16 of over 1,000 results for "pla"

Sponsored TECBEARS PLA 3D Printer Filament 1.75mm Black, Dimensional Accuracy +/- 0.02 mm, 1 Kg Spool, Pack of 1 \$19.99 Save more with Subscribe & Save Ships to Romania

Sponsored OVERTURE PLA Filament 1.75mm with 3D Build Surface 200mm x 200mm 3D Printer Consumables, 1kg Spool... \$20.99 (\$1.05/10 items) Save more with Subscribe & Save Ships to Romania

Best Seller HATCHBOX PLA 3D Printer Filament, Dimensional Accuracy +/- 0.03 mm, 1 kg Spool, 1.75 mm, Black, Pack... \$22.99 Save more with Subscribe & Save Ships to Romania More Buying Choices \$21.50 (9 used & new offers)

OVERTURE PLA Filament 1.75mm with 3D Build Surface 200mm x 200mm 3D Printer Consumables, 1kg Spool... \$22.99 (\$1.15/10 items) \$25.99 Save more with Subscribe & Save Ships to Romania More Buying Choices \$18.99 (17 new offers)

Department
3D Printing Supplies
3D Printing Filament
Movies & TV
Movies & Films
Prime Video
TV Shows
See All 6 Departments

Avg. Customer Review
★ ★ ★ ★ ★ & Up
★ ★ ★ ★ ★ & Up
★ ★ ★ ★ ★ & Up
★ ★ ★ ★ ★ & Up

Brand
 HATCHBOX
 SUNLU
 OVERTURE
 TECBEARS
 3D Solutech
 MIKAD3
 eSUN
See more

3D Printing Materials
 ABS
 HIPS
 PETG
 PLA
 PVA
 Wood-Plastic Composite

3D Printer Filament Diameter
 1.75 mm
 2.85 mm
 3.00 mm

3D Printer Filament Weight
 Up to 499 g
 500 to 999 g
 1 to 1.9 kg
 2 kg & above

From Our Brands
 Our Brands

Packaging Option
 Frustration-Free Packaging

3D printing can be used in high schools/universities from low-income countries to fabricate macromolecular models adapted to teachers needs

Do these models make a difference in teaching?



A compensatory research study



Laura Nicoleta P. Razvan Stefan B.

	Week 1	Week 2			Week 3			Week 4 - Week 7
		Pre-test 1	Lecture 1 - Proteins Structure	Post-test 1	Pre-test 2	Lecture 2 - DNA structure	Post-test 2	
Group A	Announcement Recruitment Consent	2 days before lecture, 30 minutes, 13 questions	No intervention	2 days after lecture, 30 minutes, 13 questions	2 days before lecture, 30 minutes, 10 questions	Intervention	2 days after lecture, 30 minutes, 10 questions	Intervention and Feedback form
Group B			Intervention			No intervention		

The project was approved by the ethics committee at the Department of Phycology and Education Sciences, Alexandru Ioan Cuza University of Iași (no 186/29.01.2024). Students were informed prior to the start of instruction of the purpose and objectives of the investigation. Student participation was anonymous and voluntarily, and each student was presented with the opportunity to exclude him/herself from the study at any time. Information regarding data security, the type of information obtained, data storage procedures, and the measures taken to protect participants' anonymity was provided. Furthermore, students were assured that participation would have no bearing on any score assignment and that the results could be used for publication.

Do these models make a difference in teaching?



Evaluation of impact is key

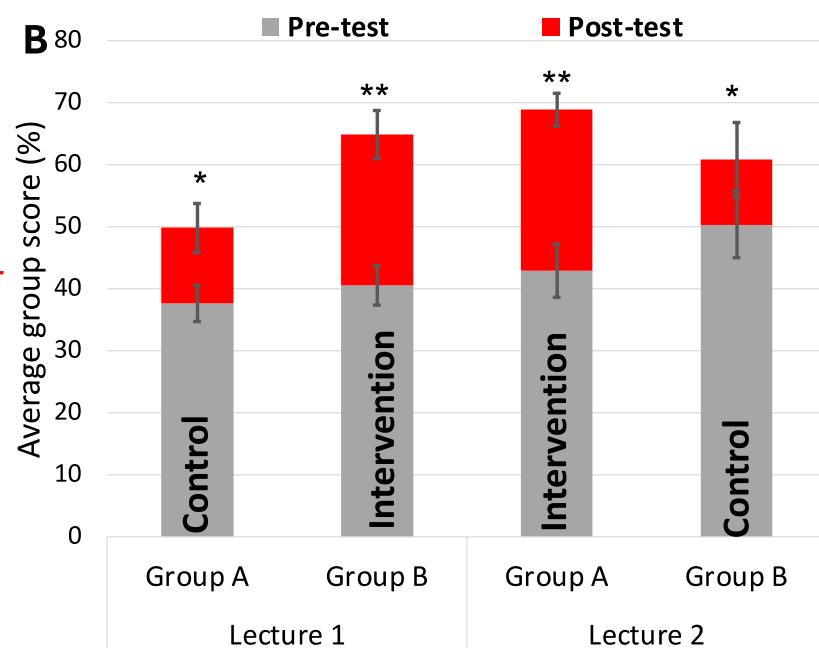
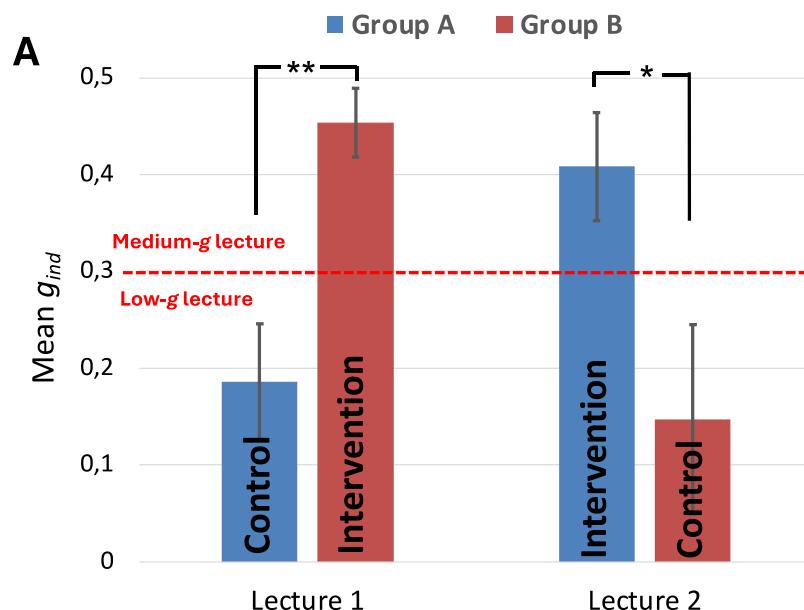
Models	NIH 3D DOI:	Assessment questions	Learning objective	Biomolecular visualization learning goals
Amino acids, peptides and proteins				
4 amino acids (L-Glycine, L-Tryptophan, L-Proline, L-Arginine) in different representations	10.60705/3dpx/21049.1	Q2, Q4	Recognize a variety of molecular representations (i.e. stick and space fill).	AR2.02 students will describe the atoms that are represented in different renderings. (novice)
Two insulin chains (PDBID 4ins, chains C and D) in 4 representations: sticks, balls and sticks, cartoon and surface	10.60705/3dpx/21051.1	Q1, Q2, Q3, Q4, Q7	Recognize a variety of molecular representations (i.e. stick and space fill). Identify features of the peptide backbone, including the amino and carboxyl ends, peptide bonds, and alpha carbon. N to C direction	MR1.01 given a rendered structure of a biological polymer students will be able to identify the ends of a biological polymer. (novice, amateur, expert) MR1.02 given a rendered structure, students will be able to divide the polymer into its monomer units. (novice)
Quaternary structure of human deoxyhaemoglobin with removable hem	10.60705/3dpx/14895.2	Q10, Q11	Describe why and how protein subunits interact to make the “quaternary structure”	TC2.06 Students can identify the levels of protein structure (e.g., parse a tertiary/quaternary structure into a series of secondary structures/motifs) and the ways in which they are connected from a three-dimensional structure. (Novice, Amateur, Expert)
Nucleotides and nucleic acids				
Deoxyribonucleotides and ribonucleotides in different representations.	10.60705/3dpx/21050.1	Q2,	Recognize a variety of molecular representations (i.e. stick and space fill).	AR2.02 students will describe the atoms that are represented in different renderings. (novice)
B-DNA dodecamer printed in flexible	10.60705/3dpx/14893.2	Q5	Understand the flexibility of DNA due to the higher number of rotatable bonds.	AG3.01 Students can identify a dihedral/torsion angle in a three-dimensional representation of a macromolecule. (Novice) AG3.02 Students can identify the planes between which a dihedral/torsion angle exists within a three-dimensional representation of a macromolecule. (Novice)

<https://biomolviz.org/>. Biochem Mol Biol Educ. 2017 Jan 2;45(1):69-75. doi: 10.1002/bmb.20991.

