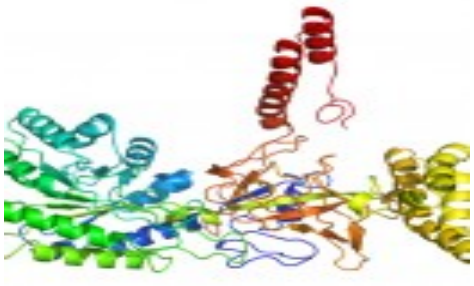
Mizzou
University of Missouri



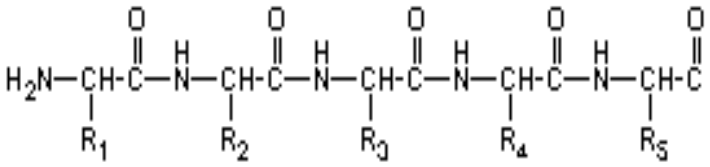
Template Based Protein Structure Modeling

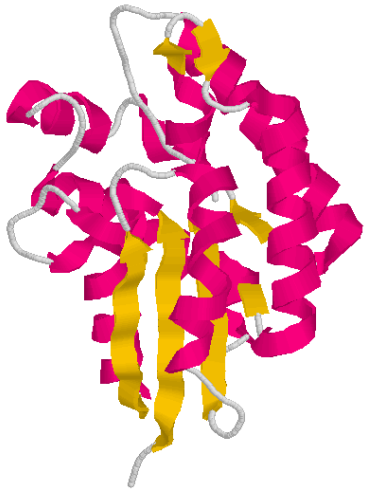
Jianlin Cheng, PhD

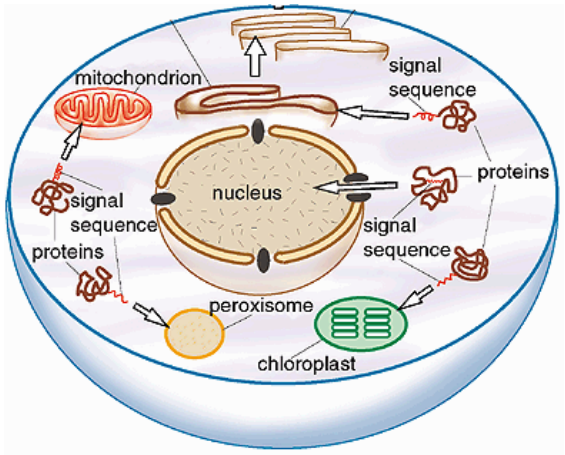
Professor
Department of EECS
Informatics Institute
University of Missouri, Columbia
2018

Sequence, Structure and Function

AGCWY……





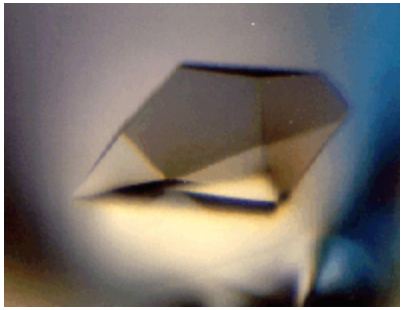


Cell

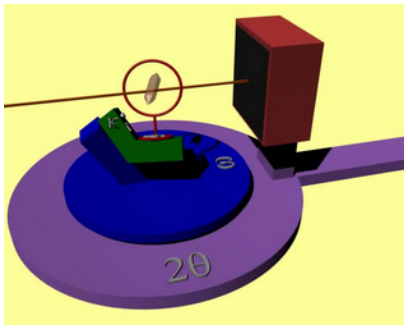
Protein Structure Determination

- X-ray crystallography
- Nuclear Magnetic Resonance (NMR) Spectroscopy
- Cryo-Electron Microscopy
- X-ray: any size, accurate (1-3 Angstrom (10^{-10} m)), sometime hard to grow crystal
- NMR: small to medium size, moderate accuracy, structure in solution

X-Ray Crystallography

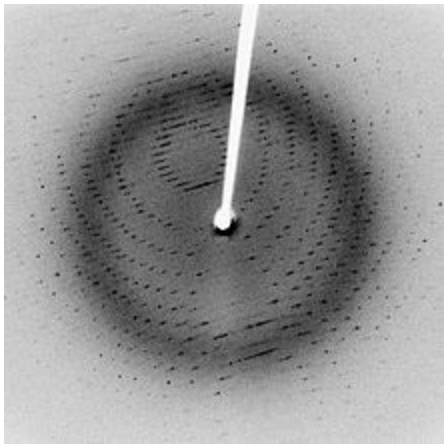


A protein crystal

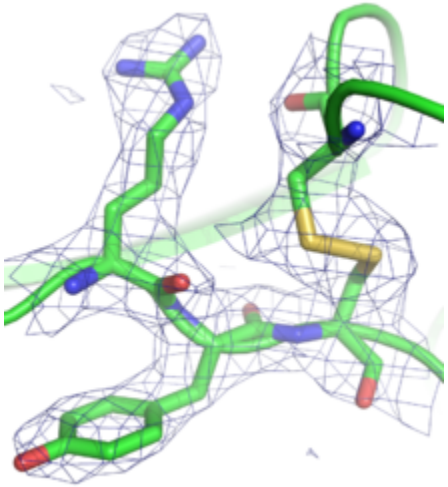


Mount a crystal

Diffractometer



Diffraction



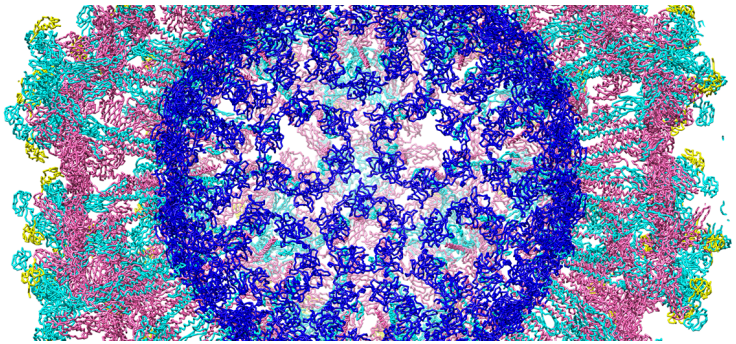
Protein structure

Wikipedia

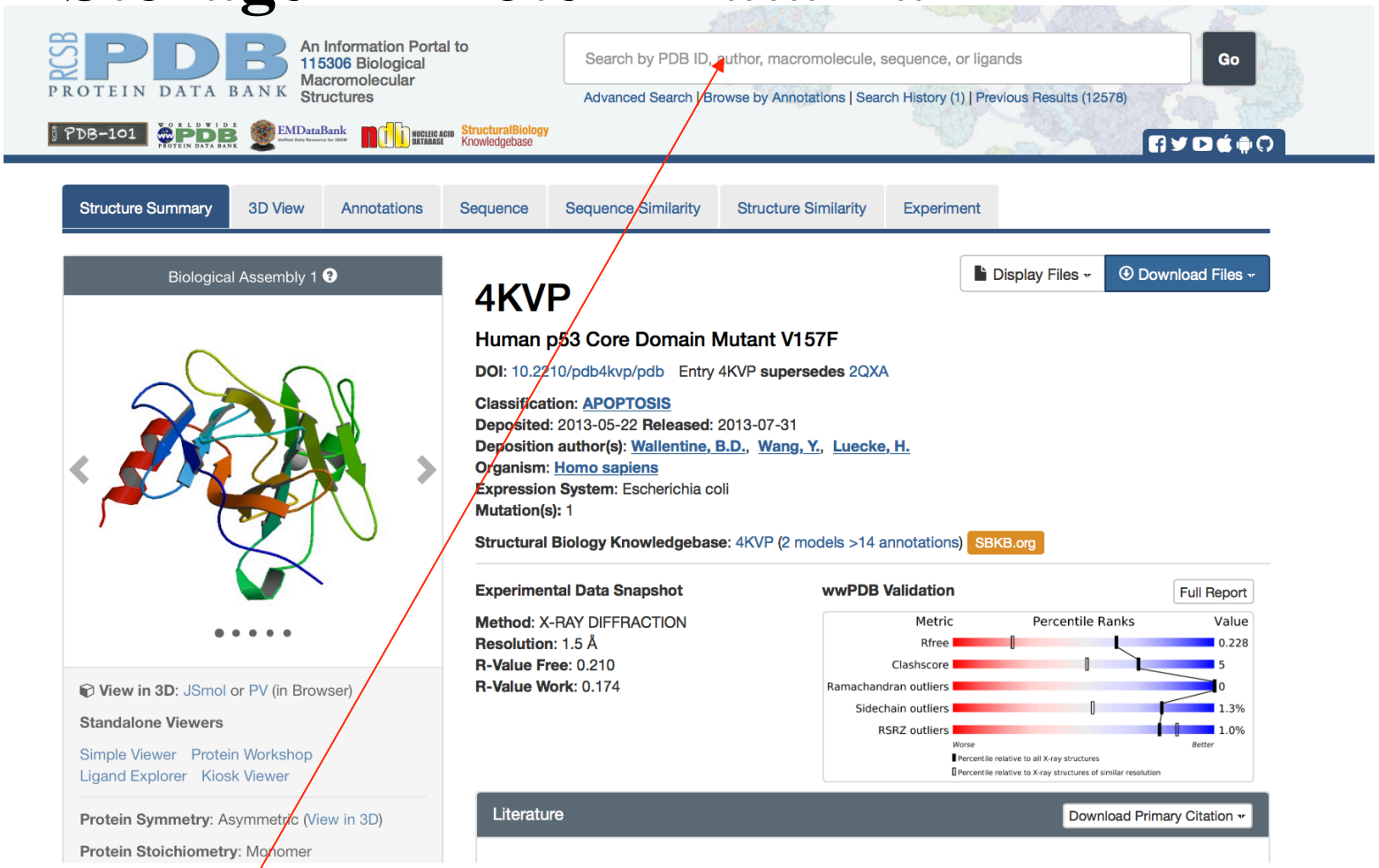
Pacific Northwest National Laboratory's high magnetic field (800 MHz, 18.8 T) NMR spectrometer being loaded with a sample.

Wikipedia, the free encyclopedia

- **Cryo-EM equipment**



Storage in Protein Data Bank



Search database

Search Demo: Human P53 protein – 1KVP

http://www.rcsb.org/pdb/explore/explore.do?structureId=4KVP

PDB Format (2C8Q, insulin)

```
HEADER    HORMONE                                 06-DEC-05   2C8Q
TITLE     INSULINE(1SEC) AND UV LASER EXCITED FLUORESCENCE
COMPND    MOL_ID: 1;
COMPND   2 MOLECULE: INSULIN A CHAIN;
COMPND   3 CHAIN: A;
COMPND   4 MOL_ID: 2;
COMPND   5 MOLECULE: INSULIN B CHAIN;
COMPND   6 CHAIN: B
SOURCE    MOL_ID: 1;
SOURCE   2 ORGANISM_SCIENTIFIC: HOMO SAPIENS;
SOURCE   3 ORGANISM_COMMON: HUMAN;
SOURCE   4 ORGAN: PANCREAS;
SOURCE   5 MOL_ID: 2;
SOURCE   6 ORGANISM_SCIENTIFIC: HOMO SAPIENS;
SOURCE   7 ORGANISM_COMMON: HUMAN;
SOURCE   8 ORGAN: PANCREAS
KEYWDS    LASER, UV, CARBOHYDRATE METABOLISM, HORMONE, DIABETES
KEYWDS   2 MELLITUS, GLUCOSE METABOLISM
EXPDTA    X-RAY DIFFRACTION
AUTHOR    X.VERNEDE,B.LAVAULT,J.OHANA,D.NURIZZO,J.JOLY,L.JACQUAMET,
AUTHOR   2 F.FELISAZ,F.CIPRIANI,D.BOURGEOIS
REVDAT   1   08-MAR-06 2C8Q    0
JRNL        AUTH   X.VERNEDE,B.LAVAULT,J.OHANA,D.NURIZZO,J.JOLY,
JRNL        AUTH 2 L.JACQUAMET,F.FELISAZ,F.CIPRIANI,D.BOURGEOIS
JRNL        TITL   UV LASER-EXCITED FLUORESCENCE AS A TOOL FOR THE
JRNL        TITL 2 VISUALIZATION OF PROTEIN CRYSTALS MOUNTED IN
JRNL        TITL 3 LOOPS.
JRNL        REF    ACTA CRYSTALLOGR.,SECT.D      V.  62   253 2006
JRNL        REFN   ASTM ABCRE6  DK ISSN 0907-4449
REMARK   2
REMARK   2 RESOLUTION. 1.95 ANGSTROMS.
REMARK   3
REMARK   3 REFINEMENT.
REMARK   3   PROGRAM     : REFMAC 5.2.0005
REMARK   3   AUTHORS     : MURSHUDOV,VAGIN,DODSON
REMARK   3
REMARK   3   REFINEMENT TARGET : MAXIMUM LIKELIHOOD
```

```
SEQRES   1 A   21  GLY ILE VAL GLU GLN CYS CYS THR SER ILE CYS SER LEU
SEQRES   2 A   21  TYR GLN LEU GLU ASN TYR CYS ASN
SEQRES   1 B   29  PHE VAL ASN GLN HIS LEU CYS GLY SER HIS LEU VAL GLU
SEQRES   2 B   29  ALA LEU TYR LEU VAL CYS GLY GLU ARG GLY PHE PHE TYR
SEQRES   3 B   29  THR PRO LYS
FORMUL   3  HOH   *31(H2 O1)
HELIX    1   1 GLY A    1  CYS A    7  1                                   7
HELIX    2   2 SER A   12  ASN A   18  1                                   7
HELIX    3   3 GLY B    8  GLY B   20  1                                  13
HELIX    4   4 GLU B   21  GLY B   23  5                                   3
SSBOND   1 CYS A    6    CYS A   11                          1555   1555
SSBOND   2 CYS A    7    CYS B    7                          1555   1555
SSBOND   3 CYS A   20    CYS B   19                          1555   1555
CRYST1   78.608   78.608   78.608  90.00  90.00  90.00 I 21 3        24
ORIGX1      1.000000  0.000000  0.000000        0.00000
ORIGX2      0.000000  1.000000  0.000000        0.00000
ORIGX3      0.000000  0.000000  1.000000        0.00000
SCALE1      0.012721  0.000000  0.000000        0.00000
SCALE2      0.000000  0.012721  0.000000        0.00000
SCALE3      0.000000  0.000000  0.012721        0.00000
ATOM      1  N   GLY A   1      45.324  26.807  11.863  1.00 24.82           N
ATOM      2  CA  GLY A   1      45.123  27.787  12.967  1.00 24.93           C
ATOM      3  C   GLY A   1      43.756  27.627  13.605  1.00 25.16           C
ATOM      4  O   GLY A   1      43.107  26.591  13.438  1.00 25.00           O
ATOM      5  N   ILE A   2      43.313  28.661  14.323  1.00 25.21           N
ATOM      6  CA  ILE A   2      42.050  28.622  15.065  1.00 25.39           C
ATOM      7  C   ILE A   2      40.818  28.303  14.200  1.00 25.69           C
ATOM      8  O   ILE A   2      39.935  27.565  14.635  1.00 25.56           O
ATOM      9  CB  ILE A   2      41.816  29.917  15.917  1.00 25.39           C
```

Structure Visualization

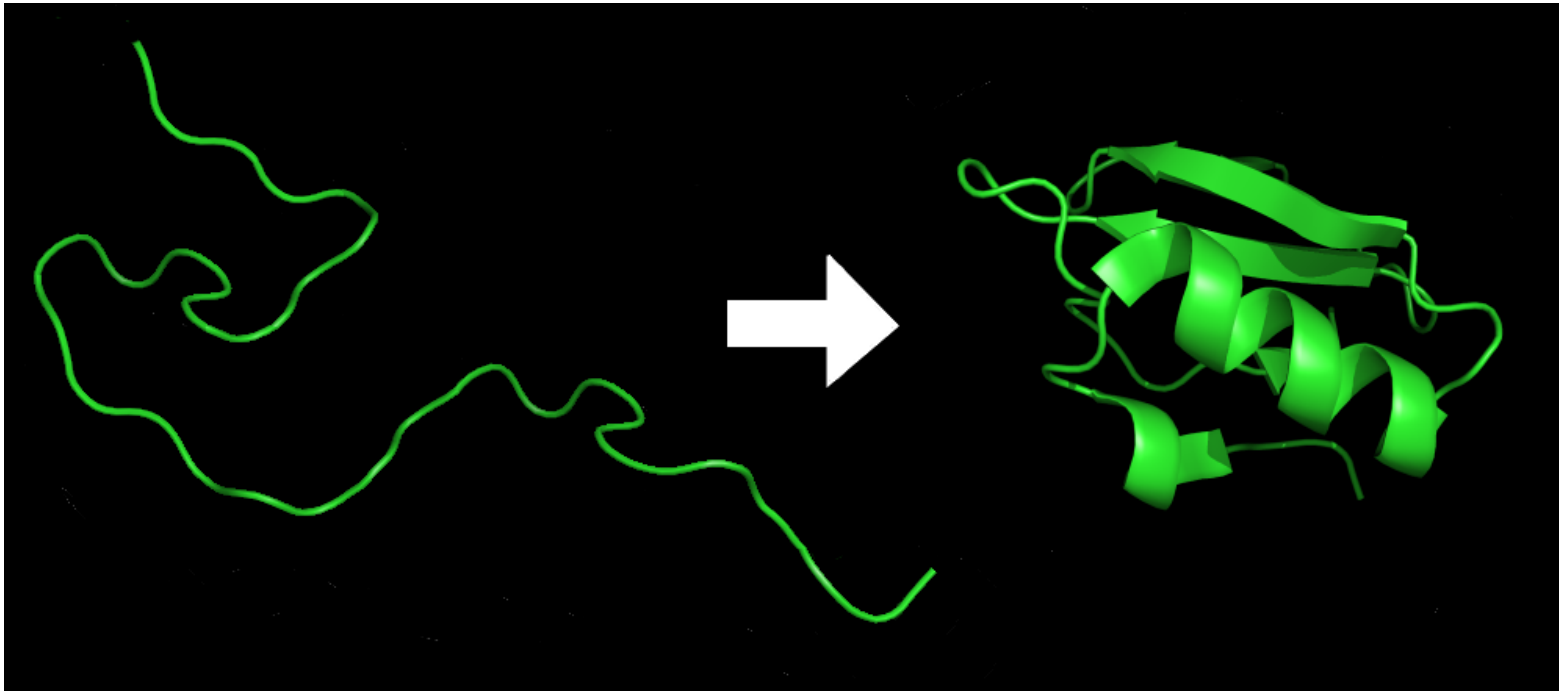
- Rasmol (http://www.umass.edu/microbio/rasmol/getras.htm)
- MDL Chime (plug-in) (http://www.mdl.com/products/framework/chime/)
- **Jmol:** http://jmol.sourceforge.net/
- **JSMol: java script version**
- **Pymol:** http://pymol.sourceforge.net/
- **Chimera:** https://www.cgl.ucsf.edu/chimera/

JSMol (4KVP, Human P53)

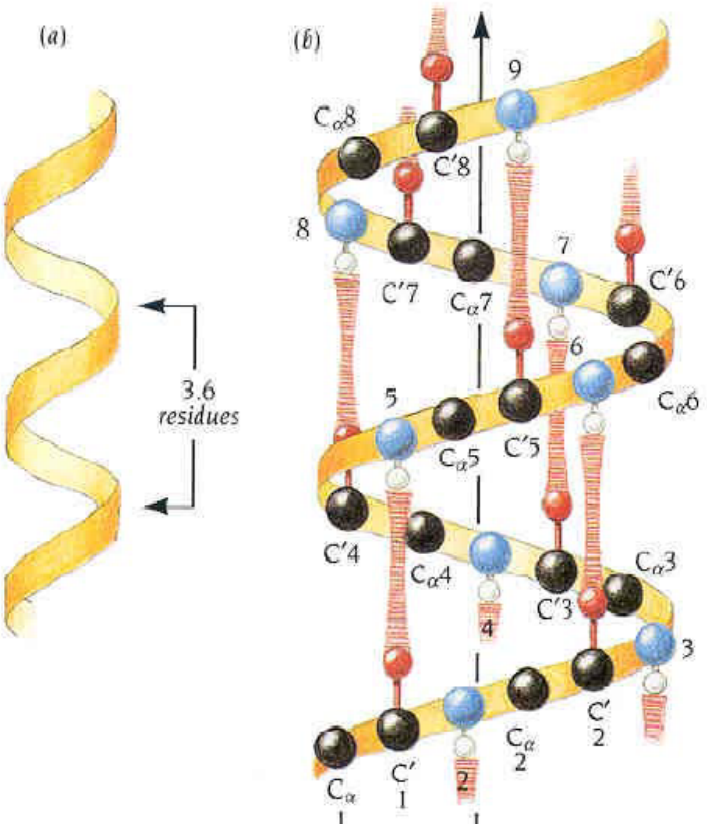
- JSMol: http://www.rcsb.org/pdb/explore/jmol.do?structureId=4KVP&bionumber=1
- JMOL: 1VJP
- Identify residues
- Recognize atoms
- Recognize peptide bonds
- Identify backbone
- Identify side chain
- Analyze different visualization style