Results



Individual learning gain



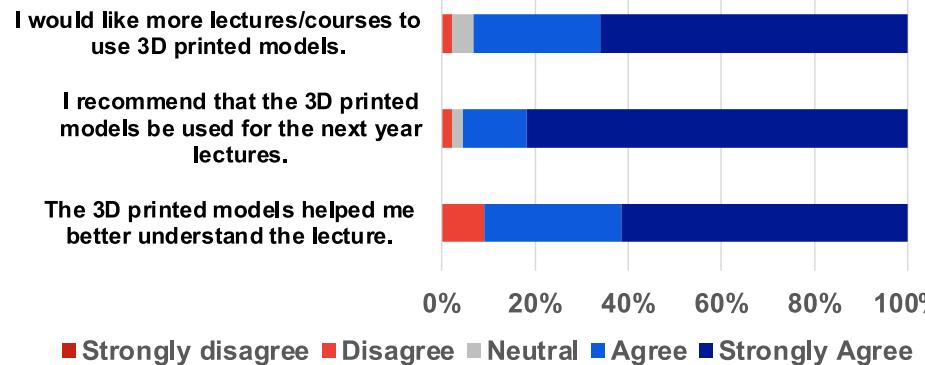
[10.1002/bmb.21902](https://doi.org/10.1002/bmb.21902)

Results

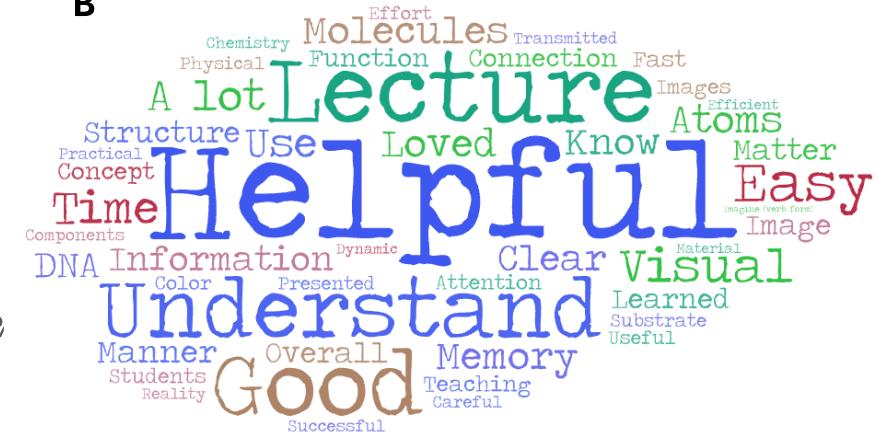


Free-form assessment

A



B



Boiangiu RS, Popa LN, Mihasan M. *Journal of Science Education and Technology*, submitted manuscript

“The 3D models were **verry useful as the **information and images were transformed into something physical** that I could touch. And this helped me better understand the content presented. **It is easier to understand a notion or a concept if one can hold it in its hand and turn it around to evaluated it from all the angles”.****

[10.1002/bmb.21902](https://doi.org/10.1002/bmb.21902)

Alternative ways of using 3D printed models in teaching



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Asking students to paint the models to recognize different structures



Alternative ways of using 3D printed models in teaching



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Guiding students to create and print their own models for presentations





Hard learned truth:

**Most teachers/students are verry enthusiastic about
the models,**

**but verry few can/want to use structural data
and design models.**

Introducing 3DP-Jmol - a script for automatic generation of 3D printable molecular models



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```
///This is where user input is required
load =4BNA //Please type here the 4-character code of the macromolecule of
interest from PDB - https://www.rcsb.org/. Alternatively, PubChem molecules can
be loaded using this command load :nicotine and codes from
https://www.ebi.ac.uk/pdbe/ using this command load *8jiv
var opt = "ballandstick" // works for ballandstick; backbone; trace; ribbon;
sesurface and sasurface.
var LigStruts = true // If ligands are to be connected with the macromolecule.
Recommended to be true for backbone; trace; ribbon; for surface (sesurface and
sasurface) needs to be false.
var NucProtStruts = 1 // If nucleic acids are to be connected with the
macromolecule. 0 or 1.
var PrintScaleFactorUser = 0; //This is where the size of the printed model is
indicated by the user as print scale. Should be 0 when first running the script to
generate a model printable at the maximum size. Based on the feedback from the
console, smaller scales could be selected by the user based on his preference. The
scale in the console is %, but here should be divided by 100. For example, for a
scale of 30%, here should be 0.3
var colorPrinter = 'no' #'yes' or 'no' // Please leave it to 'no' for now. Experimental
feature, not yet fully tested.
///This is where the required user input ends and the process starts. No edits
below this line should be required.
=====
```

The screenshot shows the Jmol Script Console window with the following output:

```
Jmol Script Console 16.3.7 2024-11-12 15:34

758 atoms selected
758 atoms selected
-- Reading information related to the molecule: size, smallest and largest atom, smallest bond length
-- Setting up 3D printing environment
32 hydrogen bonds
0 struts added
0 atoms selected
758 atoms selected
0 connections deleted
0 atoms selected
0 struts added
758 atoms selected
758 atoms selected

-----
--- Start of 3D Printing RECOMMENDATIONS for single color/material ----
Rendering and printing recommendations are provided for a medium size (i.e. Ender 3; Prusa MK3S+) FDM
-->Printed at a maximum allowed printing scale of 45 % , your model will be approx 210 mm x 124 mm x
-->Printed at a minimum printing scale of 2 % , your model will be approx 11 mm x 6 mm x 7 mm.
Your molecule is rather small. All styles are suitable and can be printed.
When deciding on the final dimensions and the corresponding scale, please keep in mind that:
- the minimum allowed scale for the Ball and stick style is 32 %;
- the minimum allowed scale for the Trace style is 23 %;
- the minimum allowed scale for the Ribbon style is 17 %;
- the minimum allowed scale for the Backbone style is 16 %;
----- The surface rendering can be as low as 2 %. Printing at smaller scales might still be possible, but at
----- End of 3D Printing RECOMMENDATIONS for single color/material ----
----- Printed at the current scale/user selected scale of 34 % , your model will be approx 155 mm x 92 mm x 105 mm ----
OK 18233684 Stl /Users/mariusmihasan/test.stl
Time for running the script version alfa1.public: 5062ms
$ >>
```

The console includes standard buttons at the bottom: Editor, Font, Clear, History, State, Undo, Redo, Close, Variables, and Help.



Development of 3DP-Jmol is supported by EDUMOL3D, Project PN-IV-P7-7.1-PED-2024-0343 financed by the Ministry of Research, Innovation and Digitization, UEFISCDI, Romania.

Introducing 3DP-Jmol - a script for automatic generation of 3D printable molecular models



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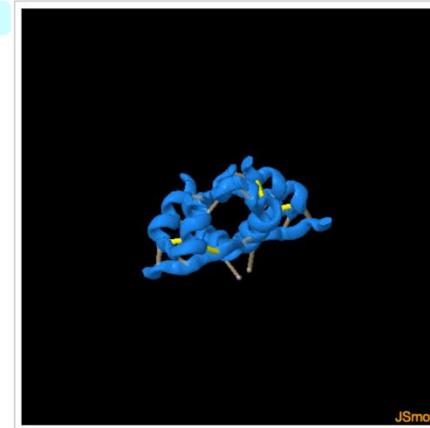


User options:

- include H atoms**
- PDB ID: 4ins
- Ball & Stick Backbone (protein/nucleic) Trace (protein/nucleic) Ribbon (protein/nucleic) Cartoon (protein) Blocks (nucleic)
 Spacefill Solvent-accessible surface Molecular surface
- Ligands connected to macromolecule. (Recommended for backbone, trace or ribbon. Disabled for surfaces)
- Create support links (struts) between protein and nucleic chains.
- Size of printed model: 0.2
This should be 0 when first running the script to generate a model printable at the maximum size. Based on the feedback from the console, smaller scales could be selected by users based on their preference. Scale in the console is %, but here it should be divided by 100. For example, enter 0.3 here for a scale of 30%.
- Prepare for color printing.
Very experimental. A decision is needed here if required to implement. If checked, output will be OBJ and color, if not, output will be STL and monochrome. OBJ files are not properly scaled yet, but can be done.

Updated: 2025-02-26 , 10:21:10.000Z

[Make file for 3D printer](#)



Angel Herráez
University of Alcalá,
Madrid, Spain

--- Start of 3D Printing RECOMMENDATIONS ---
Rendering and printing recommendations are provided for a medium size (ie. Ender 3; Prusa MK3S+) FDM 3D printer. Using SLA printers is possible, but not yet tested.
->Printed at a maximum allowed printing scale of 40% , your model will be approx 210 mm x 202 mm x 108 mm.
->Printed at a minimum printing scale of 3% , your model will be approx 16 mm x 15 mm x 8 mm.
Your molecule is medium-sized. All styles except Ball and Stick can be printed.
When deciding on the final dimensions and the corresponding scale, please keep in mind that:
- the minimum allowed scale for the Ball and stick style is 48%;
-- the minimum allowed scale for the Trace style is 23%;
-- the minimum allowed scale for the Ribbon style is 17%;
-- the minimum allowed scale for the Backbone style is 16%;
---- The surface rendering can be as low as 3%. Printing at smaller scales might still be possible, but atomic details (H atoms) will be lost.
--- End of 3D Printing RECOMMENDATIONS ---

Printed at the current scale/user selected scale of 20% , your model will be approx 105 mm x 101 mm x 54 mm.

Help:

STL file viewers: [online](#) :: [ModuleWorks STView](#) :: [Cravesoft STL Viewer](#)

WRL file viewers: [online](#) :: [FreeWRL](#)

TasksBoard | Desktop app

https://biomodel.uah.es/JSmol2/Marius_Mihasan/PDB2STL.htm



Development of 3DP-Jmol is supported by EDUMOL3D, Project PN-IV-P7-7.1-PED-2024-0343 financed by the Ministry of Research, Innovation and Digitization, UEFISCDI, Romania.

3DP-Jmol - integration with Proteopedia



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JB Journal of Biological Inorganic Chemistry A publication of the Society of Biological Inorganic Chemistry

Structure of Anticancer Ruthenium Half-Sandwich Complex Bound to Glycogen Synthase Kinase 3B
G. Atilla-Gocumen, L. Di Costanzo, E. Meggers [1]

Molecular Tour
A crystal structure of an organometallic half-sandwich ruthenium complex bound to the protein kinase glycogen synthase kinase 3B (GSK-3B) has been determined (PDB entry 3m1s) and reveals that the inhibitor binds to the ATP binding site via an induced fit mechanism utilizing several hydrogen bonds and hydrophobic interactions. Importantly, the metal is not involved in any direct interaction with the protein kinase but fulfills a purely structural role. The unique, bulky molecular structure of the half-sandwich complex with the CO-ligand oriented perpendicular to the pyridocarbazole heterocycle allows the complex to stretch the whole distance sandwiched between the faces of the N- and C-terminal lobes and to interact tightly with the flexible glycine-rich loop.

Although this complex is a conventional ATP-competitive binder, the unique shape of the complex allows novel interactions with the glycine-rich loop which are crucial for binding potency and selectivity. It can be hypothesized that coordination spheres which present other ligands towards the glycine-rich loop might display completely different protein kinase selectivities.

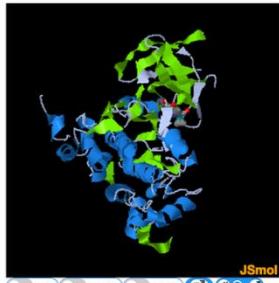
PDB reference: Structure of Ruthenium Half-Sandwich Complex Bound to Glycogen Synthase Kinase 3, 3m1s.

References

Proteopedia Page Contributors and Editors (what is this?)
David Canner, Alexander Berchansky, Jaime Prilusky