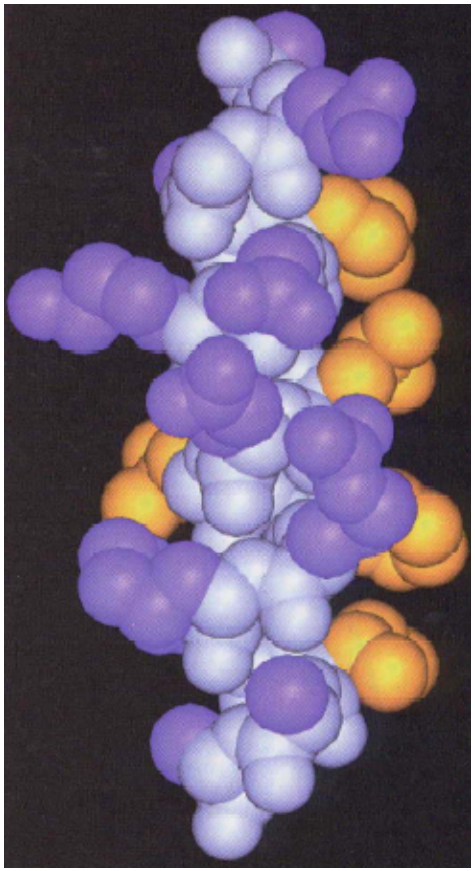
Protein Folding

http://www.youtube.com/watch?v=fvBO3TqJ6FE&feature=fvw



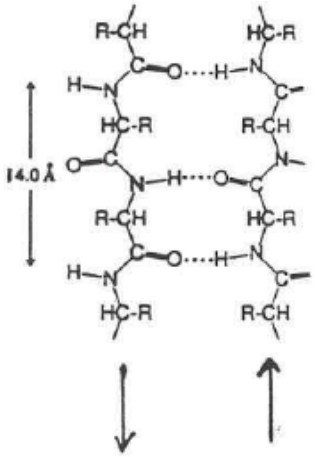
Alpha-Helix

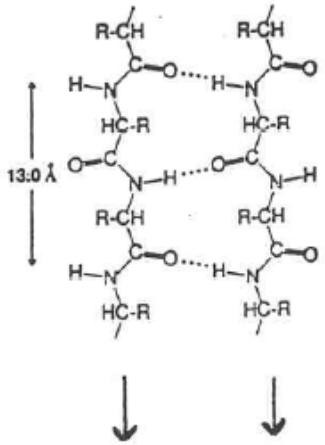


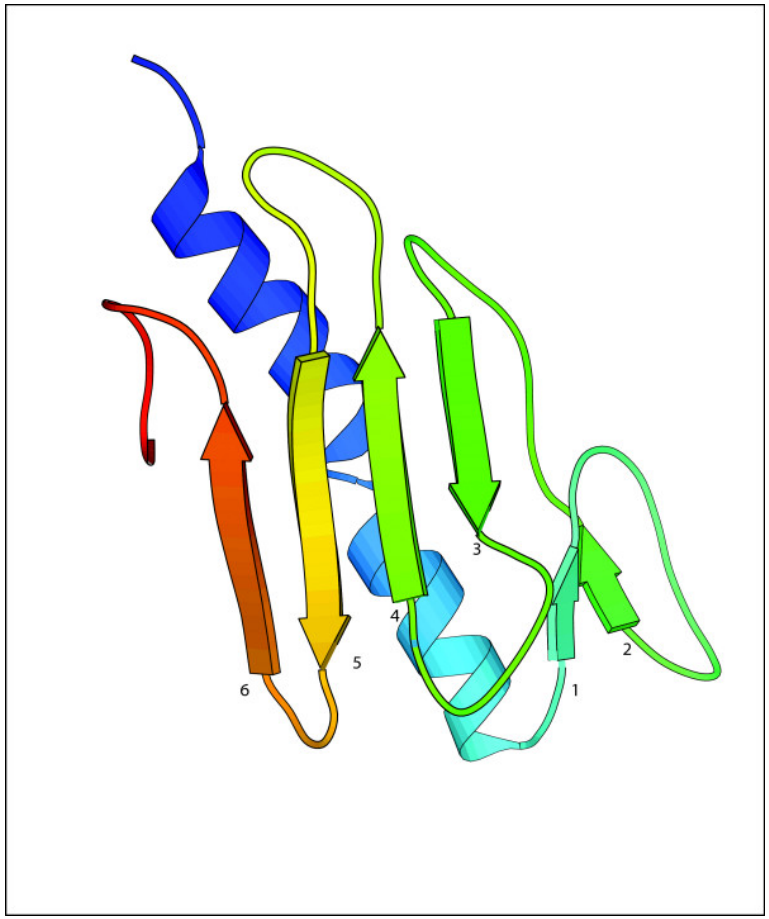


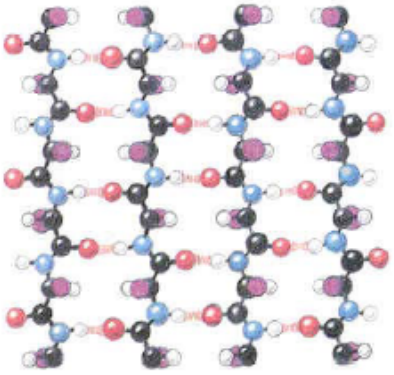
Jurnak, 2003

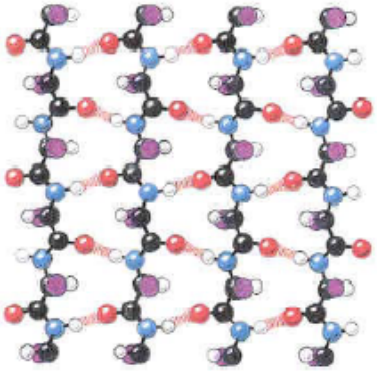
Beta-Sheet







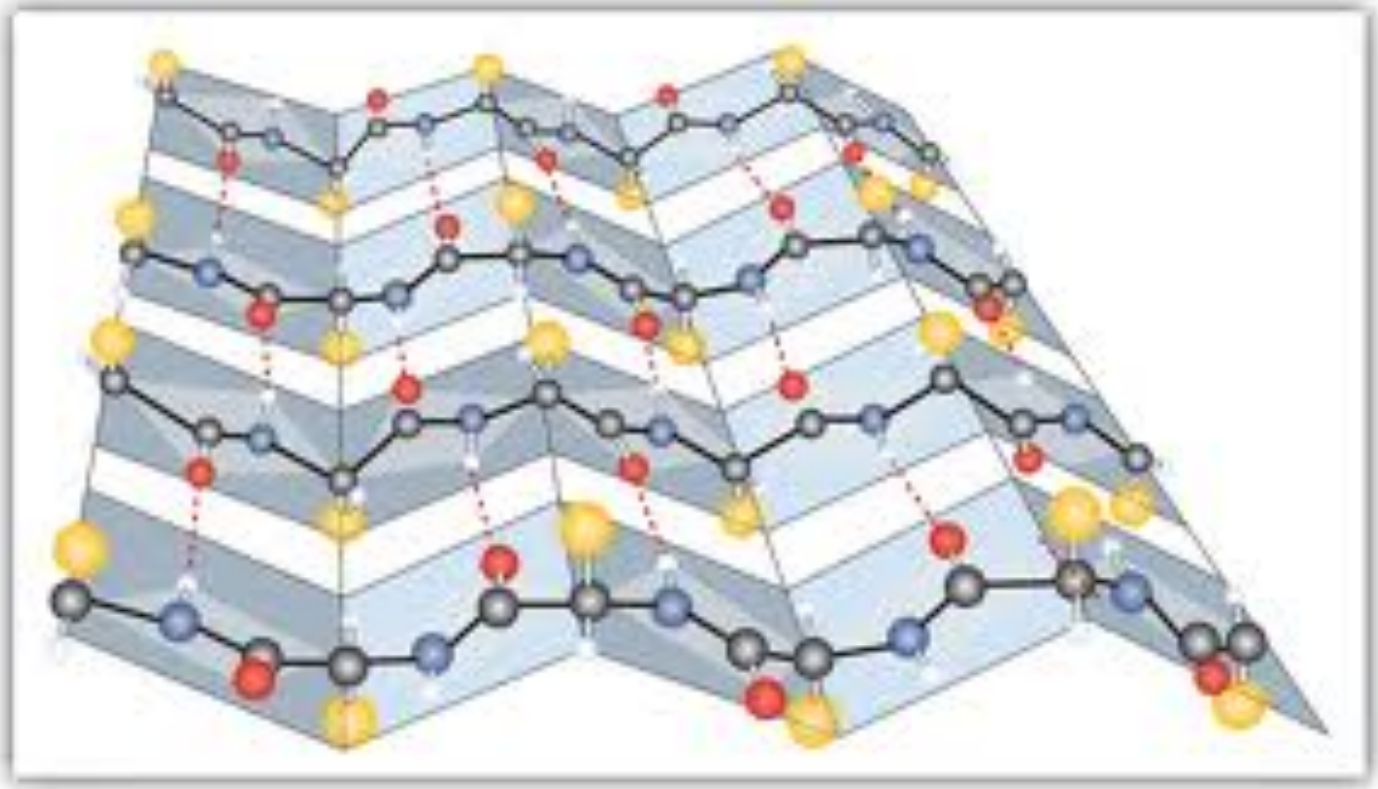




Anti-Parallel

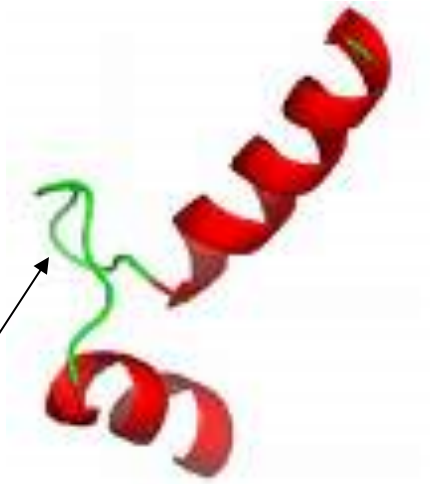
Parallel

Beta-Sheet



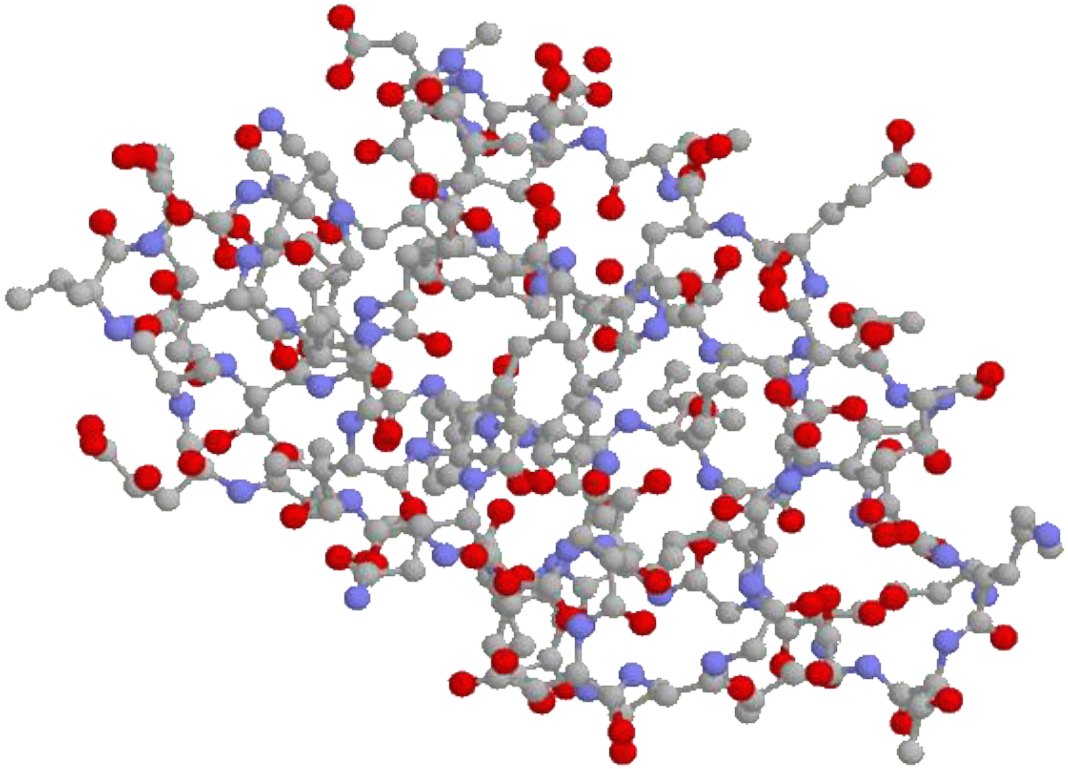
Non-Repetitive Secondary Structure

Beta-Turn



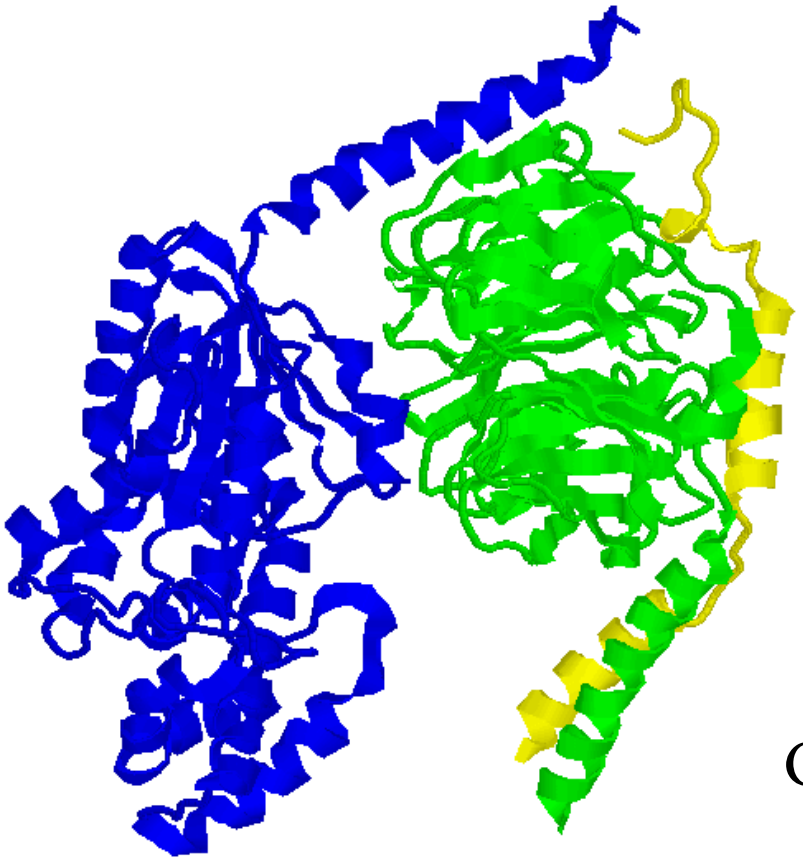
Loop

myoglobin



tertiary structure
(all atom)

Quaternary Structure: Complex



G-Protein Complex

Structure Analysis

- Assign secondary structure for amino acids from 3D structure
- Generate solvent accessible area for amino acids from 3D structure
- Most widely used tool: DSSP (Dictionary of Protein Secondary Structure: Pattern Recognition of Hydrogen-Bonded and Geometrical Features. **Kabsch and Sander, 1983**)

DSSP server: http://bioweb.pasteur.fr/seqanal/interfaces/dssp-simple.html
DSSP download: http://swift.cmbi.ru.nl/gv/dssp/

DSSP Code:
H = alpha helix
G = 3-helix (3/10 helix)
I = 5 helix (pi helix)
B = residue in isolated beta-bridge
E = extended strand, participates in beta ladder
T = hydrogen bonded turn
S = bend
Blank = loop

DSSP Web Service

DSSP : Definition of secondary structure of proteins given a set of 3D coordinates (W.Kabsch, C. Sander)

Reset | Run dssp | jianlin.cheng@gmail.com your e-mail

PDB File

1vjg or you can instead enter a PDB id.

http://bioweb.pasteur.fr/seqanal/interfaces/dssp-simple.html

#	RESIDUE	AA	STRUCTURE	BP1	BP2	ACC	N-H-->O	O-->H-N	N-H-->O	O-->H-N	TCO	KAPPA	ALPHA	PHI	PSI	X-CA	Y-CA	Z-CA
1	5	A	S		0	0	179	0, 0.0	2,-0.0	0, 0.0	0, 0.0	0.000	360.0	360.0	360.0	125.7	-8.6	43.0	43.9
2	6	A	K	-	0	0	123	1,-0.1	2,-0.4	37,-0.1	37,-0.2	-0.235	360.0	-108.7	-87.0	151.4	-7.5	41.4	40.6
3	7	A	T	E -a	39	0A	75	35,-0.6	37,-2.5	1,-0.0	2,-0.3	-0.593	34.7	-132.0	-72.2	128.3	-4.3	39.5	39.6
4	8	A	Q	E +a	40	0A	91	-2,-0.4	69,-0.6	35,-0.2	2,-0.4	-0.639	26.0	179.8	-86.4	132.7	-2.0	41.5	37.4
5	9	A	I	E -ab	41	73A	3	35,-1.9	37,-2.9	-2,-0.3	2,-0.5	-0.991	13.3	-156.5	-129.4	131.5	-0.7	39.9	34.2
6	10	A	R	E -ab	42	74A	48	67,-2.8	69,-1.7	-2,-0.4	2,-0.4	-0.910	14.8	-173.2	-105.2	126.8	1.6	41.6	31.8
7	11	A	I	E -ab	43	75A	0	35,-2.5	37,-2.6	-2,-0.5	2,-0.5	-0.983	11.9	-162.4	-124.9	124.4	1.7	40.3	28.2
8	12	A	C	E -ab	44	76A	0	67,-2.3	69,-2.6	-2,-0.4	2,-0.6	-0.931	6.5	-159.9	-100.8	130.8	3.9	41.2	25.3
9	13	A	F	E -ab	45	77A	0	35,-2.2	37,-3.0	-2,-0.5	2,-0.5	-0.955	13.2	-169.0	-109.5	117.1	2.7	40.2	21.8
10	14	A	V	E +ab	46	78A	0	67,-3.1	69,-2.2	-2,-0.6	2,-0.3	-0.926	34.8	71.1	-116.5	129.9	5.6	40.1	19.4
11	15	A	G	E S-ab	47	79A	0	35,-0.9	37,-1.9	-2,-0.5	69,-0.2	-0.921	70.2	-50.2	169.0	-146.4	5.3	39.9	15.6
12	16	A	D	S >> S-	0	0	4	67,-0.8	4,-2.2	-2,-0.3	3,-0.6	-0.023	78.2	-51.3	-111.5	-151.8	4.2	41.6	12.4
13	17	A	S	H 3>>S+	0	0	7	35,-0.3	5,-1.7	1,-0.2	4,-1.5	0.803	130.2	57.8	-67.3	-28.8	1.2	43.5	11.1
14	18	A	F	H 345S+	0	0	5	2,-0.2	12,-0.5	1,-0.2	-1,-0.2	0.884	108.5	46.5	-68.2	-33.2	-1.2	40.8	12.2
15	19	A	V	H <45S+	0	0	1	-3,-0.6	12,-0.3	64,-0.2	-2,-0.2	0.900	111.1	52.2	-68.9	-41.4	-0.0	41.1	15.7
16	20	A	N	H <5S-	0	0	71	-4,-2.2	-2,-0.2	30,-0.1	-1,-0.2	0.774	110.8	-127.0	-62.6	-26.6	-0.3	45.0	15.4
17	21	A	G	T ><5 -	0	0	5	-4,-1.5	3,-2.2	-5,-0.2	8,-0.4	0.741	36.4	-174.6	83.1	25.3	-3.9	44.5	14.2
18	22	A	T	T 3 < +	0	0	14	-5,-1.7	-1,-0.2	1,-0.3	-2,-0.0	-0.199	68.4	29.2	-54.0	135.4	-3.4	46.6	11.0
19	23	A	G	T 3 S+	0	0	28	1,-0.3	-1,-0.3	159,-0.1	162,-0.2	0.121	86.2	120.8	94.7	-21.4	-6.7	47.0	9.2
20	24	A	D	X -	0	0	9	-3,-2.2	3,-1.2	160,-0.2	-1,-0.3	-0.706	48.9	-160.5	-79.7	117.6	-8.9	46.8	12.4
21	25	A	P	T 3 S+	0	0	91	0, 0.0	-1,-0.2	0, 0.0	159,-0.0	0.677	91.8	60.1	-70.9	-17.3	-10.9	50.1	12.6
22	26	A	E	T 3 S-	0	0	119	-3,-0.0	-2,-0.1	3,-0.0	158,-0.0	0.426	105.0	-132.3	-87.9	-3.3	-11.4	49.4	16.3
23	27	A	C	S < S+	0	0	112	-3,-1.2	-5,-0.1	-6,-0.2	-6,-0.0	0.730	80.2	98.1	62.8	28.1	-7.6	49.4	16.9

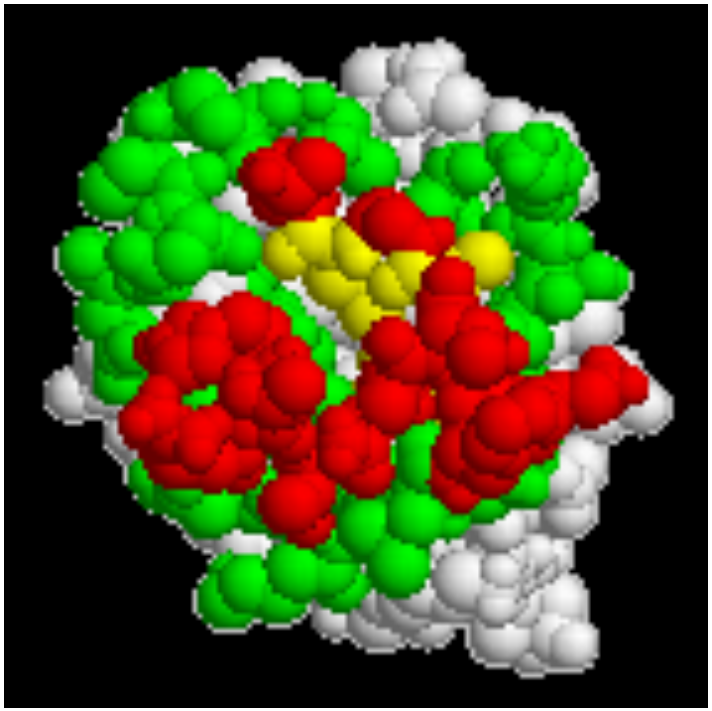
Amino Acids

Secondary Structure

Solvent Accessibility

Solvent Accessibility

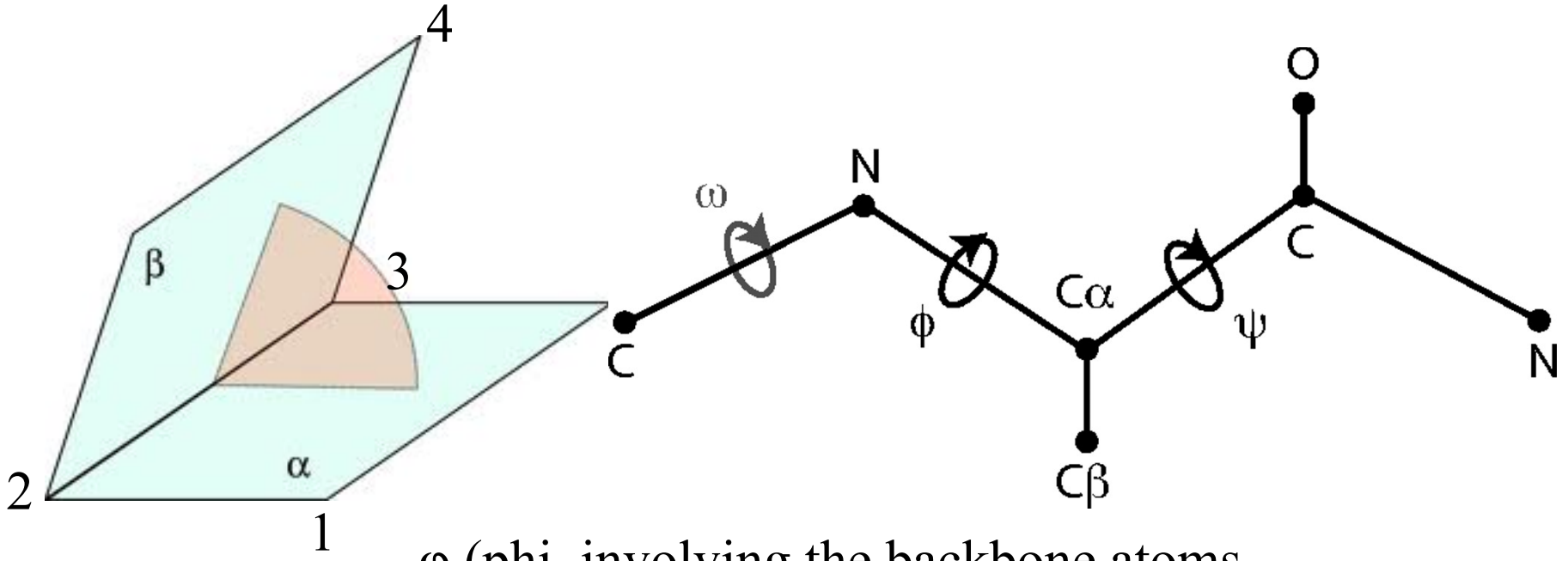
Size of the area of an amino acid that is exposed to solvent (water).



Maximum solvent accessible area for each amino acid is its whole surface area.

Hydrophobic residues like to be Buried inside (interior).
Hydrophilic residues like to be exposed on the surface.

Dihedral / Torsional Angle



φ (phi, involving the backbone atoms C'-N-Cα-C'), ψ (psi, involving the backbone atoms N-Cα-C'-N)

- http://en.wikipedia.org/wiki/Dihedral_angle

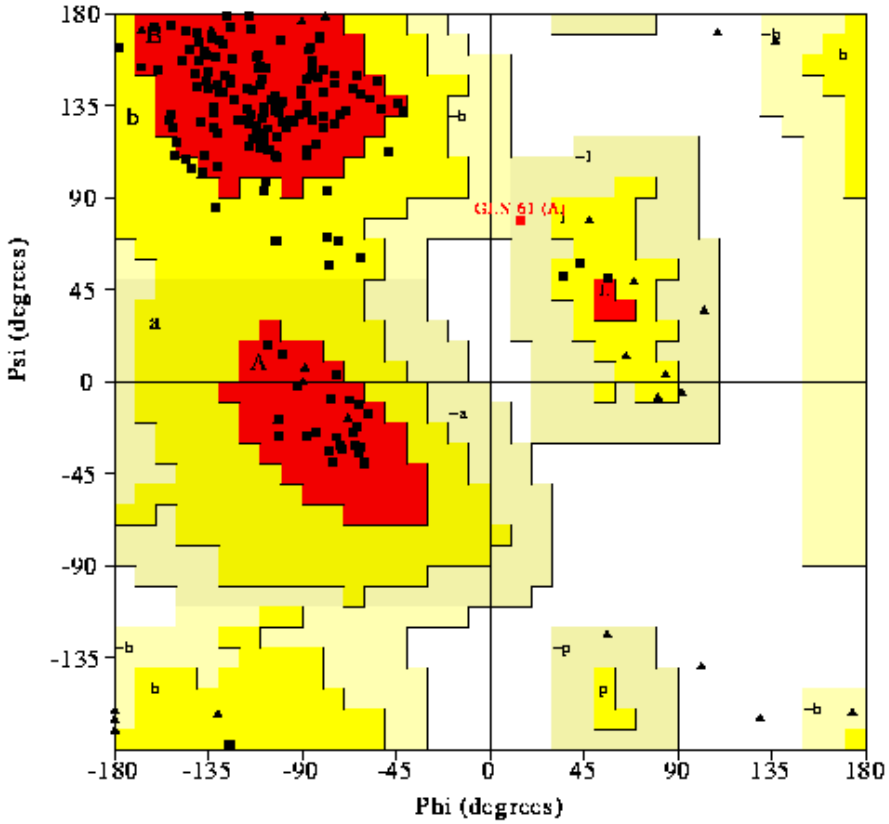
Project Groups

- 11 students?
- Form 3 groups (3-4 students per group)

PROCHECK

Ramachandran Plot

1abc

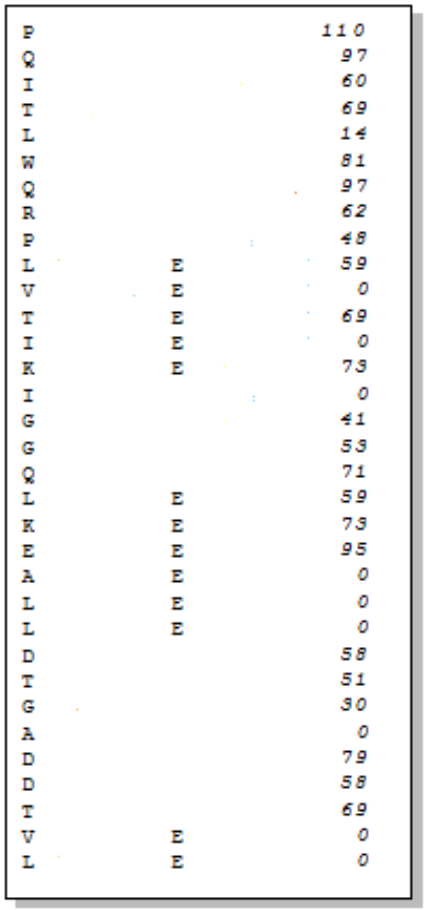


Plot statistics

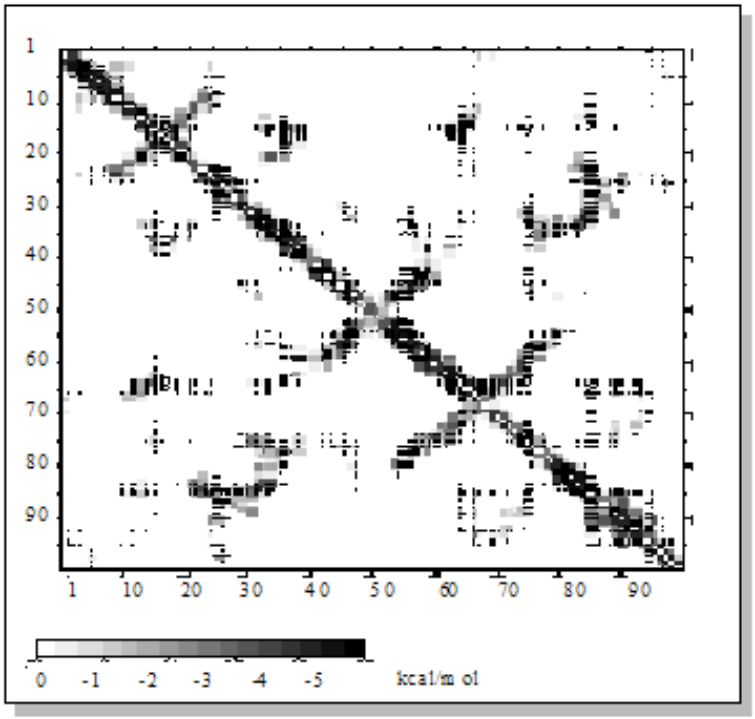
Residues in most favoured regions [A,B,L]	141	89.9%
Residues in additional allowed regions [a,b,l,p]	15	9.4%
Residues in generously allowed regions [~a,~b,~l,~p]	1	0.6%
Residues in disallowed regions	0	0.0%
Number of non-glycine and non-proline residues	159	100.0%
Number of end-residues (excl. Gly and Pro)	5	
Number of glycine residues (shown as triangles)	26	
Number of proline residues	15	
Total number of residues	205	

Based on an analysis of 118 structures of resolution of at least 2.0 Angstroms and R-factor no greater than 20%, a good quality model would be expected to have over 90% in the most favoured regions.

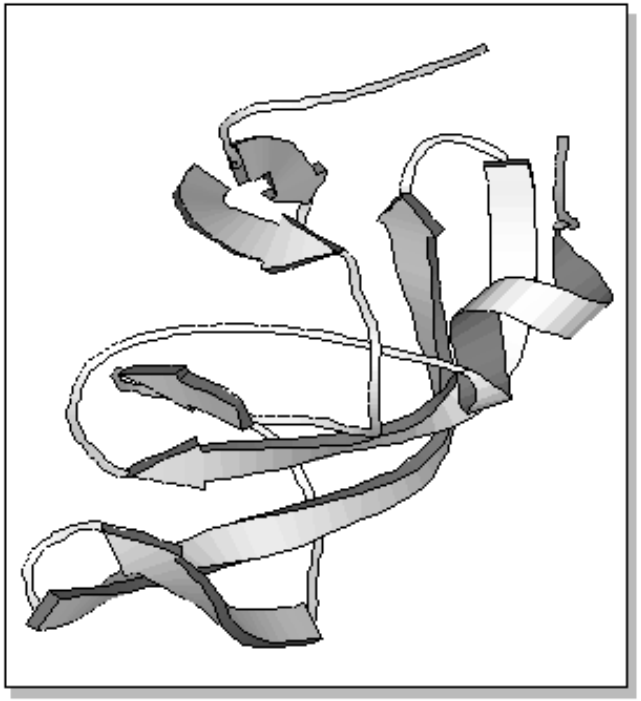
Protein Structure 1D, 2D, 3D



1D



2D



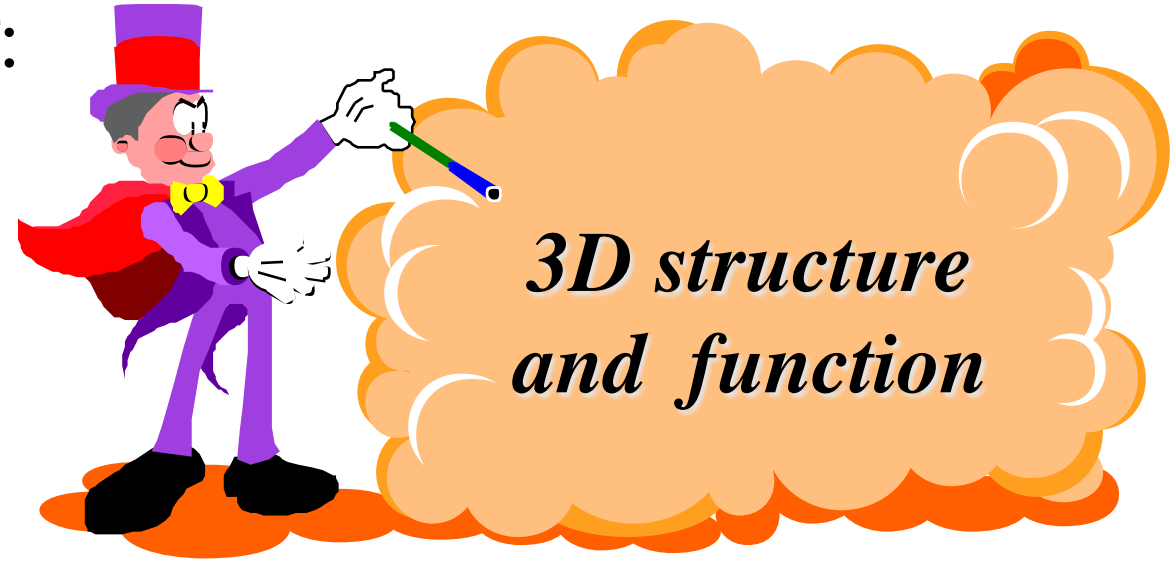
3D

B. Rost, 2005

Goal of Structure Prediction

- Epstein & Anfinsen, 1961:
  sequence uniquely determines structure

- INPUT: sequence
- OUTPUT:



B. Rost, 2005

CASP – Olympics of Protein Structure Prediction

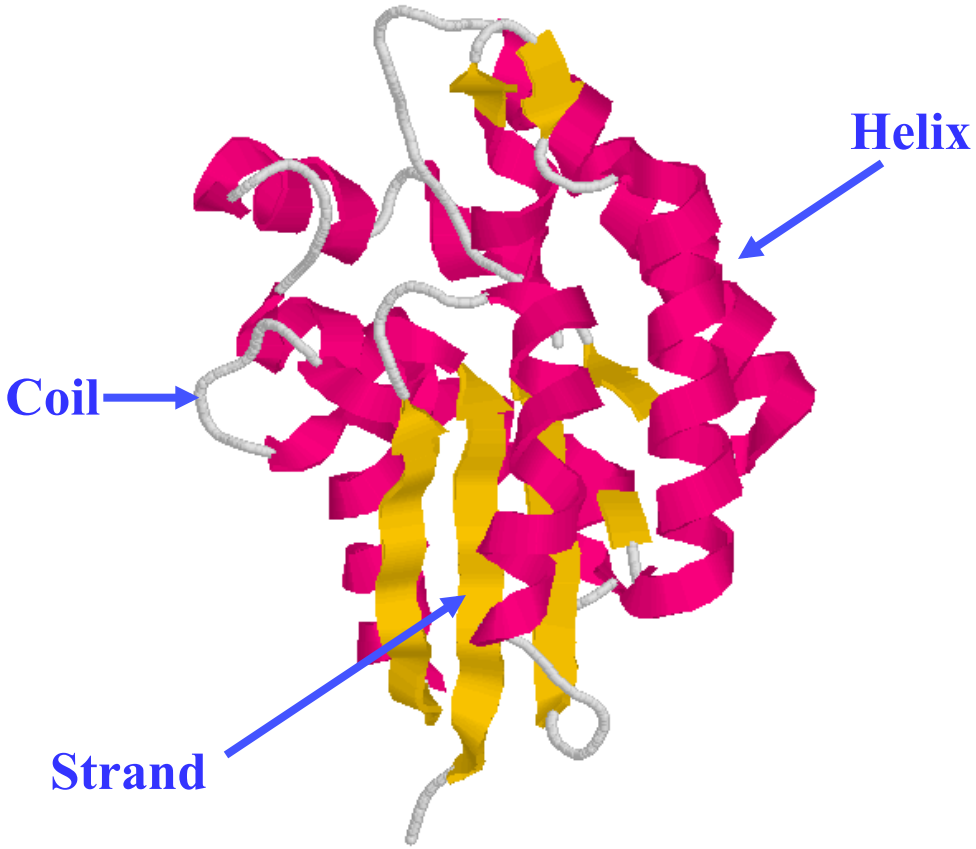
- Critical Assessment of Techniques of Protein Structure Prediction
- 1994,1996,1998,2000,2002,2004,2006, 2008, 2010, 2012, 2014, 2016
- Blind Test, Independent Evaluation

- CASP12 (http://predictioncenter.org/casp12/index.cgi)

CASP12 Demo

- http://predictioncenter.org/casp12/index.cgi

1D: Secondary Structure Prediction



MWLKKFGINLLIGQSV…

Neural Networks / Deep Learning + Alignments

CCCCHHHHHCCCSSSSS…

Cheng, Randall, Sweredoski, Baldi. *Nucleic Acid Research*, 2005

Widely Used Tools (~78-80%)