This page complements a publication in scientific journals and is one of the Proteopedia's Interactive 3D Complement pages. For additional details please see i3DC.

1.



Please choose the parameters to tailor the aspect of the resulting printed model on page **Journal:JBIC:2**

Scheme **Proteopedia Scene**

Hydrogen atoms **OFF**

Recommended to be off unless you have particular reasons to have the hydrogen atoms shown in the model. H atoms might be required when the model is represented as ball and sticks, or when ligands are present. If not H atoms are not mandatory, keep in mind that keeping this option on will increase the minimum scale at which the model can be printed.

If nucleic acids are to be connected with the macromolecule.

If ligands are to be connected with the macromolecule.

Nuclear struts **ON**

Ligand struts **ON**

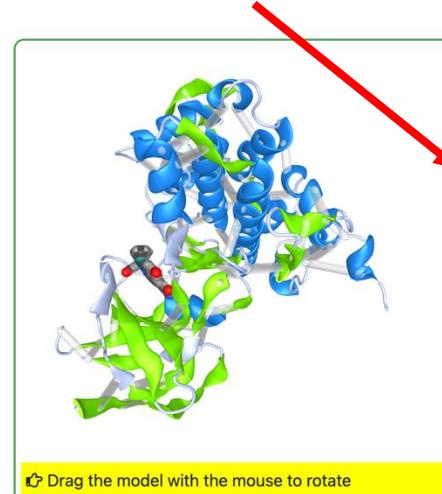
Printer **Multimaterial/Multicolor**

Printer scale **32 %**

Make printer files

2.

Note: Before processing, we removed from the structure solvent (UREA, SO4, PO4, HOH, DOD, WAT), NA, K, CL, BR, GOL, DIO, DOX, NO, NO3, EDO, DMS, FMT, ACT, IPA, and they **will not appear** on the printed model.



3.

Page: **Journal:JBIC:2**

Scheme: scene

Scale: 32%

Ligand struts: true

Nucleic acids struts: true

Download Files **Download SCRIPT**

With these OBJ and MTL files, your printer will generate a **Scene model of Journal:JBIC:2**

The size of your model will be approximately (x,y,z) **192 x 210 x 194 mm**.

Generate files for the **Same structure** with different parameters.



Programming and implementation by Jaime Prilusky. STL/OBJ/MTL files generated with **Jmol** and **3DP-Jmol**. Model **3DP-Jmol** preview powered with [Online 3D viewer](#)

Summary



**Usage of physical models of (macro)molecules improves learning outcomes,
but need to be tailored to teachers needs**

**3D printing offers a cheap way of fabricating and distributing molecular models
applicable in low-income countries**

The 3D printed models were received by students as being helpful as it provided a hands-on advantage. Allowing students 3-5 minutes to handle models converted a low-g lecture into a medium-g lecture.

Workflows for printing macromolecular models from PDB are available and are based on free software

Updates and new printed models



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Identification and Characterization of Biological Active Molecules

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About

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Păcurari Ticău Alexandru cel Bun Iași

- The group is based at the Faculty of Biology, Alexandru Ioan Cuza University of Iasi, Romania. It consists of several academia members and researchers, technicians as well as students and Ph.D's which share common research interests.
- The group is based at the Faculty of Biology, Alexandru Ioan Cuza University of Iasi, Romania. It consists of several academia members and researcher... See More

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521 people follow this

<http://www.bio.uaic.ro/cercetare/grupuri/bioactive/content/people/people.html>

0232 201 102

Send Message

Create Post

Photo/Video Check in Tag Friends

PINNED POST

Identification and Characterization of Biological Active Molecules

March 9 at 2:09 PM

Ever wondered how an antibody looks like? Now you can print your own molecular model of an antibody using a 3D printer. Instructions and printable files available at <https://3dprint.nih.gov/discover/3DPX-015554>. Details in the molecule are available at <https://pdb101.rcsb.org/motm/21/>

V-ați întrebat cu arată în realitate un anticorp? Acum poate vizualizat și manipulați sub forma unui model tipărit la imprimanta 3D! Modelele tridimensionale gata de tipărit pentru doi anticor... See More

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3DP-Jmol

A Practical Introduction to 3DP-Jmol and 3D Printing



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www.uaic.ro

Marius Mihăşan, PhD.

Faculty of Biology

Alexandru Ioan Cuza University of Iași, Romania

E-mail: marius.mihasan@uaic.ro

<https://github.com/mariusmihasan/3DP-Jmol>



How difficult it is to create your own 3D printable molecular model?

Let's walk through the process together, and judge yourself

3D printed models - how to get them



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The easy, but not necessarily the cheap way:



Home Examples of our work FAQs Contact Us

SARS-CoV-2 Spike Protein



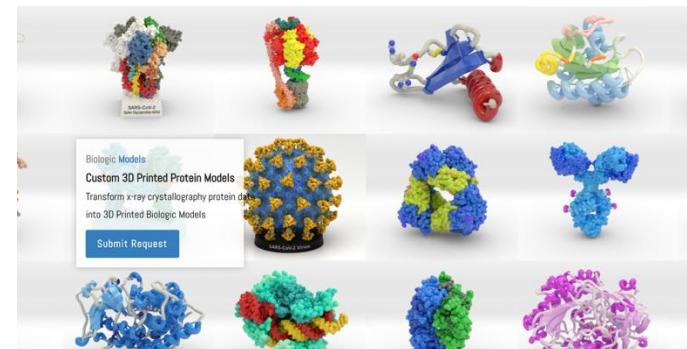
Molecular Models in collaboration with Lee 3D, have been working with life-science researchers and scientists across the UK and beyond to bring molecular structures to life using colour 3D printing. We printed the SARS-CoV-2 spike trimer for Prof. Jason McLellan (University of Texas at Austin).

Copies of the model have been gifted to the vaccine development teams at Oxford University and

BIOLOGIC MODELS

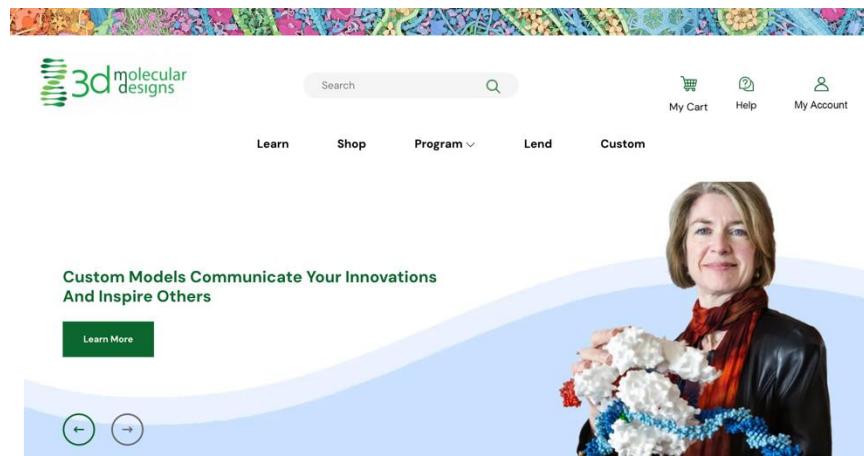
Home Explore 3D Print Shop Contact

0 items



<http://www.molecmodels.co.uk/>

<https://biologicmodels.com/>



Custom Models Communicate Your Innovations
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Learn More



<https://3dmoleculardesigns.com/>

3D printed models - how to get them



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The almost easy, but a bit cheaper way:

A1. Find an already available model at:

<https://3dprint.nih.gov/>

<https://modelemoleculare.ro/>

OR



A2. Automatically create your own model with
Proteopedia Print3D tool

or

OR

A3. Ask somebody else to do it such as:

<https://modelemoleculare.ro/product-category/modele-la-cerere/>

AND

B. Fabricate your model using your own 3D printer or access an on demand 3D printing service
printari-3d.ro 3dp.ro fablab.ro

Generating printable files on Proteopedia

Proteopedia integrates a dedicated Print3D tool within each molecular scene, enabling logged-in users to effortlessly generate 3D printable molecular models directly from its pages. The tool is powered by 3DP-Jmol (3), a script that analyses the structural data and automatically scales the model's geometry to match the printable volume of a medium-size desktop 3D printer (e.g., Endure3, 210x210x210 mm). During this process, the tool evaluates the molecular bounding box, atom radii, and bond lengths, then proportionally adjusts all dimensions to achieve a realistic and mechanically robust print scale — preserving scientific accuracy while ensuring manufacturability. For advanced users, 3DP-Jmol (3) may also be used in conjunction with the Jmol (3) program, providing full access to its scripting capabilities and advanced export features.

Step-by-step guide for automatic generation of printable files on Proteopedia

Open a structure and access the Print3D tool

Log in with your Proteopedia Username and password. Navigate to any Proteopedia page (for example, [Introduction_to_protein_structures](#)). The corresponding 3D structure will load in the viewer on the right.

At the bottom of the structure display window, locate and click the Print3D button. The tool will launch and begin analyzing the current molecular structure. This process may take some time to complete, depending on the size of the structure. Please wait until the message Analyzing structure... disappears and the next page is displayed — this marks the start of the two-step printing workflow.

Select a molecular representation and a printing scale

In this new page, some user input is required. Each option includes a short explanation; the key steps are outlined below, but feel free to explore and adapt the settings that best fit your use case.

(1) Choose a molecular representation from the Selection list, based on your goal:

- **Ball & Stick** — for most molecules. Effective for teaching protein folds.
- **Surface** — to highlight molecular surfaces.
- **Surface + Ball & Stick** — to highlight molecular surfaces and show ball-and-stick details.

(2) In the Printer section, select whether you want a single-color or a multi-color print.

- **Single color** — for most molecules.
- **Multi-color** — for molecules containing multiple distinct components.

(3) In the Printer scale section, set the desired size of the printed model. The tool constrains safe sizes based on the chosen representation and displays the physical dimensions (mm). Important! Please note the **printer scale value in %** if it is going to be required downstream in the next section of this workflow, [Printing files from Proteopedia](#).

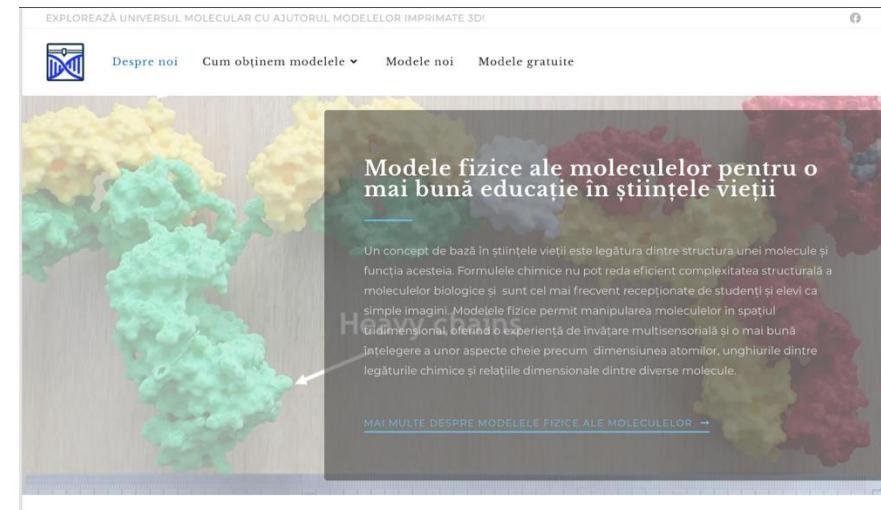
(4) When ready, click the green Make printer files button. Please wait patiently until the Generating files for 3D printing... message disappears and the final step is displayed.

Download the .STL or .OBJ files

In this final page, a 3D preview of the generated model is displayed. You can use the mouse to rotate, zoom, and inspect the model from different angles. If the result meets your needs, click the green (A) Download files button and save the compressed .zip archive containing the .STL or .OBJ files on your computer. If your model needs further improvements, hit the green (B) Same structure button to return to the previous screen and adjust your settings.

EXPLOREAZĂ UNIVERSUL MOLECULAR CU AJUTORUL MODELELOR IMPRIMATE 3D!

Despre noi Cum obținem modelele ▾ Modele noi Modele gratuite



Un concept de bază în științele vieții este legătura dintre structura unei molecule și funcția acesteia. Formulele chimice nu pot reda eficient complexitatea structurală a moleculelor biologice și sunt cel mai frecvent recepționate de studenți și elevi ca simple imagini. Modele fizice permit manipularea moleculelor în spațiu tridimensional, oferind o experiență de învățare multisensorială și o mai bună înțelegere a unor aspecte cheie precum dimensiunea atomilor, unghierile dintre legăturile chimice și relațiile dimensionale dintre diverse molecule.

[MAI MULTE DESPRE MODELELE FIZICE ALE MOLECULELOR](#) →



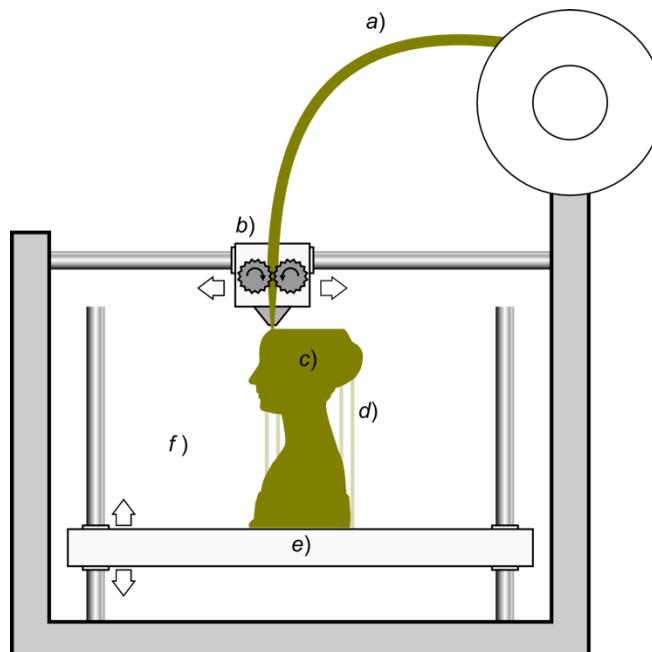
What is 3D printing?

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3D printing - construction of a three-dimensional object from a digital 3D model.
Also termed **additive manufacturing**.

Material extrusion / Fused filament fabrication (FFF) / fused deposition modeling (FDM)



Scopigno R et al. (2017). "Digital Fabrication Techniques for Cultural Heritage: A Survey". Computer Graphics Forum 36 (1): 6-21



Steps involving fabricating a macromolecular model



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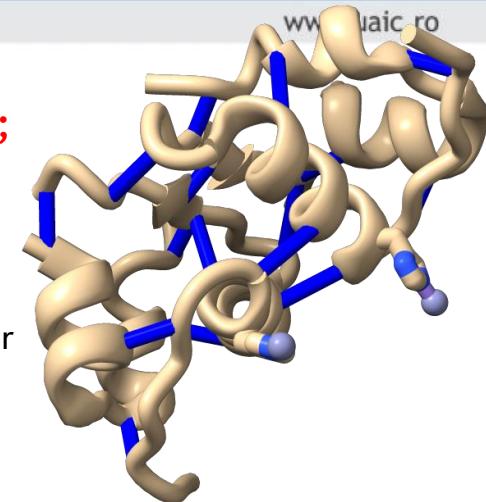
www.uaic.ro

Download structure from

PDBe **PDB** **PDBj**
Protein Data Bank in Europe Protein DATA BANK Protein Data Bank Japan

PDB or CIF file

1. Choose or combine **visualization styles**;
2. Add H bonds or **create struts** to make the model more sturdy (mandatory for cartoon and balls and sticks models, not required for surface);
3. Increase the thickness of each printed element and/or improve the smoothness for molecular surfaces.



Visualize and prepare the model in

UCSF ChimeraX / Jmol

STL file

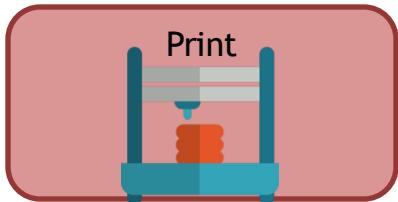
1. Set the printing scale;
2. Orient the model on printing bed;
3. Set printing resolution;
4. Set shell wall thickness and infill %;
5. Automatically add support;
6. Slice the model;
7. Send the resulting gcode to printer (via SD-Card, USB or WiFi)

Prepare the file for printing using

Cura/PrusaSlicer/BambooStudio

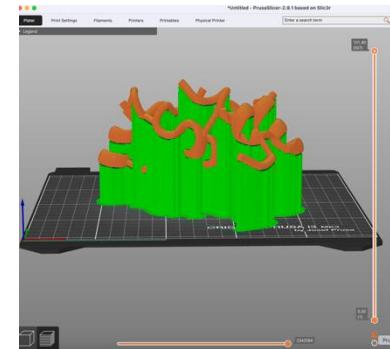
GCODE file

Print



28.10.2025
10.3791/55427 ; 10.1002/bmb.21493

A. Generate the computer model



B. Print the model



Support material removal



C. Clean up and finalize the physical model

Slide 22 / 25

A. How to generate of the computer model (or .STL/.OBJ file)



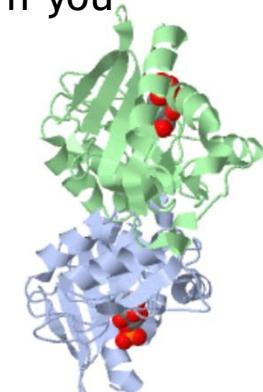
A1. Using **Proteopedia** and **Print3D** tool;

- Navigate to https://proteopedia.org/wiki/index.php/Main_Page
Alternatively, search in Google for “Proteopedia” to navigate to the link above
- Log-in with your username and password
- On the left side, locate the **Navigation** panel and hit **Table of Contents**
- Expand the folders and chose your **molecule of interest**. *Alternatively*, if you know already a PDB ID of interest, type it in the **Search box**.