Sspro 5: http://download.igb.uci.edu

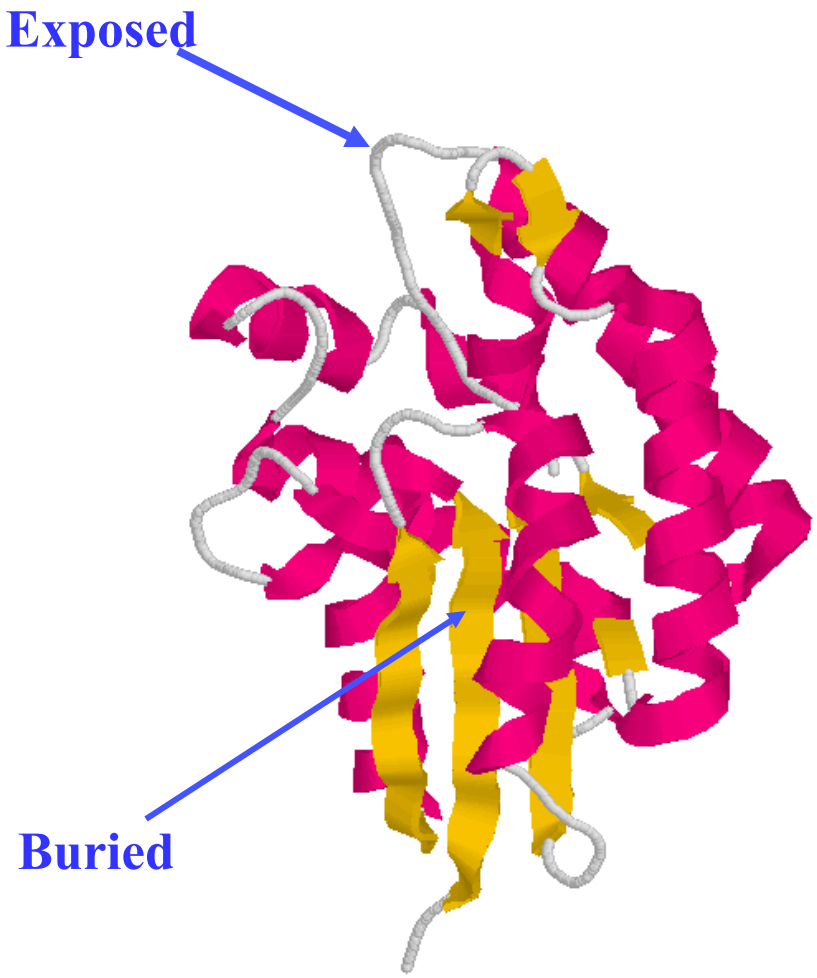
Distill: http://distill.ucd.ie/porter/

PSI-PRED: http://bioinf.cs.ucl.ac.uk/psipred/psiform.html
software is also available

SAM: http://compbio.soe.ucsc.edu/SAM_T08/T08-query.html

PHD: http://www.predictprotein.org/
DNSS: http://sysbio.rnet.missouri.edu/multicom_toolbox/tools.html

1D: Solvent Accessibility Prediction



MWLKKFGINLLIGQSV…

Neural Networks / Deep Learning + Alignments

eeeeeeebbbbbbbbeeeebbb…

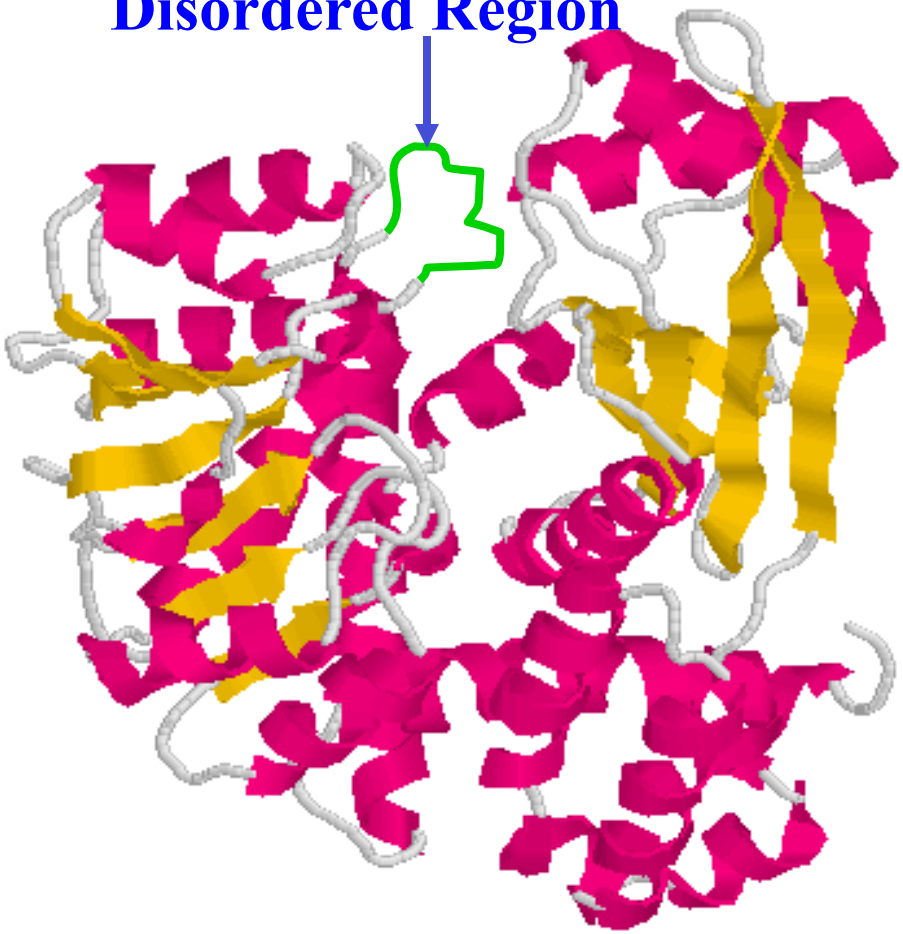
Accuracy: 79% at 25% threshold

Cheng, Randall, Sweredoski, Baldi. *Nucleic Acid Research*, 2005

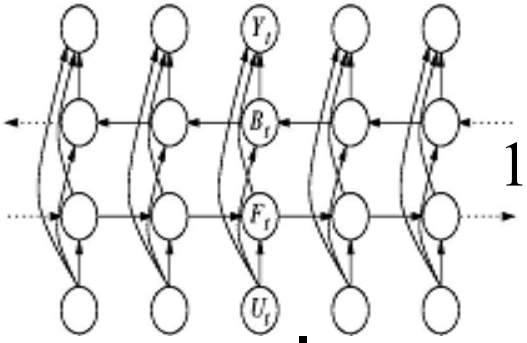
Widely Used Tools (78%)

- ACCpro 5: http://download.igb.uci.edu
- SCRATCH: http://scratch.proteomics.ics.uci.edu/
- PHD: http://www.predictprotein.org/
- Distill: http://distill.ucd.ie/porter/

1D: Disordered Region Prediction Using Neural Networks



MWLKKFGINLLIGQSV…



1D-RNN

OOOOODDDDOOOOO…

93% TP at 5% FP

Deng, Eickholt, Cheng. BMC Bioinformatics, 2009

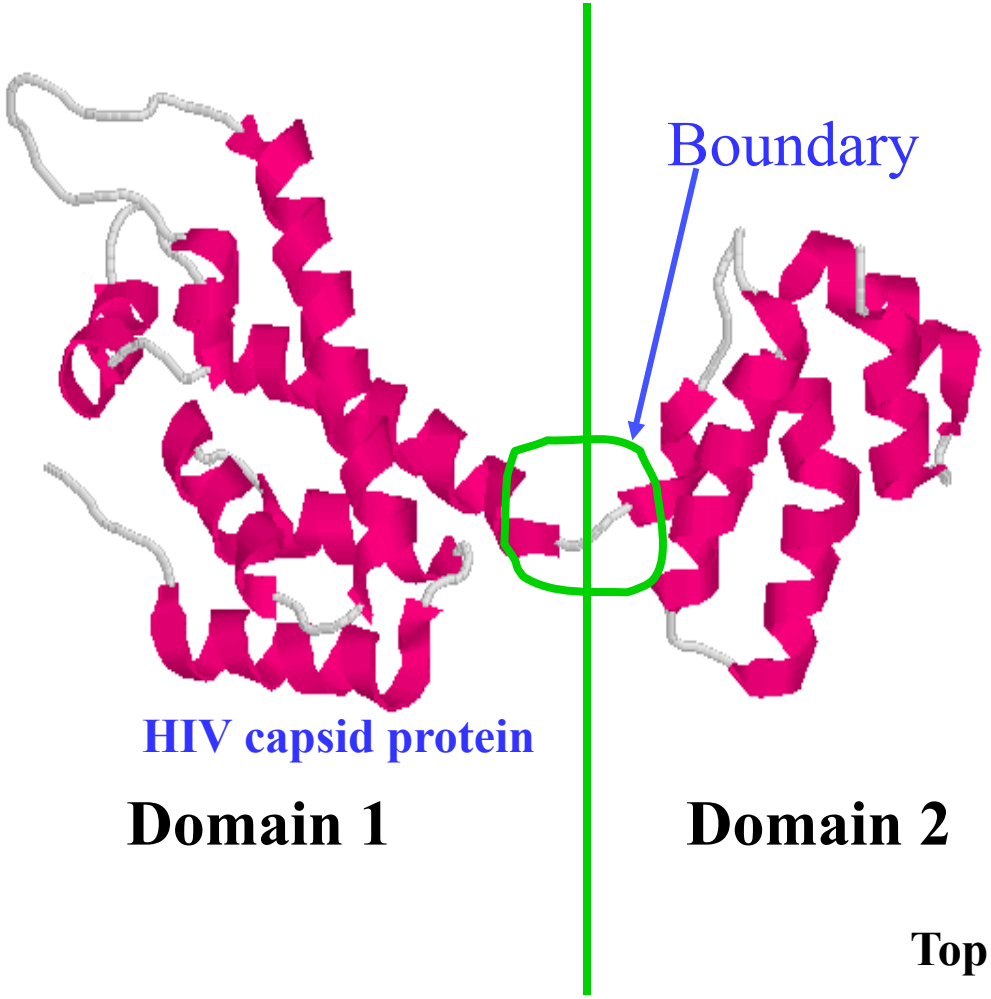
Tools

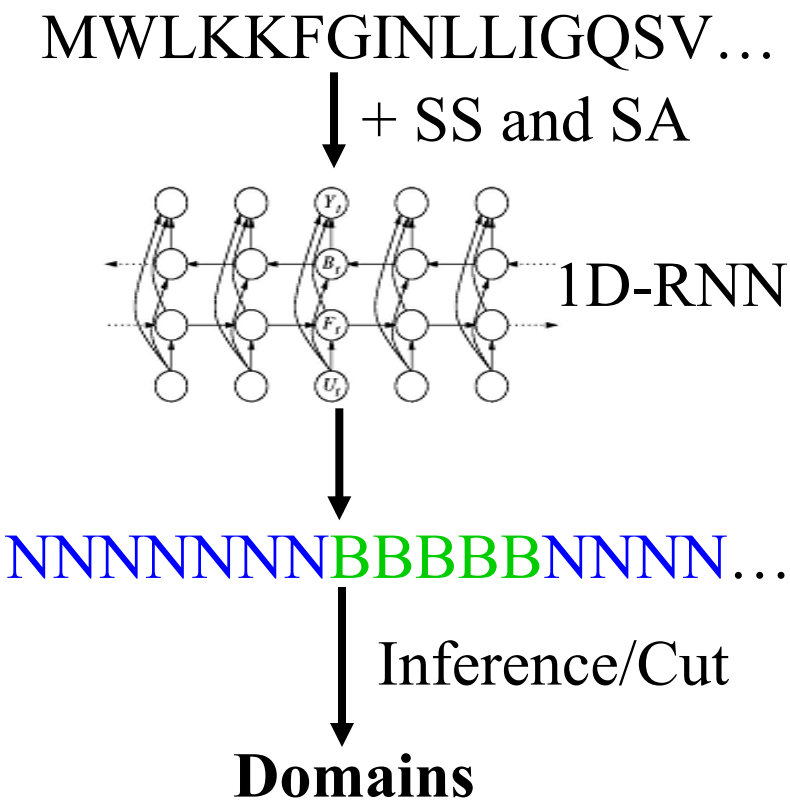
PreDisorder: http://sysbio.rnet.missouri.edu/multicom_toolbox/

A collection of disorder predictors:
http://www.disprot.org/predictors.php

Deng, Eickholt, Cheng. BMC Bioinformatics, 2009 & Mol. Biosystem, 2011

1D: Protein Domain Prediction Using Neural Networks





Top *ab-initio* domain predictor in CAFASP4

Cheng, Sweredoski, Baldi. *Data Mining and Knowledge Discovery*, 2006.

DoBo

Protein domain boundary prediction by integrating evolutionary signals and machine learning

Have a question? Maybe it's answered in the FAQ

Job Details

Job title (optional)

Sequence

Plain sequence. Spaces, newlines and any FASTA header will be ignored.
Mininum sequence length is 90 residues.

Confidence level 60%

Set a minimum threshold for the confidence of domain boundary predictions.

Single/multi-domain classification No

Run an additional check to classify query as a single or multi-domain protein.

Submit Job

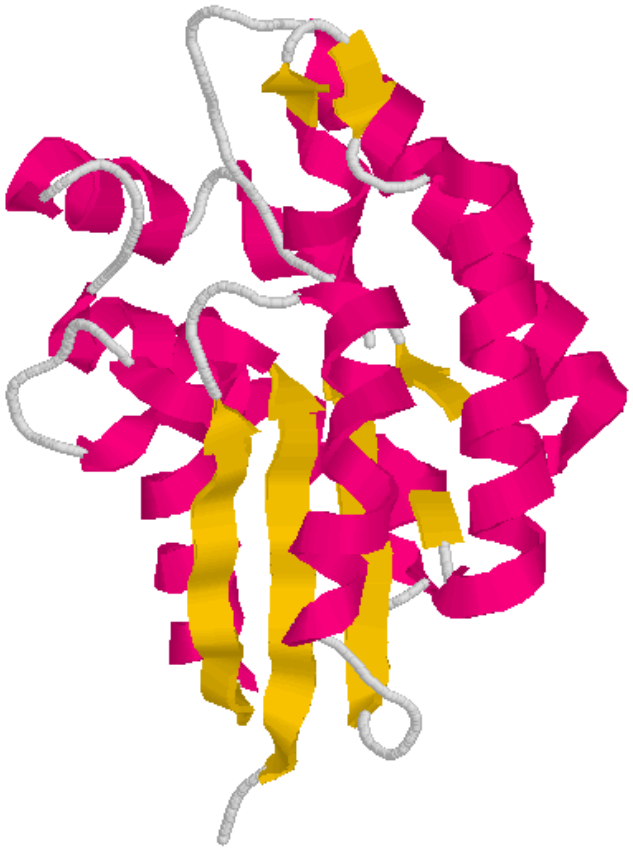
Web: http://sysbio.rnet.missouri.edu/multicom_toolbox/index.html

Reference:

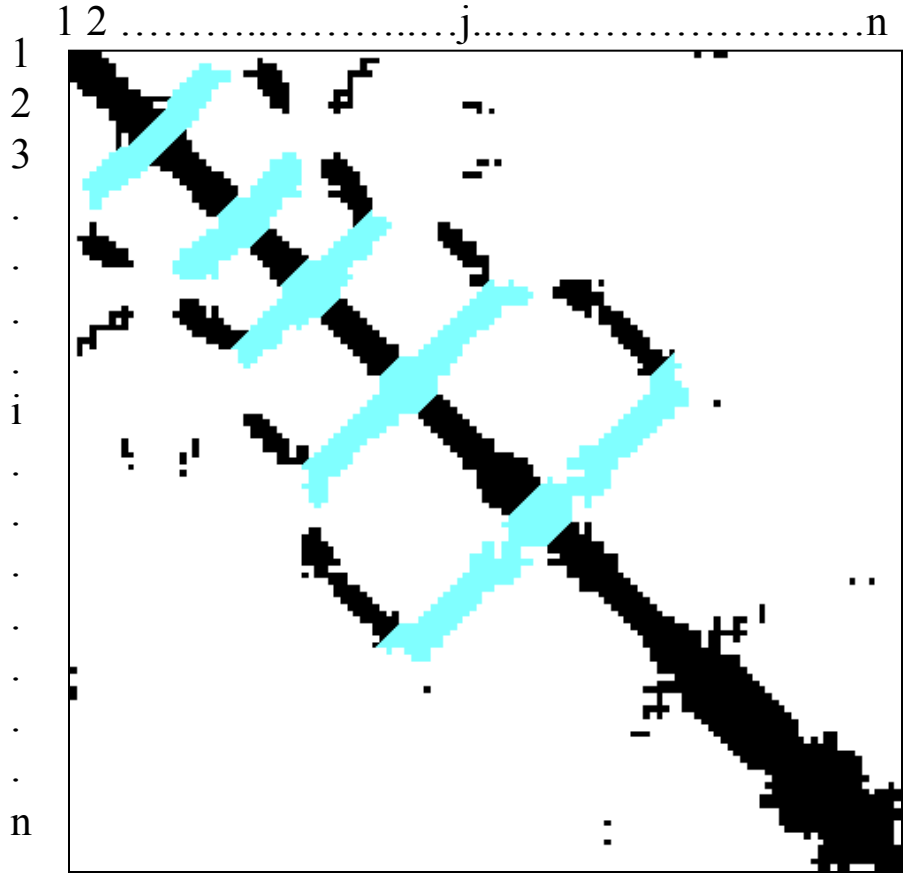
J. Eickholt, X. Deng, and J. Cheng. **DoBo: Protein Domain Boundary Prediction by Integrating Evolutionary Signals and Machine Learning.** ***BMC Bioinformatics***. 12:43, 2011.