- The new page that opens has on the right-side a section displaying a structure. Most, if not all pages in Proteopedia, have such a **Structure Section**. The content of the **Structure Section** can be modified by clicking in any on any of the **green links**. The **Structure Section** is initially opened in view only mode - recognizable by the **Display Interactive Model** button.

navigation

- Main Page
- Table of Contents
- Structure Index
- Random
- Recent Changes
- Help
- Cookbook

search

Display Interactive Model

Ribose-5-phosphate isomerase A dimer complex with ribulose-5-phosphate, Jemw

Drag the structure with the mouse to rotate

A. How to generate of the computer model (or .STL/.OBJ file)



- Click on the **Display Interactive Model** button to activate an extra set of controls, including the **Print3D** tool. Clicking the **Print3D** will start the two-step interactive conversion process;

The screenshot shows a 3D molecular model of a Ribose-5-phosphate isomerase A dimer complex with ribulose-5-phosphate. The interface includes various controls like spin, quality, labels, and a note about biological assembly confidence. A prominent red arrow points from the 'Print3D' button at the bottom left to the detailed 'Print3D' configuration panel on the right.

Print3D Configuration Panel:

- Please choose the parameters to tailor the aspect of the resulting printed model on page *Ribose-5-phosphate_isomerase*
- Scheme: Trace
- Hydrogen atoms: OFF
- Nuclear struts: ON
- Ligand struts: ON
- Printer: Single Color/Material
- Printer scale: 25 %
- Make printer files
- Note: Before processing, we removed from the structure solvent (UREA, SO4, PO4, HOH, DOD, WAT), NA,K,CL,BR,GOL,DIQ,DOX,NO,NO3,EDO,DMS,FMT,ACT,IPA, and they **will not appear** on the printed model.
- What, How and other tips at [Print3D Help](#)
- Browse our [Gallery of 3DPrinted Models](#)

A. How to generate of the computer model (or .STL/.OBJ file)



Step one:

Please choose the parameters to tailor the aspect of the resulting printed model on page *Ribose-5-phosphate_isomerase*

Scheme Ribbon
Hydrogen atoms OFF

Recommended to be off unless you have particular reasons to have the hydrogen atoms shown in the model. H atoms might be required when the model is represented as ball and sticks, or when ligands are present. If not H atoms are not mandatory, keep in mind that keeping this option on will increase the minimum scale at which the model can be printed.

Nuclear struts ON
If nucleic acids are to be connected with the macromolecule.

Ligand struts ON
If ligands are to be connected with the macromolecule.

Printer Multimaterial/Multicolor
Printer scale 25 %
You may set from 17% to 25%. With the current scale, your model will be approximately (x,y,z) 203 x 108 x 184 mm.

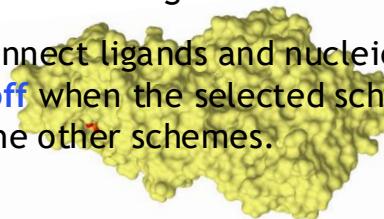
Make printer files

Note: Before processing, we removed from the structure solvent (UREA, SO4, PO4, HOH, DOD, WAT), NAK, CL, BR, GOL, DIO, DOX, NO, NO3, EDO, DMS, FMT, ACT, IPA, and they will not appear on the printed model.

- What, How and other tips at [Print3D Help](#)
- Browse our [Gallery of 3DPrinted Models](#)

Surface

Great for arguing the complementary of molecular shapes
Extremely easy to print without any processing
Works well also for large macromolecular complexes



Struts to connect ligands and nucleic acids to the models.
Should be **off** when the selected scheme is **Surface**. Can be **on** for all the other schemes.

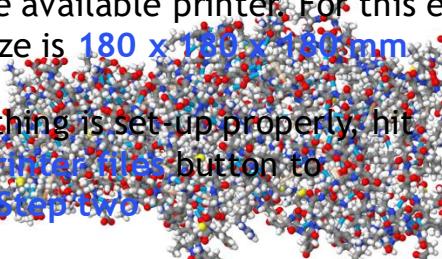
Depending on the available printer, color models can also be generated. Generation of Multicolor/ Multimaterial Struts have been added. All elements are thicker. Works for small proteins; Can be difficult to print at times it to **Single Color/Material** for this exercise.



Size of your final printed model. Usually, larger is better but takes more time and material. Smaller is faster, but fine details might be lost and is always more difficult to print.

Ball & Stick

The tool automatically select the largest possible size for you and calculates the final dimensions in mm. Adjust based on the available printer. For this exercise, the maximum size is 180 x 180 x 180 mm



Once everything is set-up properly, hit the **Make printer files** button to proceed to **Step two**.

A. How to generate of the computer model (or .STL/.OBJ file)



Step two:

Preview of the rendered model. Can be rotated for a closer examination.

Drag the model with the mouse to rotate

Page:
Ribose-5-phosphate_isomerase

Scheme: backbone
Scale: 25%
Ligand struts: true
Nucleic acids struts: true

With this STL file, your printer will generate a **Backbone** model of the **Biological Assembly** of **Ribose-5-phosphate_isomerase**

The size of your model will be approximately (x,y,z) **203 x 108 x 184 mm.**

Applied setting for rendering the model. Please **note the scale in %**. It is going to be needed in downstream steps.

Finally download the files in your computer

Generate files for the
 with different
parameters.

If the model is not as expected, hit this button to get back to **Step One**

✓ Programming and implementation by [Jaime Prilusky](#). ✓ STL/OBJ/MTL files generated with [Jmol](#) and [3DP-Jmol](#). ✓ Model preview powered with [Online 3D viewer](#)

- What, How and other tips at [Print3D Help](#)
- Browse our [Gallery of 3DPrinted Models](#)

A. How to generate of the computer model (or .STL/.OBJ file)



A2. Using 3DP-Jmol and Jmol offline;

1. Download and unpack **Jmol**;

<https://jmol.sourceforge.net/>

Alternative molecular visualization programs that will work but are not covered here:

1. ChimeraX - <https://www.rbvi.ucsf.edu/chimerax/>
2. PyMOL - <https://www.pymol.org/> some extra steps in CAD software are required
3. Molecular Maya -<https://clarafi.com/tools/mmaya/> - the plugin is free, but the Maya software is not
4. Mol* - <https://molstar.org/>

2. Access and copy **3DP-Jmol** code by:

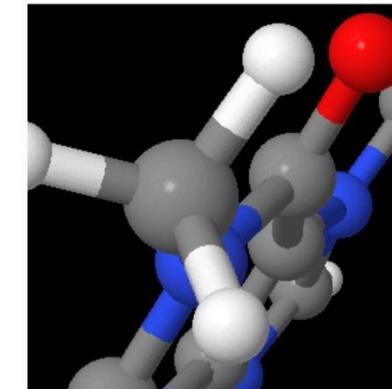
- Access the 3DP-Jmol Hithub at <https://github.com/mariusmihasan/3DP-Jmol>
- Click on the file [3DP-Jmol.v.alfa1.public](#)
- Select the whole text and copy it.

3. Open a text editor of your choice (**Microsoft word works also**) and paste the code. Edit the first lines as indicated to select your molecule of interest and other relevant parameters. Read carefully and only edit the lines indicated. Do not close the text editor window!!

4. Open the previously unzipped Jmol application and navigate in the menu to **File>Console**.... A new window entitled **Console** will open;



Jmol: an open-source Java viewer for chemical structures in 3D
with features for chemicals, crystals, materials and biomolecules



JSmol is the HTML5 modality of Jmol, able to be embedded into web pages. All the functionality of Jmol (as a standalone application) is also present in JSmol.

JSmol is an interactive web browser object.

This is a still image, but you can see several animated displays of Jmol abilities by clicking [here](#) or on the image itself.

(The JSmol library may take some seconds to load. Please, wait and do not reload the page in the meantime.)

Quick links:

[Download Jmol+JSmol](#). The complete package is named Jmol-xx.xx.xx-binary.zip ; inside it you will find:

Jmol.jar , the Jmol application (runs without installation, even from a portable disk, but needs Java installed)
jsmol.zip , the package needed for implementing JSmol in web pages (does not need Java)

[Main project page](#) (source code) for Jmol+JSmol at SourceForge.

[JSmol scripting documentation](#)

SourceForge awards for the Jmol project (March 2022):



A. How to generate of the computer model (or .STL/.OBJ file)



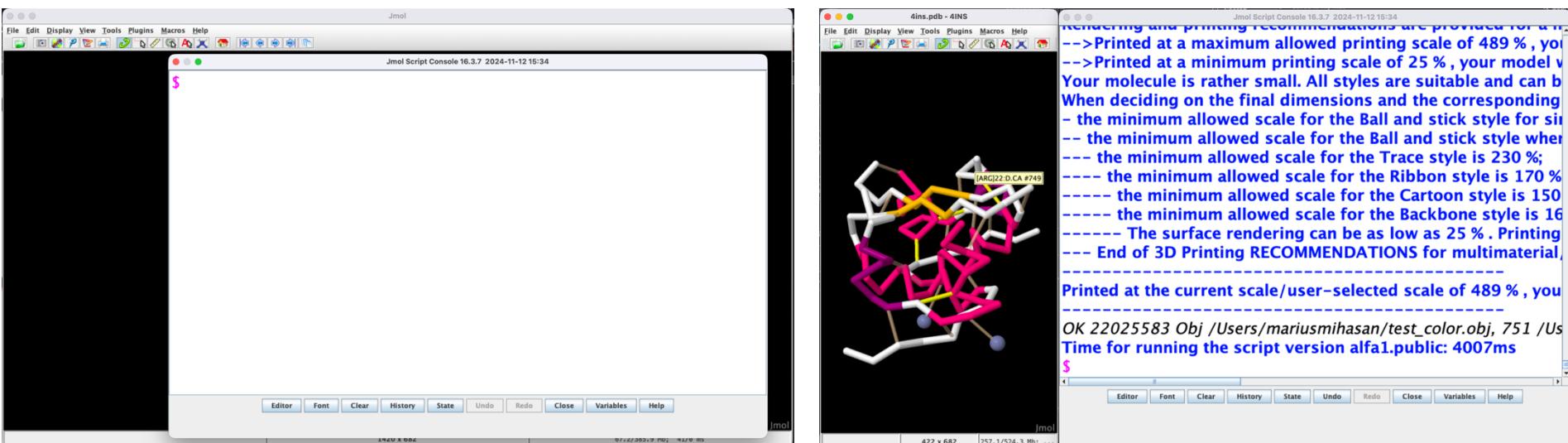
4. Copy the entire content of the text file edited in step 3 and paste it in the **Console** window using the **Ctrl-V** keyboard combination (or **Cmd+V** for Mac);

5. Wait patiently until JMol generates your printable file. This should be signaled by the appearance of a text similar to:

OK 20527284 Stl /Users/mariusmihasan/test.stl

Time for running the script version alfa1.public is: 4956ms

6. Check the instructions in the **Console** and, if required, based on the indications and your choice, come back to step 3 and repeat. The path for the **test.stl** file generated is indicated before the last line in the **Console**. Print it and enjoy!



B. 3D Printing the computer generated model



1. Download and install **BambuStudio**;

<https://bambulab.com/en/download/studio>

Alternative slicer programs used to control 3D printers:

1. Prusa Slicer - https://www.prusa3d.com/page/prusaslicer_424/
2. Ultimaker Cura - <https://ultimaker.com/software/ultimaker-cura/>
3. Slic3r - <https://slic3r.org/>
4. Simplify3D - <https://www.simplify3d.com/> not free

Choosing one or another depends on the printer one has available

Bambu Studio

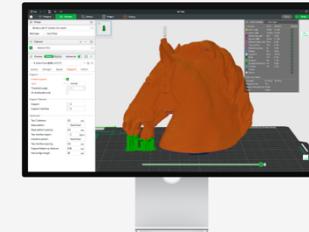
Bambu Studio is an open-source, cutting-edge, feature-rich slicing software. It contains project-based workflows, systematically optimized slicing algorithms, and an easy-to-use graphical interface, bringing users an incredibly smooth printing experience.

Bambu Studio (Win)

Windows 10 (64-bit) or above.

Bambu Studio (Mac)

macOS 10.15 or above.



[Download the Linux version from GitHub, or check the latest release notes](#) >

2. Open **BambuStudio** and run the **Configuration Wizard**. Accept all the defaults, except for the printer selection screen. Here make sure that **only the BambuLab A1 mini printer is selected** (not critical, but helps).

3. Download the configuration bundle. Link in the e-mail from the organisers

<https://drive.google.com/file/d/1YM3sqMOEYSa7XxrpmzS5EqOsNFwNfaT8/view>

4. In **BambuStudio** navigate to **Menu > File > Import > Import Configs...**

Point to the newly downloaded file .BBSCFG and hit **Open**

What we just did is to install the printer control software and configs required to run my printer

B. 3D Printing the computer generated model



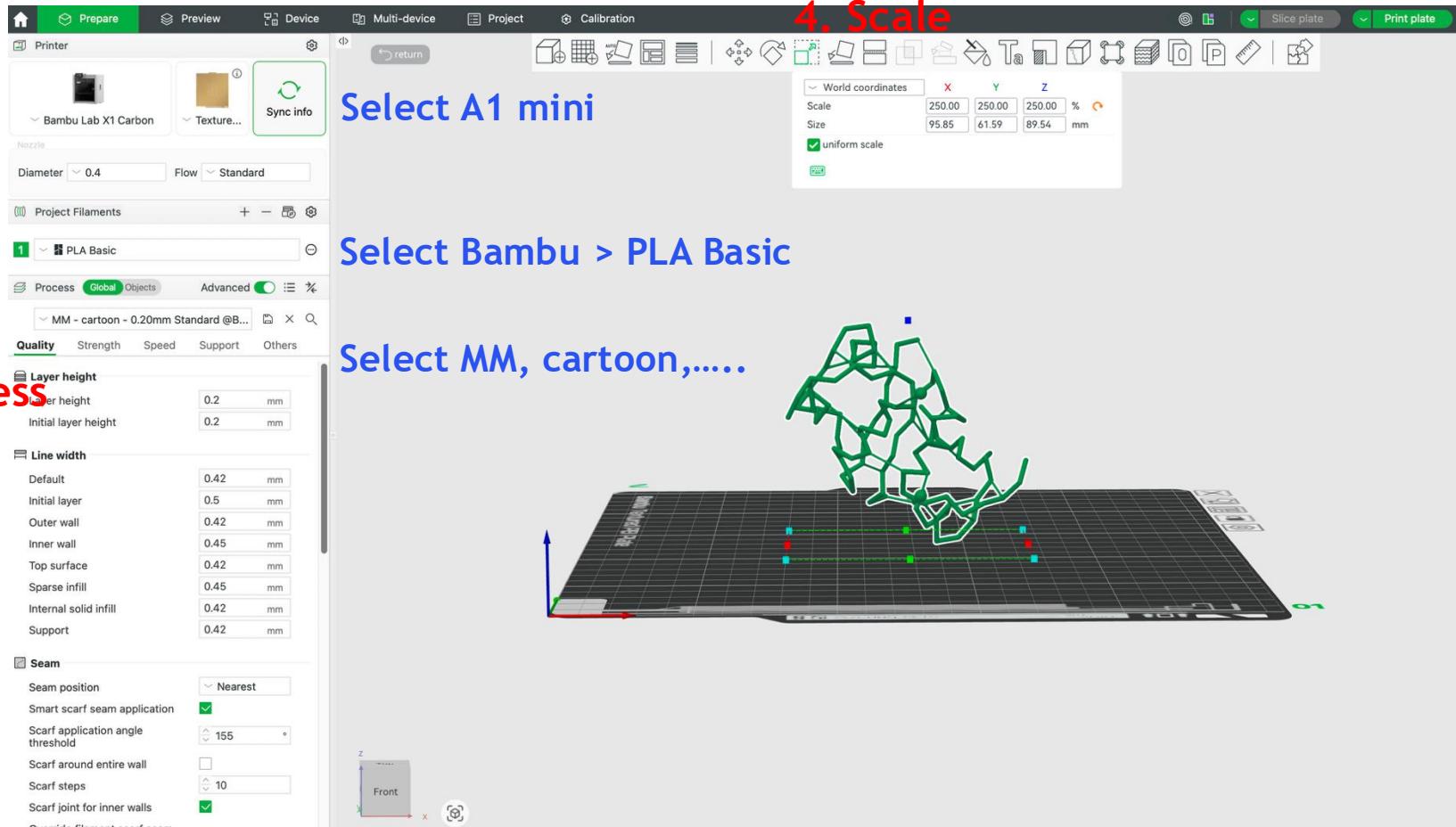
4. Load the created .stl file - In **BambuStudio** navigate to **Menu > File > Import > Import STL/3MF/STEP...**
Point to the .stl file and hit **Open**

Set

1. Printer

2. Material

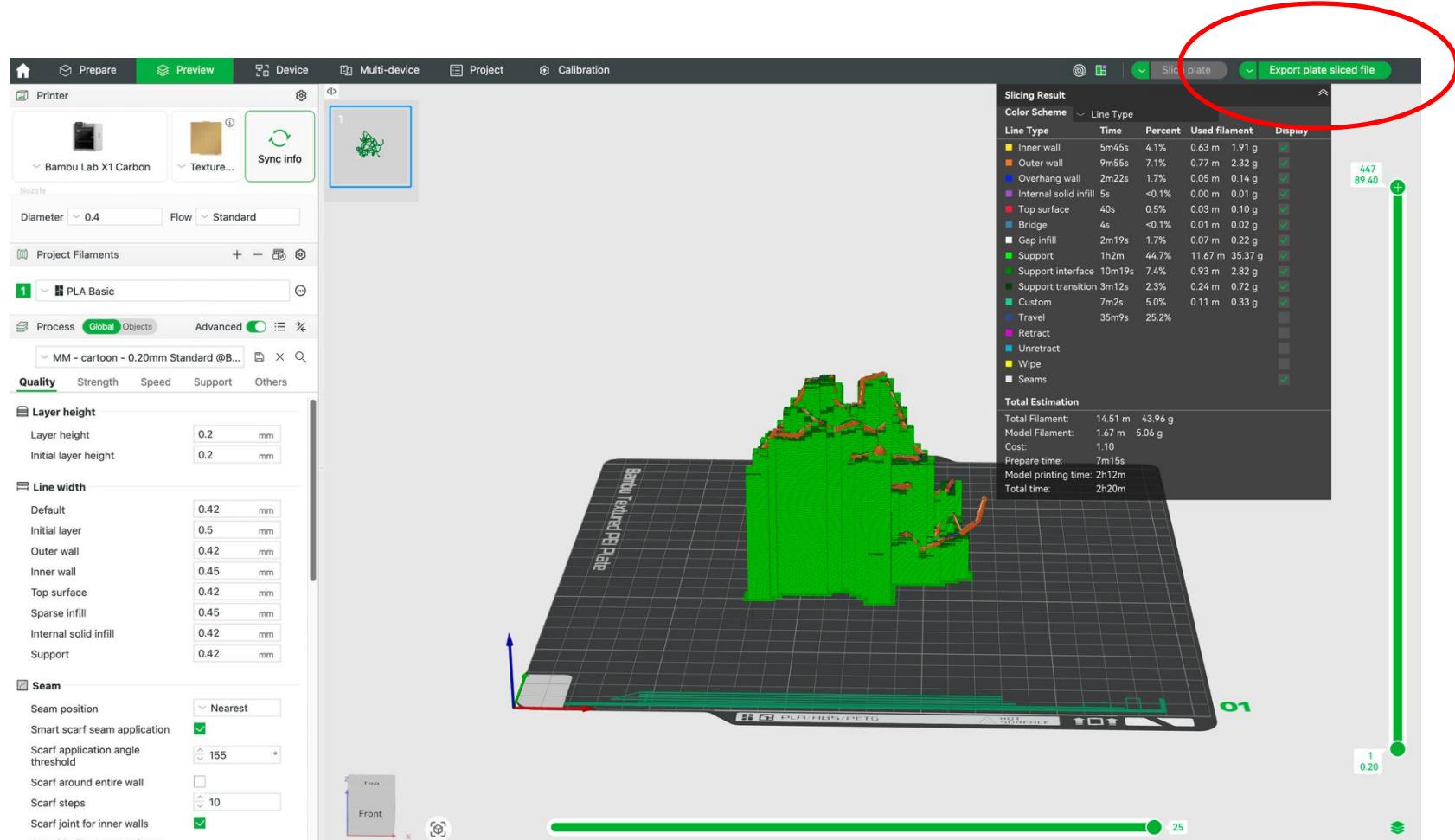
**3.
Print/process
settings**



B. 3D Printing the computer generated model



5. Export .gcode file and transfer it to the printer via a SD-Card



Guidelines and more details are available



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User:Marius Mihasan/Print3D help

< User:Marius Mihasan

Contents [hide]

- 1 Proteopedia and 3D Printing
- 2 «3D Printing 101»: an introduction to 3D printing
 - 2.1 Printer Types: FDM vs. SLA/DLP
 - 2.2 Single- vs. Multi-Material Printers
 - 2.3 File Formats Used in 3D Printing
- 3 Overview of the 3D printing process
 - 3.1 Preparing the structure and generating a printable File
 - 3.2 Slicing the Model
 - 3.3 3D Printing the Model
 - 3.4 Post-Processing
- 4 Generating printable files on Proteopedia
- 5 Step-by-step guide for automatic generation of printable files on Proteopedia
 - 5.1 Open a structure and access the Print3D tool
 - 5.2 Select a printer, orientation and a printing scale
 - 5.3 Download the STL or OBJ files
- 6 Printing files from Proteopedia
 - 6.1 Using 3D printing services
 - 6.2 Using a desktop 3D printer
 - 6.2.1 Notes on multi-color printing
- 7 Other relevant resources
- 8 References

Proteopedia and 3D Printing

Physical molecular models, by engaging both visual and tactile senses, provide an effective means of deepening the understanding of complex concepts in molecular biology and biochemistry. They allow students to perceive the three-dimensional organization of macromolecules, thereby enhancing comprehension of the relationship between structure and function [1] [2]. Numerous studies have demonstrated that the use of tangible models in science education improves learning outcomes, fosters conceptual reasoning, and increases student engagement [3] [4] [5]. The rapid development of 3D-printing technologies has made it possible to create customized and affordable molecular models [6] [7] [8]. Affordable desktop 3D printers can now be used to fabricate physical models from virtually any structure or scene on Proteopedia. This page provides an introduction to 3D printing, a step-by-step guide to generating printable files directly from Proteopedia, and several tested printing profiles for common printers (e.g., Prusa Research, Bambu Lab, Creataly, or Elegoo).