2D: Contact Map Prediction

3D Structure



2D Contact Map



Distance Threshold = 8A°

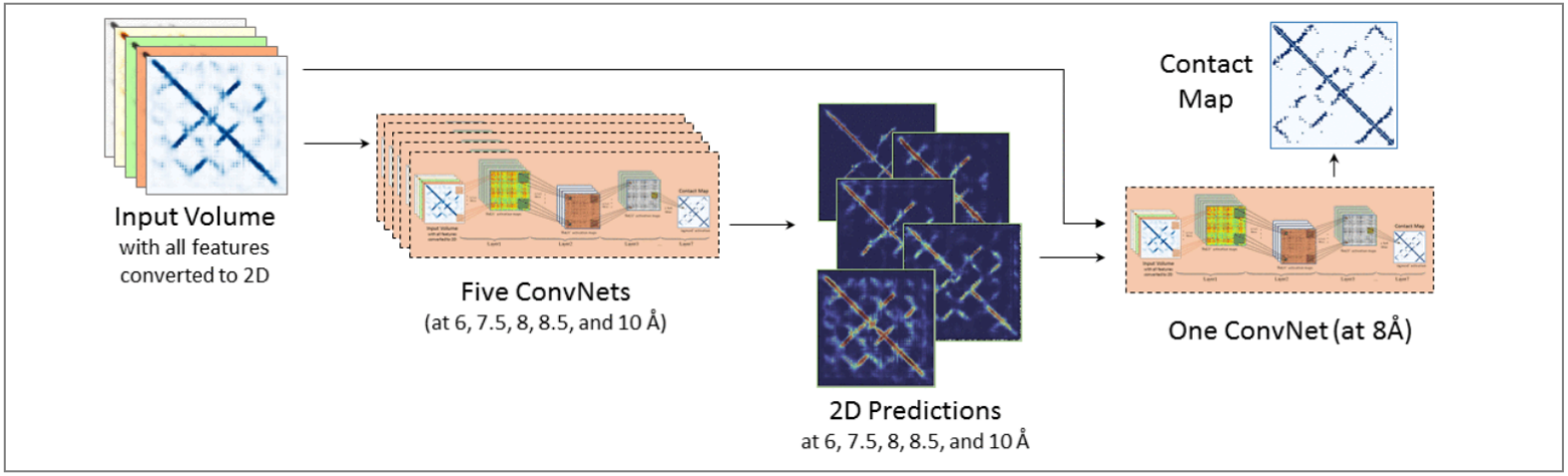
Cheng, Randall, Sweredoski, Baldi. *Nucleic Acid Research*, 2005

Contact Prediction

- SVMcon/NNcon/DNcon: http://casp.rnet.missouri.edu/svmcon.html

- PISCOV: http://bioinfadmin.cs.ucl.ac.uk/downloads/PSICOV/
- DNCON2: https://github.com/multicom-toolbox/DNCON2

DNCON2: Protein Contact Prediction Using Deep CNN



Submit Your Job

[Please submit maximum two sequences at a time]

Job Id: no spaces please

E-mail: Predictions will be sent here

Sequence: Paste protein sequence here (no headers, no newlines, no spaces, nothing else)

Run DNCON2

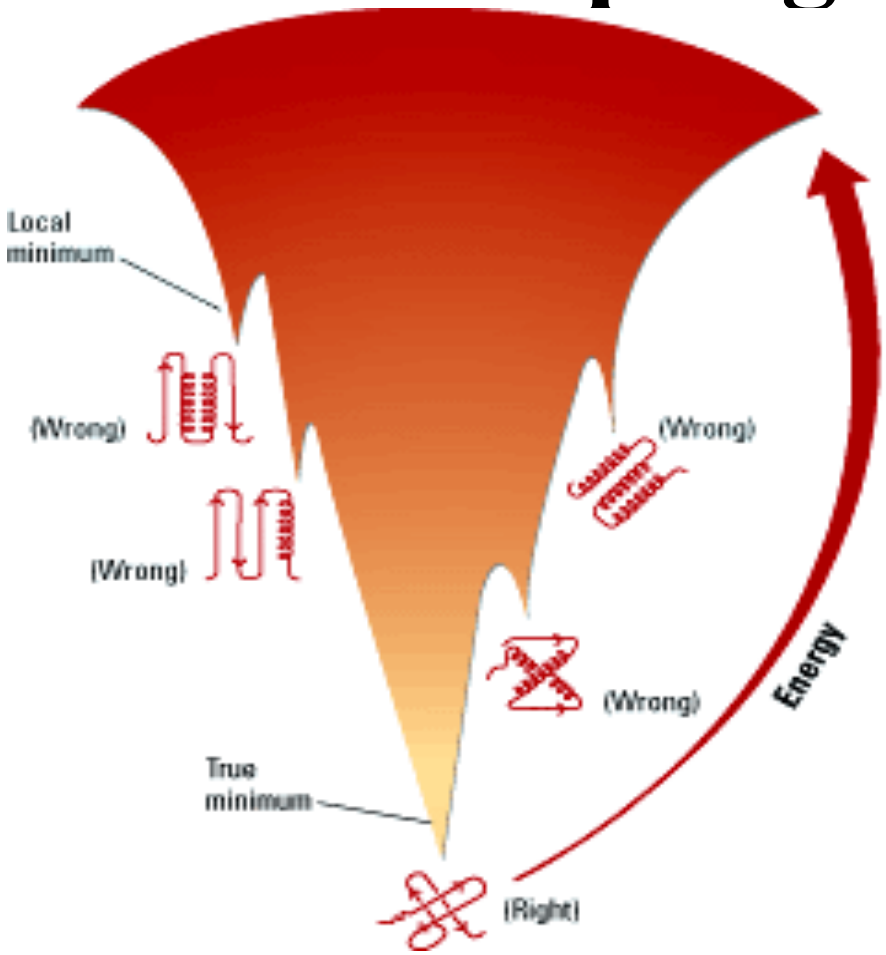
Download DNCON2 code here.

Download DNCON2's predictions for CASP 10, 11, and 12 datasets here.

Download DNCON2's training/testing dataset (fastas and lists) here.

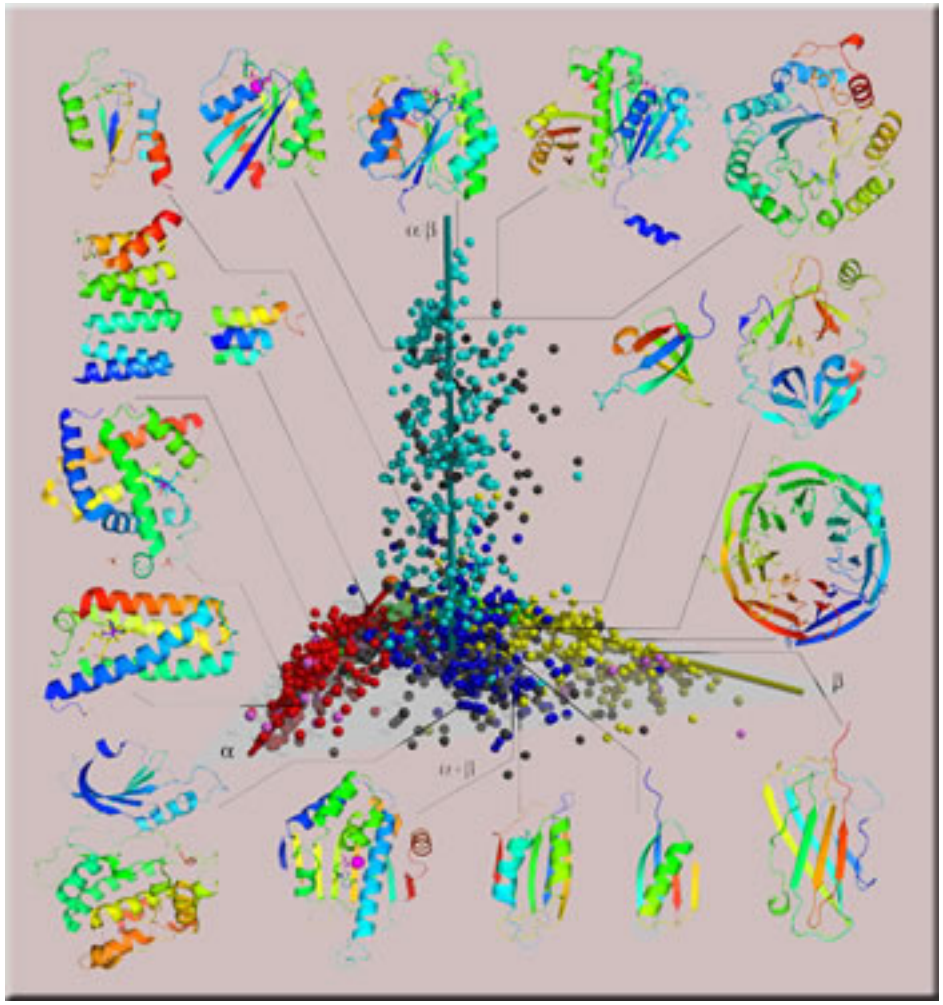
Protein tertiary structure prediction is a space sampling / simuation problem.

Protein Energy Landscape & Free Sampling



http://pubs.acs.org/subscribe/archive/mdd/v03/i09/html/willis.html

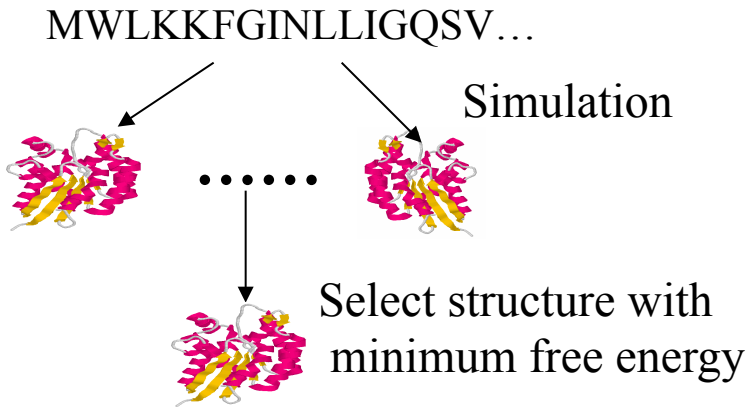
Protein Structure Space & Target Sampling



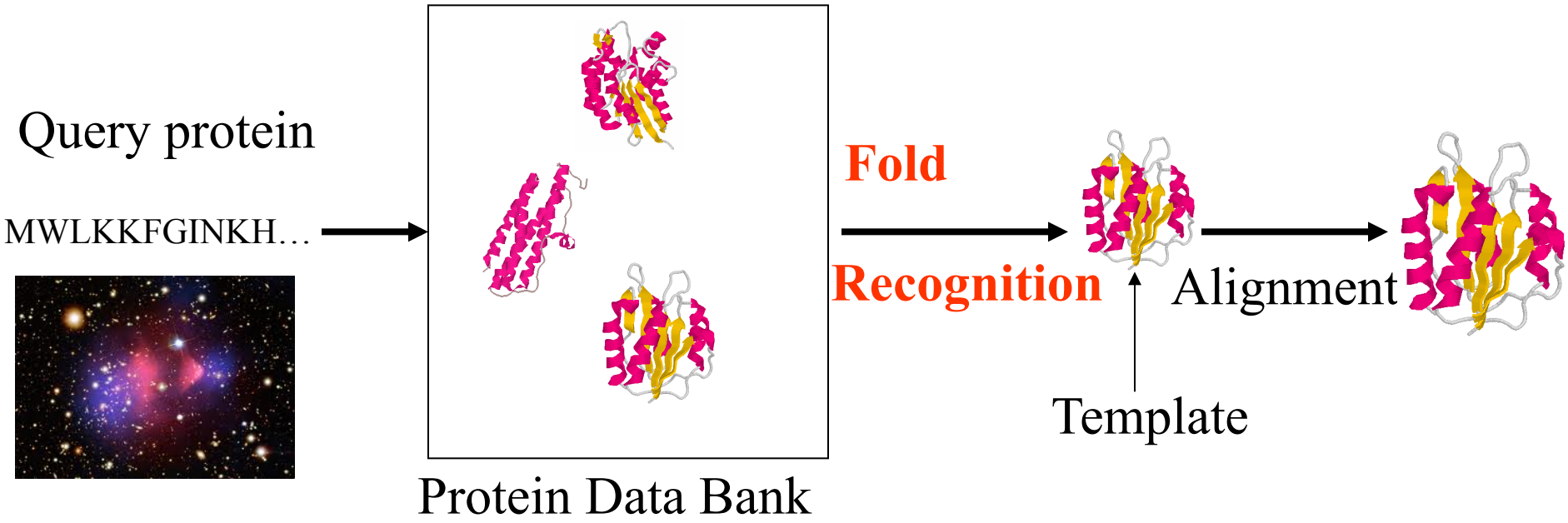
Two Approaches for 3D Structure Prediction

- **Ab Initio Structure Prediction**

  Physical force field – protein folding
  Contact map - reconstruction



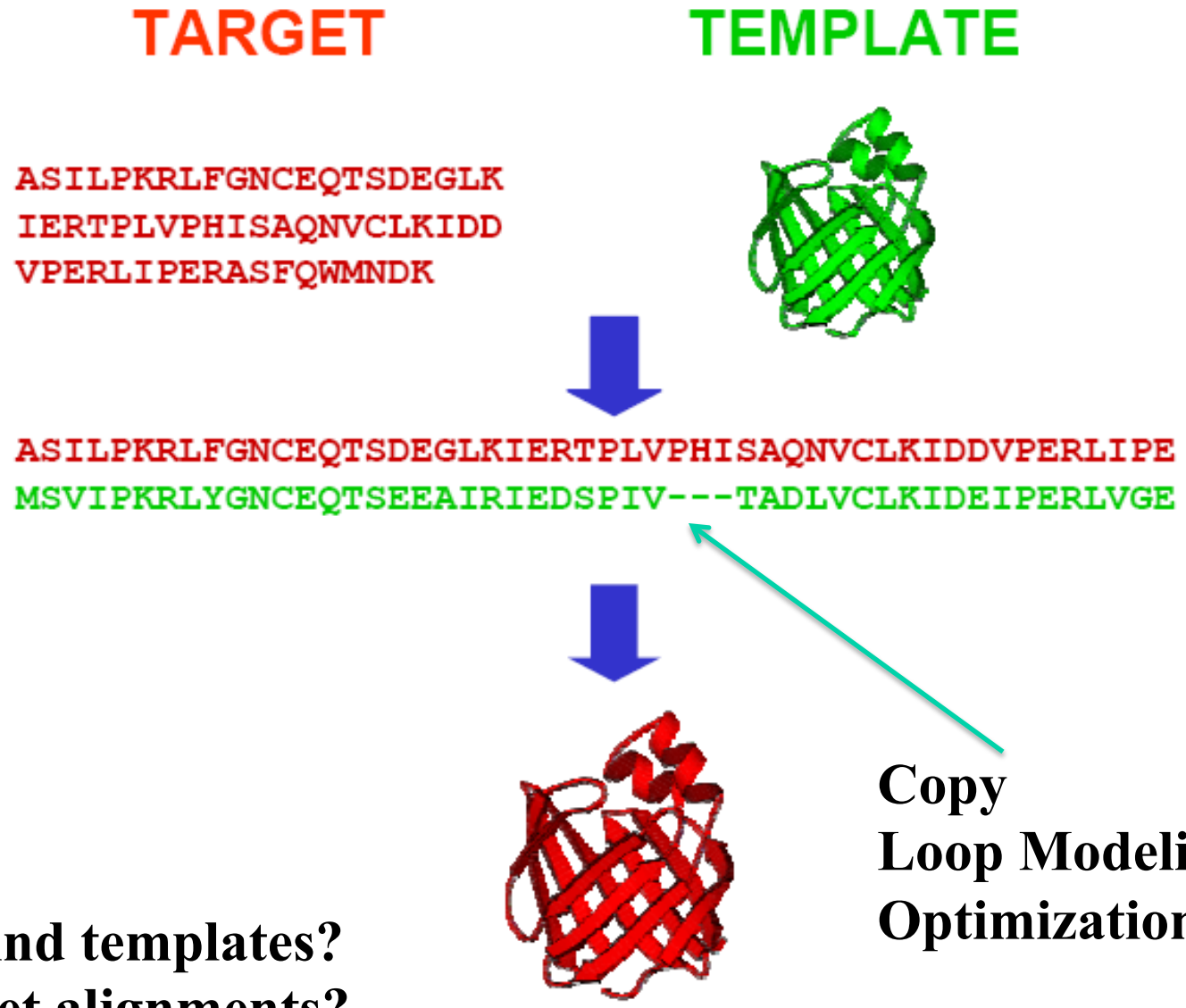
- **Template-Based Structure Prediction**



Template-Based Structure Prediction

1. Template identification
2. Query-template alignment
3. Model generation
4. Model evaluation
5. Model refinement

Notes: if template is easy to identify, it is often called **comparative Modeling or homology** modeling. If template is hard to identify, it is often called **fold recognition**.



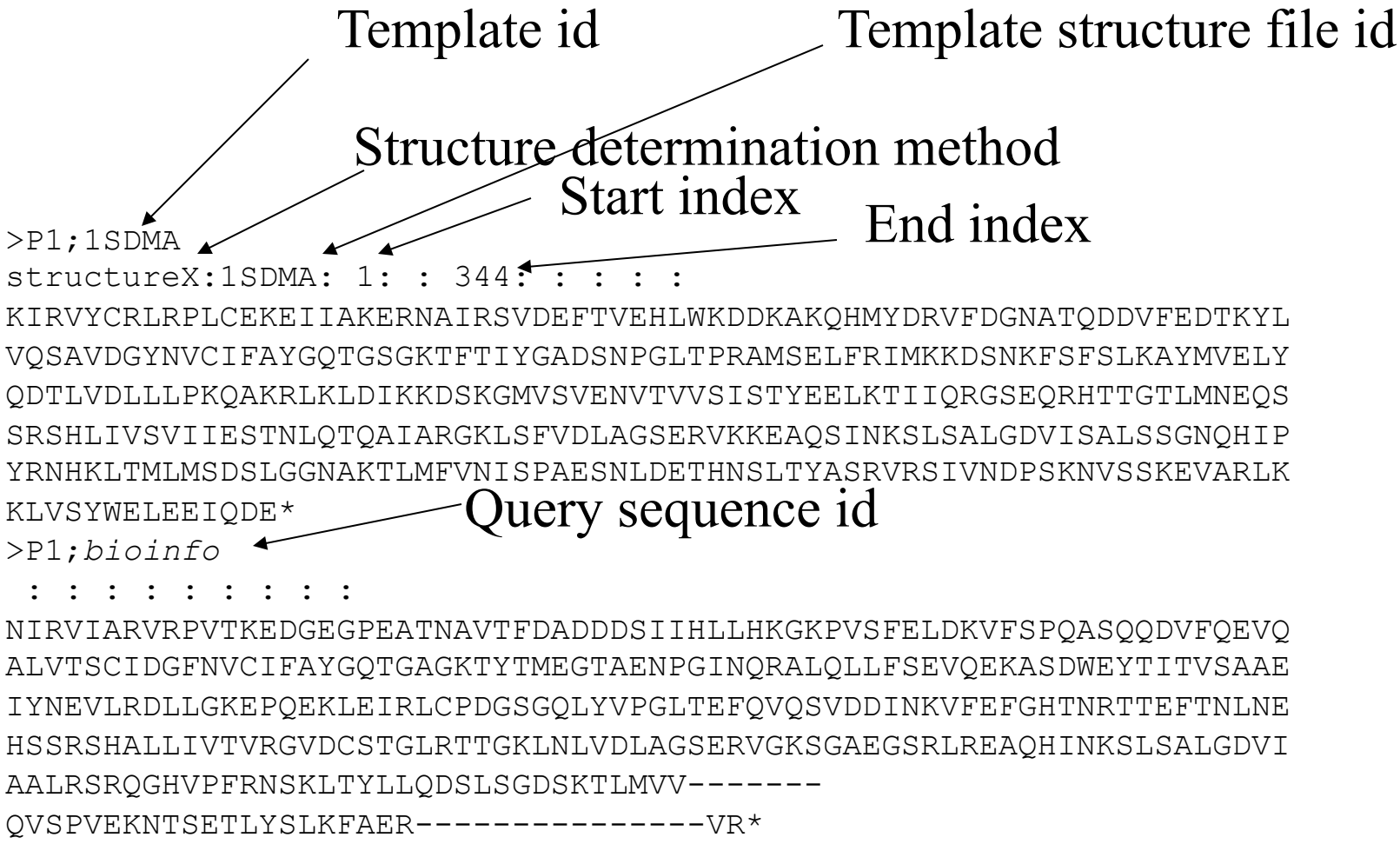
How to find templates?
How to get alignments?

A. Fisher, 2005

Modeller

- Need an alignment file between query and template sequence in the PIR format
- Need the structure (atom coordinates) file of template protein
- You need to write a simple script (Python for version 8.2) to tell how to generate the model and where to find the alignment file and template structure file.
- Run Modeller on the script. Modeller will automatically copy coordinates and make necessary adjustments to generate a model.

An PIR Alignment Example



Structure File Example (1SDMA.atm)

```
ATOM      1  N   LYS     1      -3.978  26.298 113.043  1.00 31.75           N
ATOM      2  CA  LYS     1      -4.532  25.067 113.678  1.00 31.58           C
ATOM      3  C   LYS     1      -5.805  25.389 114.448  1.00 30.38           C
ATOM      4  O   LYS     1      -6.887  24.945 114.072  1.00 32.68           O
ATOM      5  CB  LYS     1      -3.507  24.446 114.631  1.00 34.97           C
ATOM      6  CG  LYS     1      -3.743  22.970 114.942  1.00 36.49           C
ATOM      7  CD  LYS     1      -3.886  22.172 113.644  1.00 39.52           C
ATOM      8  CE  LYS     1      -3.318  20.766 113.761  1.00 41.58           C
ATOM      9  NZ  LYS     1      -1.817  20.761 113.756  1.00 43.48           N
ATOM     10  N   ILE     2      -5.687  26.161 115.522  1.00 26.16           N
ATOM     11  CA  ILE     2      -6.867  26.500 116.302  1.00 22.75           C
ATOM     12  C   ILE     2      -7.887  27.226 115.439  1.00 21.35           C
ATOM     13  O   ILE     2      -7.565  28.200 114.770  1.00 20.95           O
ATOM     14  CB  ILE     2      -6.513  27.377 117.523  1.00 21.68           C
ATOM     15  CG1 ILE     2      -5.701  26.563 118.526  1.00 21.13           C
ATOM     16  CG2 ILE     2      -7.782  27.875 118.200  1.00 18.96           C
ATOM     17  CD1 ILE     2      -5.368  27.325 119.787  1.00 21.39           C
ATOM     18  N   ARG     3      -9.120  26.737 115.461  1.00 22.04           N
ATOM     19  CA  ARG     3     -10.214  27.327 114.693  1.00 23.95           C
ATOM     20  C   ARG     3     -10.783  28.563 115.400  1.00 22.82           C
ATOM     21  O   ARG     3     -10.771  28.645 116.629  1.00 22.62           O
ATOM     22  CB  ARG     3     -11.327  26.290 114.510  1.00 26.34           C
ATOM     23  CG  ARG     3     -11.351  25.586 113.161  1.00 30.68           C
ATOM     24  CD  ARG     3     -10.004  25.034 112.771  1.00 35.43           C
ATOM     25  NE  ARG     3     -10.104  24.072 111.672  1.00 43.37           N
ATOM     26  CZ  ARG     3     -10.575  24.350 110.458  1.00 46.04           C
ATOM     27  NH1 ARG     3     -10.997  25.572 110.168  1.00 48.68           N
ATOM     28  NH2 ARG     3     -10.627  23.400 109.532  1.00 48.37           N
ATOM     29  N   VAL     4     -11.278  29.524 114.630  1.00 20.49           N
ATOM     30  CA  VAL     4     -11.853  30.724 115.225  1.00 17.59           C
ATOM     31  C   VAL     4     -13.082  31.211 114.471  1.00 18.31           C
ATOM     32  O   VAL     4     -13.030  31.446 113.264  1.00 16.37           O
ATOM     33  CB  VAL     4     -10.834  31.872 115.272  1.00 19.94           C
ATOM     34  CG1 VAL     4     -11.512  33.168 115.759  1.00 15.64           C
ATOM     35  CG2 VAL     4      -9.668  31.489 116.168  1.00 15.45           C
```

Modeller Python Script
(bioinfo.py)

```
# Homology modelling by the automodel class

from modeller.automodel import *    # Load the automodel class

log.verbose()    # request verbose output
env = environ()  # create a new MODELLER environment to build this model in

# directories for input atom files
env.io.atom_files_directory = './:../atom_files'

a = automodel(env,
              alnfile  = 'bioinfo.pir',  # alignment filename
              knowns   = '1SDMA',        # codes of the templates
              sequence = 'bioinfo')      # code of the target
a.starting_model= 1                 # index of the first model
a.ending_model  = 1                 # index of the last model
                                    # (determines how many models to calculate)
a.make()                            # do the actual homology modelling
```

Where to find structure file

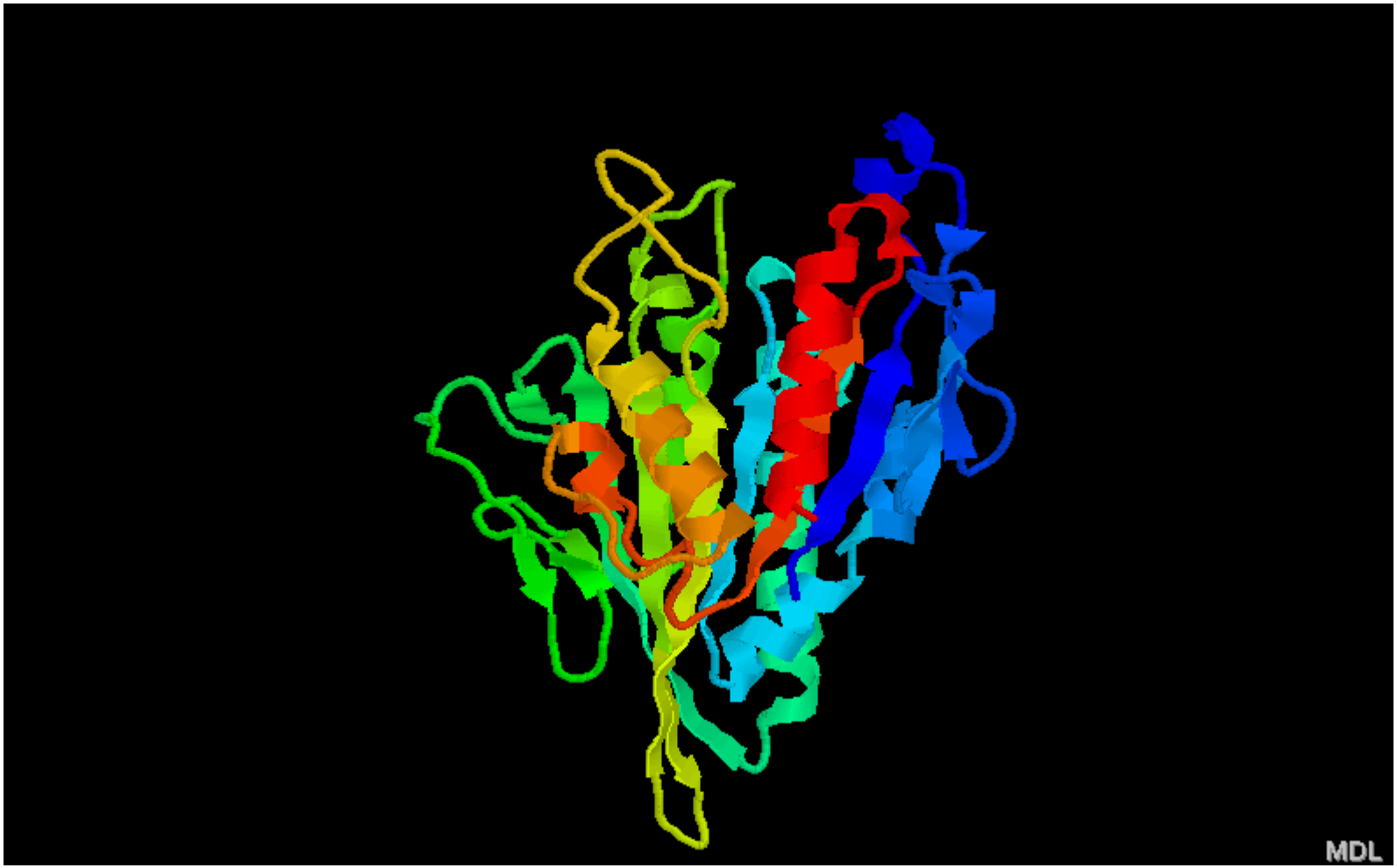
PIR alignment file name

Template structure file id

Query sequence id

Output Example

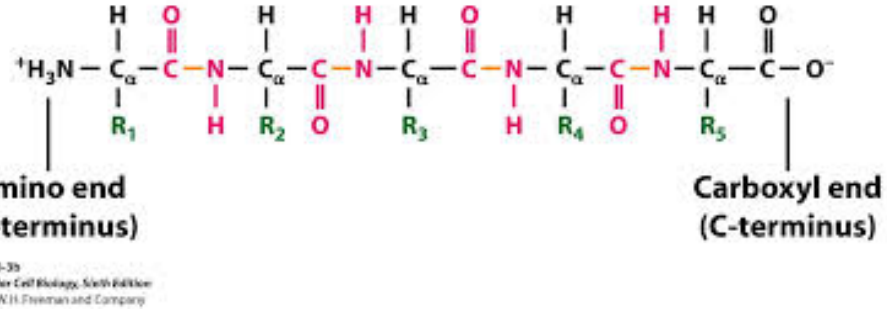
Command: mod8v2 bioinfo.py



Template Based Modeling Methods

- Comparative Protein Modeling by Satisfaction of Spatial Restraints by Andrej Sali and Tom L. Blundell
- 3D Model is obtained by satisfying spatial restraints derived from alignment with a known structure, which are expressed as probability density functions (pdfs) of the restraints.
- Pdfs serve as an objective function for optimization