Let's 3D-print the whole Proteopedia!

«3D Printing 101»: an introduction to 3D printing

3D printing, also known as *additive manufacturing*, builds physical objects layer by layer from digital designs. For more technical details please head for the excellent introductory article on [AIDP](#). In structural biology education, 3D printing provides an affordable and accessible way to transform atomic coordinate data (e.g., from PDB, MOL or SDF files) into tangible molecular models that can be observed, handled, and discussed in class or laboratory settings.

Printer Types: FDM vs. SLA/DLP

The two most accessible 3D-printing technologies that can be used to create molecular models are:

- » **FDM (Fused Deposition Modeling)**
This method extrudes a heated thermoplastic filament (such as PLA, PETG or TPU) through a fine nozzle, depositing successive layers that form the model. FDM printers have the advantages of low cost, easy maintenance, wide availability, and being capable of printing large and colorful molecular models. This technology has a few limitations, such as: visible layer lines, lower surface resolution, and less suited for very small or intricate molecular details.
- » **SLA/DLP (Resin Printing)**
This technique uses liquid photopolymer resin, cured layer by layer with ultraviolet light. SLA/DLP printers have the advantages of a very high resolution, smooth surfaces and are ideal for compact and detailed models (e.g., small proteins rendered as surface, ligands, or symmetric assemblies). This technology has its own limitations, such as higher material cost, post-processing requirements (washing and UV-curing), and the need for careful handling of resin.

When choosing between FDM and SLA printers, model size and resolution are the key criteria: **FDM** is preferred for large, educational display models; **SLA/DLP** is optimal for small, precise structures.

While FDM and SLA/DLP are the most widely used technologies in educational and research contexts due to their accessibility, other additive manufacturing methods also exist – such as *Selective Laser Sintering* (SLS), *PolyJet*, and *Binder Jetting* – each employing different materials and curing mechanisms. These industrial-grade techniques can produce highly detailed or multi-material parts but are generally more expensive and less accessible for classroom use. For an overview of major 3D-printing technologies, see [AIDP](#). Complete Overview of the Types of 3D Printers

Single- vs. Multi-Material Printers

Most entry-level desktop 3D printers use a single filament or resin, producing models in one color or material. However, multi-material systems (such as [Bambu Lab AMS](#) and its variants or [Prusa MMU](#)) can simultaneously print multiple filaments, enabling color-coded domains, subunits, or ligands directly in one print. For complex color information, users can also apply post-print color coding (painting or labeling) or print separate parts and assemble them manually.

A large FDM-printed model	A multi-material FDM-printed model	Small resin-printed models

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User:Marius Mihasan/Print3D models gallery

Welcome to the Proteopedia gallery of 3D printed models

Did you use the **Print3D** tool in Proteopedia to create a printable model?

Do you have pictures of the final 3D printed model of a molecule?

Or better, do you have a picture of the model put to good use?

We would love to know more about it. Please feel free to contribute to this page and share your prints! Note: If editing this page it's not for you and you would prefer to focus on 3D printing, drop us an e-mail at marius.mihasan@uaic.ro and we would love to hear your story and share it on this page.

Model	Picture	Details (including link to Proteopedia page if possible)
A simplified model of SV40 Capsid		Model of SV40 Capsid printed on multi-material printer (BambuLab A1 Mini). Printable files available on Printables.com . Generated with the Proteopedia Print3D tool from SV40_Capsid_Simplified . Printed by Marius Mihasan 12:27, 8 October 2025 (UTC).
GABAA receptor		Trace Model of the GABAA receptor 6x3x printed on a single material FDM-Printer (Prusa MK3S+). Each of the 5 subunits was printed separately and can be assembled. Printable files available on Printables.com . Printed by Marius Mihasan 12:27, 8 October 2025 (UTC)
Model 3		Description of model 3

Let's 3D-print the whole Proteopedia!

Proteopedia Page Contributors and Editors (what is this?)

Marius Mihasan

Category: 3D printer files

navigation

- Main Page
- Table of Contents
- Structure Index
- Random
- Recent Changes
- Help
- Cookbook

search

Go Search

toolbox

- What links here
- Related changes
- Upload file
- Special pages
- Printable version
- Permanent link

Proteopedia is hosted by the ISPC at the Weizmann Institute of Science in Israel

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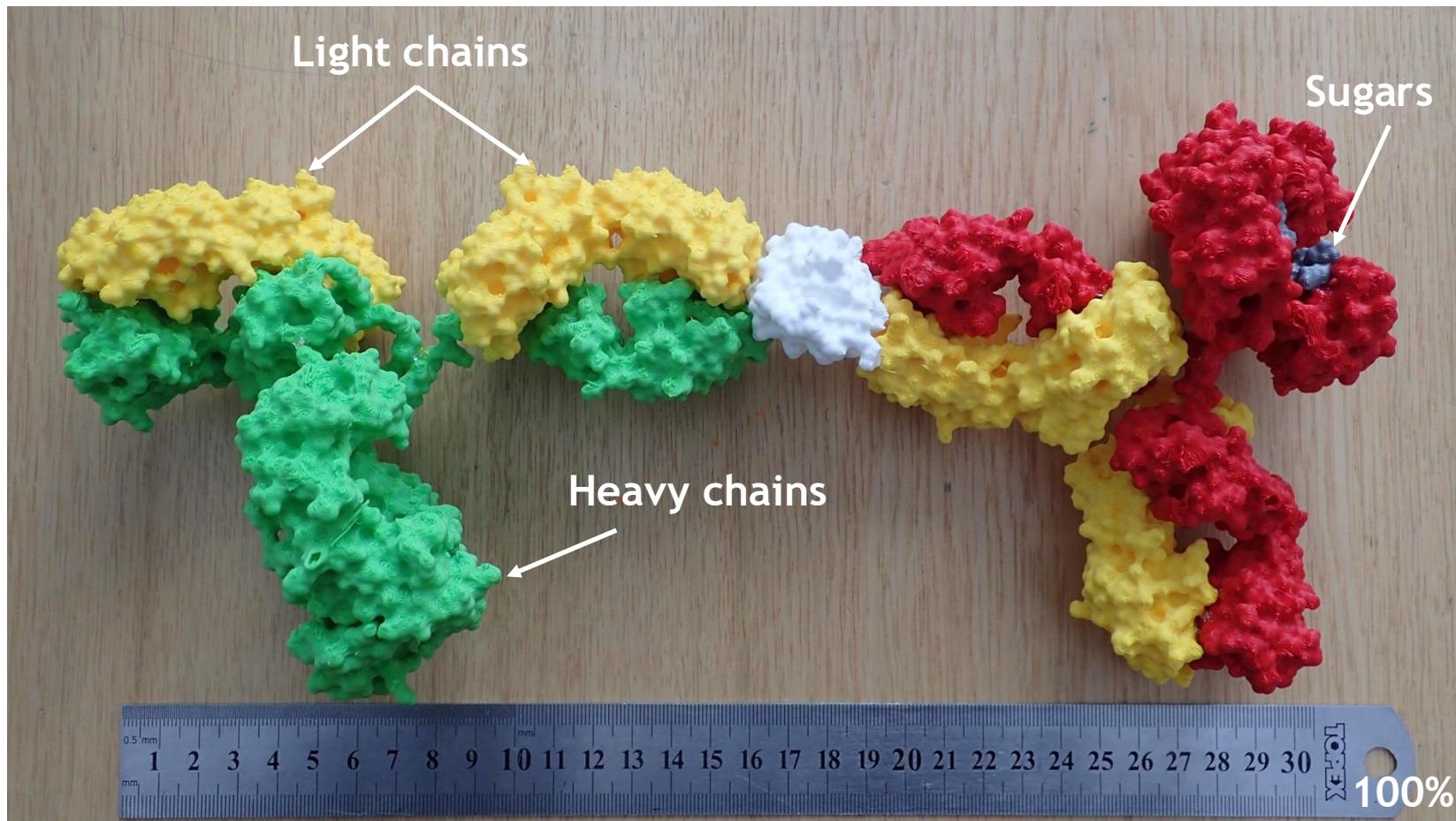
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Examples of printed models currently used for teaching



Antibodies interacting with an antigen (lysozyme)



<https://3dprint.nih.gov/discover/3dp-015554>

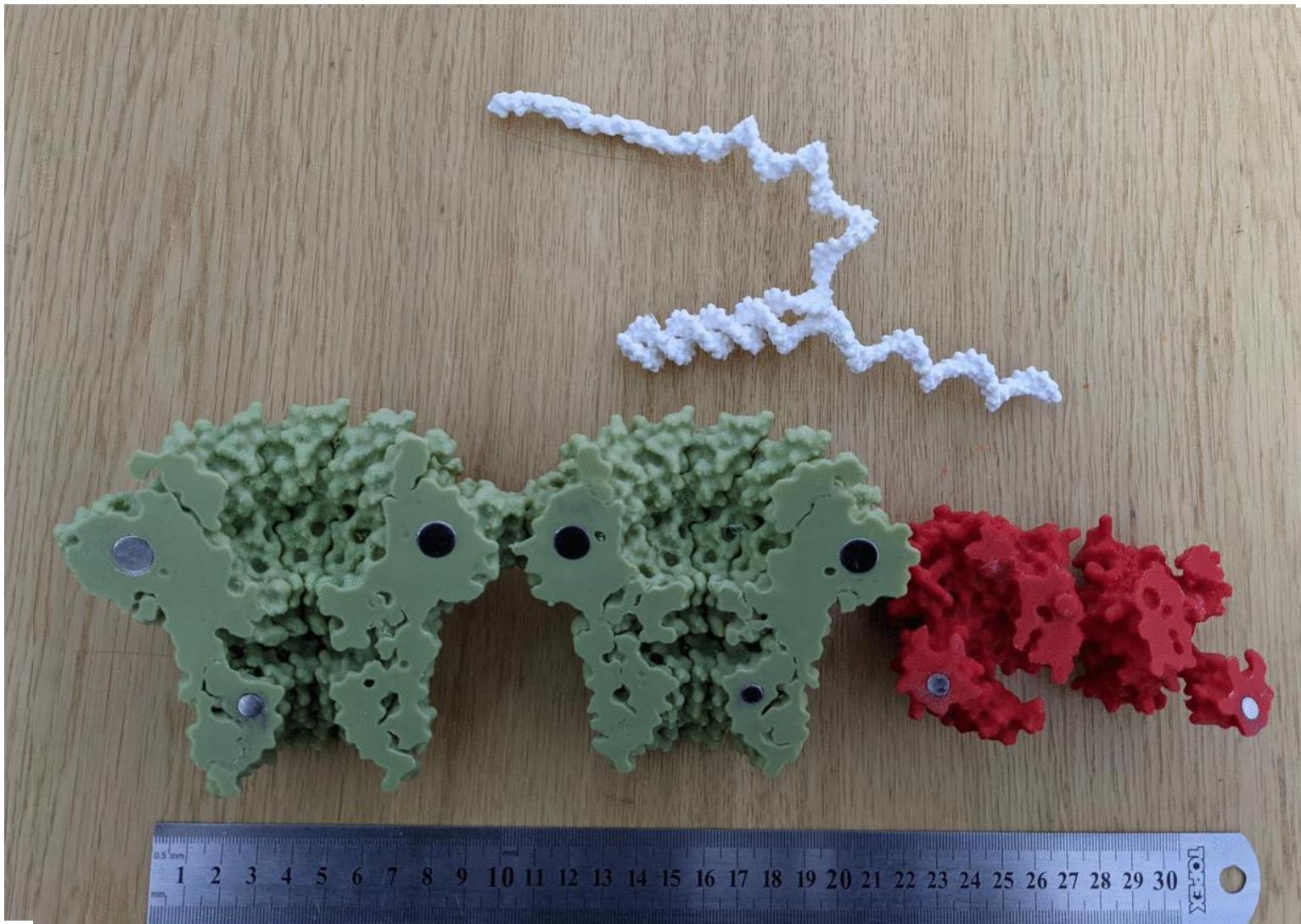
Examples of printed models currently used for teaching



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A protein nanopore sequencing DNA



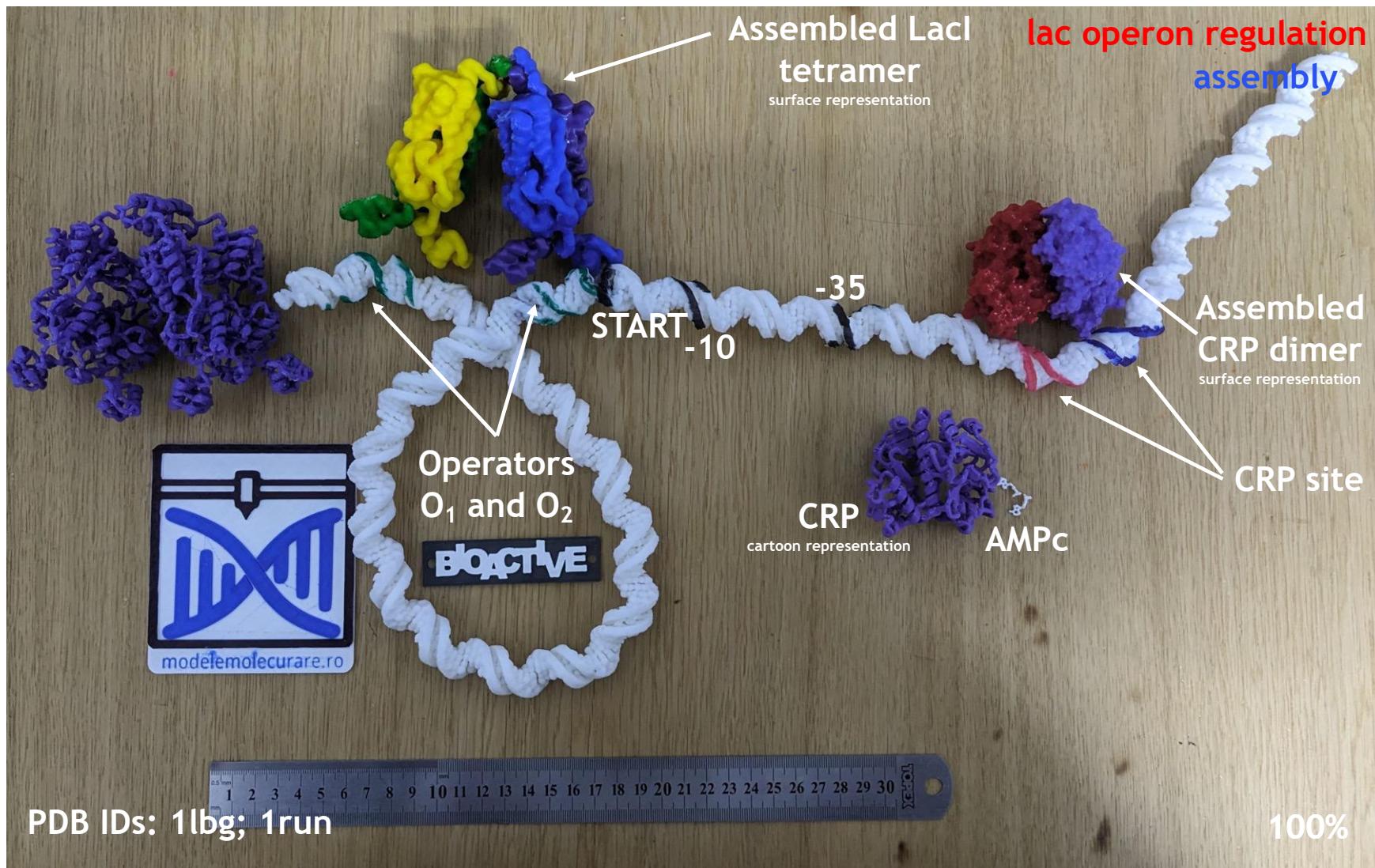
Examples of printed models currently used for teaching



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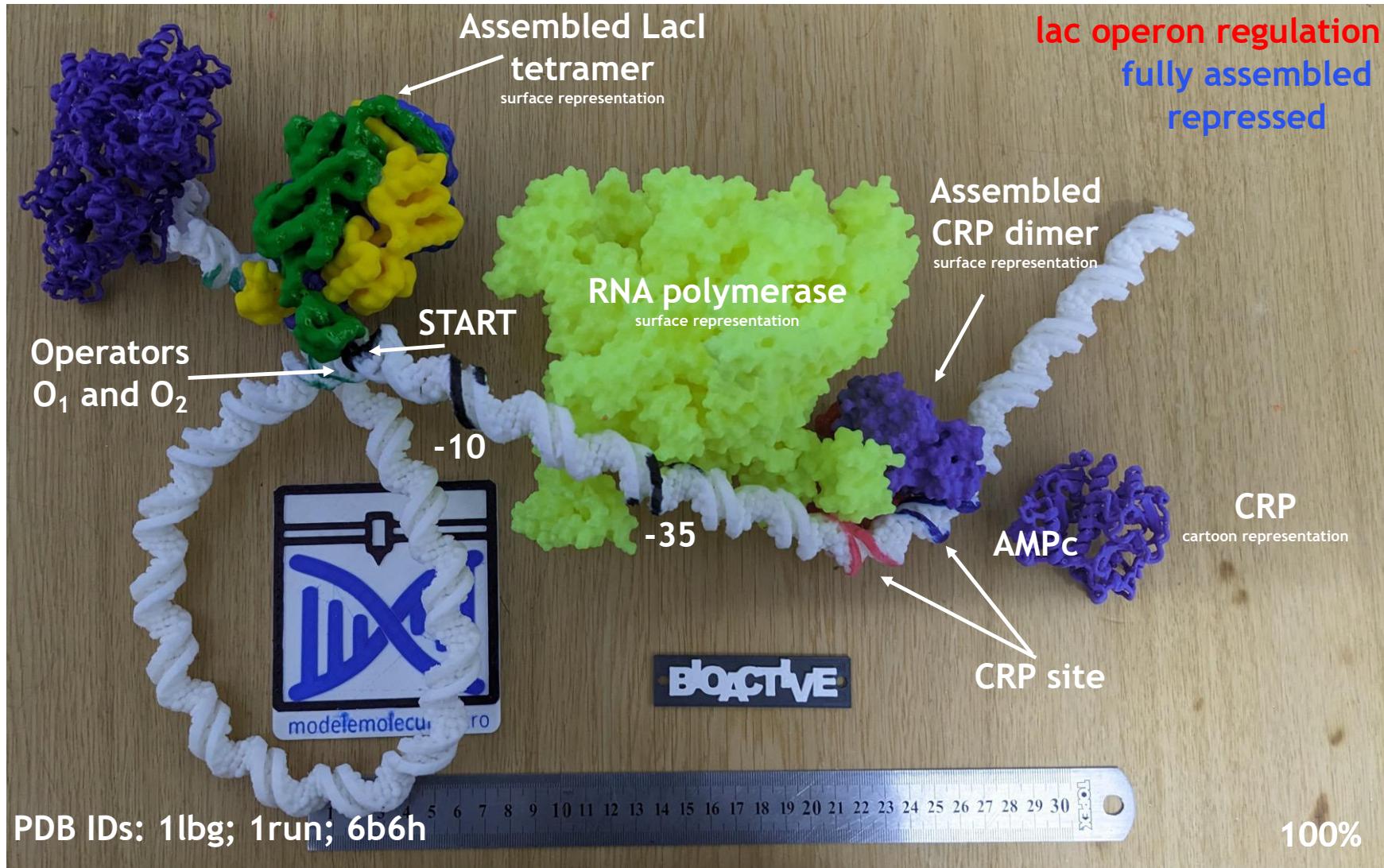
Physical model for teaching lac operon regulation



Examples of printed models currently used for teaching



Physical model for teaching lac operon regulation



Examples of printed models currently used for teaching



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Physical model for teaching lac operon regulation