Probability Density Functions of Features



- Ca – Ca distances
- Main-chain N-O distance
- Main-chain dihedral angles
- Side-chain dihedral angles
- A protein pdf is a combination of individual pdfs of features of the whole protein

Optimization Procedure

- Objective: the pdf of a protein derived from restraints extracted from templates and alignments
- Initial input: initial (x, y, z) of each residue satisfying bond length / angle restraints
- Optimization: adjust x, y, z to maximize the pdf (i.e. probability), i.e. reduce the violations of feature restraint as much as possible

Topic 1 – Template Based Modeling

- CASP12 TBM targets
- Known templates at CASP12 web sites
- Develop a homology-based algorithm / tool to build models from templates
- Assess the quality of models
- Implement from scratch
- **Form your group**

Feature Restraints from Templates

- A database of 17 family alignments including 80 proteins was constructed to obtain feature statistics.
- Feature constraint is represented as conditional distribution. E.g. P(ca-ca distance in target | ca-ca distance in template,…), P(psi angle of a residue in target | psi angle of an equivalent residue in template, …)

Side Chain & Main Chain

- P(X1 | residue type, phi, psi)
- Main-chain and side-chain modeling can be separated or carried out simultaneously

Function Fitting from Known Data

- $P(x|a,b,c) \sim Wx,a,b,c \sim f(x,a,b,c,q)$
- W is a multi-dimensional table calculated from relative frequencies in the data
- *f* is a function that fits W by minimizing root mean square difference
- Fitting algorithm: *Levenberg-Marquardt* algorithm for non-constrained least-squares fitting of a non-linear multidimensional model implemented in the program LSQ.

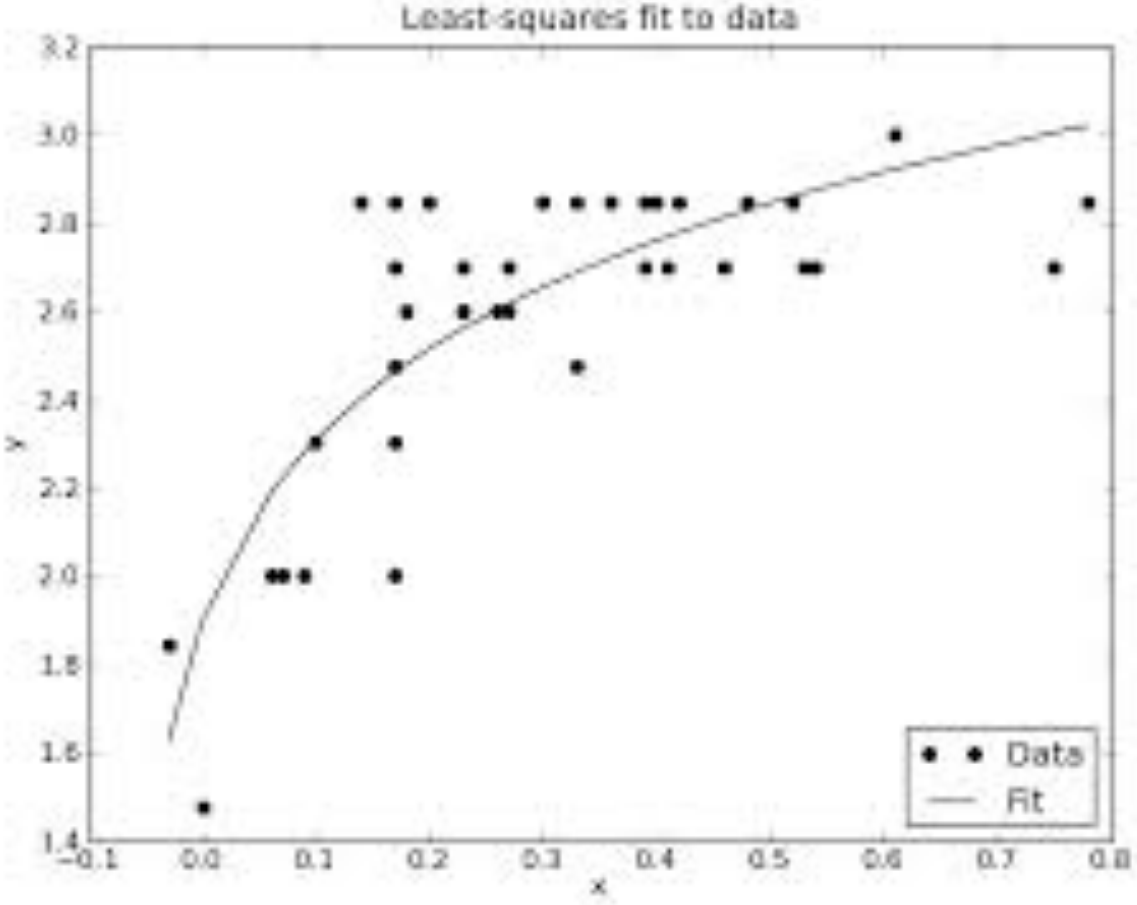
Features in Multi-Dimensional Table (MDT) Program

- Residue type
- Main-chain dihedral angle of a residue
- Secondary structure of a residue

An Example of Generating a pdf for one feature (phi angle)

Residue A in target	Residue B in template	Angle in Template	Angle in Target
A	C	50	58, 60, 49, …
A	C	70	67, 82, 87
A	K	10	9.5, 11, 10.8…
…	…	…	…

Levenberg-Marquardt algorithm



1	r	Amino acid residue type
2	Φ	Main-chain dihedral angle Φ
3	Ψ	Main-chain dihedral angle Ψ
4	t	Secondary structure class of a residue
5	M	Main-chain conformation class of a residue
6	α	Fractional content of residues in the main-chain conformation class A
7	χ_i	Side-chain dihedral angle χ_i, $i = 1, 2, 3, 4$
8	c_i	Side-chain dihedral angle χ_i class, $i = 1, 2, 3, 4$
9	a	Residue solvent accessibility
10	$\bar{a}$	Average accessibility of two residues in one protein
11	s	Residue neighbourhood difference between two proteins
12	$\bar{s}$	Average residue neighbourhood difference between two proteins
13	i	Fractional sequence identity between two proteins
14	d	C^α–C^α distance
15	Δd	Difference between two C^α–C^α distances in two proteins
16	h	Main-chain N–O distance
17	Δh	Difference between two main-chain N–O distances in two proteins
18	b	Average residue B_{iso}
19	R	Resolution of X-ray analysis
20	g	Distance of a residue from a gap in alignment
21	$\bar{g}$	Average distance of a residue from a gap

Main Chain Conformation Class

Parameters of the main-chain conformation classes

	Mean (°)		Standard deviation (°)	
	Φ_i	$\bar{\Psi}_i$	$\sigma_i(\Phi)$	$\sigma_i(\Psi)$
A	−65	−41	15	15
B	−130	135	15	20
P	−65	140	15	15
G	60	40	10	10
L	90	−10	15	10
E	130	180	25	25

Usefulness of Features

- The most useful pdf is the one that predicts the unknown feature most accurately
- Measured by the entropy of a pdf

Stereochemical Restraints (Generic)

- Obtained from sequence of a protein
- Bond distance, bond angle, planarity of peptide groups, side-chain rings, chiralities of Ca atoms and side-chains, van der Waals contact distance (radii values)
- Mean value and standard deviations for bond lengths, bond angles, and dihedral angles are obtained from GROMOS86

Bond Length and Angles (harmoic model)

The classical harmonic model for the bond length between two atoms gives the vibrational potential energy of the bond as:

$$E(b) = \tfrac{1}{2}c(b-b_o)^2. \tag{19}$$

$$p^b(b) = \frac{1}{\sigma_b\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{b-\bar{b}}{\sigma_b}\right)^2\right] = N(\bar{b}, \sigma_b).$$

Van der Waals Repulsion (only non-harmonic feature)

(ii) *van der Waals repulsion*

van der Waals repulsion is the only stereochemical feature which is not described by the harmonic model. Instead, the following pdf is used for two atoms:

$$p^v(d) = c \cdot \begin{cases} N(d_o, \sigma_w); & d \leq d_o \\ \dfrac{1}{\sigma_w \sqrt{2\pi}}; & d_o < d < d_{\max}, \end{cases} \qquad (22)$$

where d is the distance between the two atoms, d_o is the sum of their van der Waals radii and σ_w is the standard deviation of the Gaussian part of the whole pdf (usually 0·05 Å). $d_{\max}$ is the maximal possible linear dimension of a protein and constant c is chosen so that $p^v(d)$ integrates to 1. This pdf does not differentiate between contact distances larger than d_o, but it does select against distances smaller than d_o. This is achieved by imposing a repulsive harmonic potential on atoms that are less than d_o apart.

Ca-Ca Distance Features

$$p^{d}(d/\bar{g}, i, \bar{a}', d') = \frac{1}{\sigma(\bar{g}, i, \bar{a}', d')\sqrt{2\pi}} \times \exp\left[-\frac{1}{2}\left(\frac{d-d'}{\sigma(\bar{g}, i, \bar{a}', d')}\right)^{2}\right]$$

Standard deviation depends on solvent accessibility, gaps of alignment, and sequence identity.

Combine pdfs of a Feature (Ca-Ca distance) from Multiple Templates

- Weighted sum of the same type of pdfs from multiple known structures

The last step in the derivation of the feature pdf is to include the van der Waals restraint. Since all stereochemical restraints have to be satisfied in all structures, these restraints are multiplied into the feature pdf and we obtain the final feature pdf:

$$p^D(d) = [\omega_1 p_1^d(d) + \omega_2 p_2^d(d)]p^v(d).$$

Derivation of a molecular pdf from feature pdfs

- Combine all feature pdfs into a molecular pdf $P = \prod_i p^F(f_i).$ (34)
- 3D structure of a protein is uniquely determined if a sufficient large number of its features, f_i, are specified
- The goal is to find the 3D structure that is consistent with the most probable values of individual features f_i, i.e. to maximize the molecular pdf.

Optimization

- Optimize the logarithm of molecular pdf – the objective function F.

$$F = -\ln(P), \qquad (35)$$

- All the features of the molecular pdf is expressed in terms of atomic Cartesian coordinates (x, y, z)

- F is more suitable for optimization because multiplication is converted into addition and the problem of floating point overflow is smaller for F.

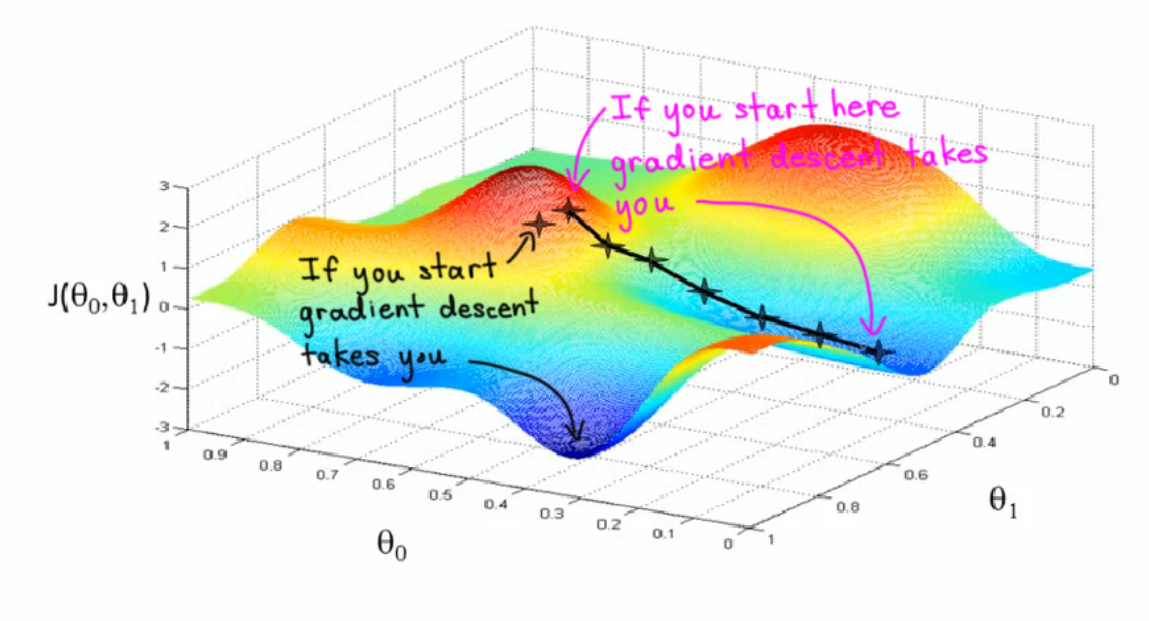
Successive Optimization

- The optimum of the molecular pdf is found by successive optimization of increasingly more complex target function till the whole molecular pdf.
- From local restraints to long-range restraints to all the restraints
- Restraints is ordered by the sequence distance between atoms / residues (1, 2, … N-1), N is the sequence length.
- Successively adding restraints with <= sequence distance i at each step i.

Initial Conformation of Step i

- At step 1, initial conformation can be an extended chain, or a conformation derived from the extended chain by rotation of dihedral angles
- At step i, the initial conformation is the final conformation of step i – 1.
- An ensemble of conformations will be produced by using different initial conformations.

Optimization: Gradient Descent



Wikipedia

Gradient Descent

$$x^{t+1} = x^t + d^t$$

$$d^t = -\eta \frac{\partial f}{\partial x^t}$$

Gradient Descent

- **Random Initialization**: $(x_1^0\ y_1^0, z_1^0), (x_2^0\ y_2^0, z_2^0), \ldots, (x_N^0\ y_N^0, z_N^0)$
- **Update**:

$$X_1^{t+1} = X_1^t - \eta * \Delta X \quad Y_1^{t+1} = Y_1^t - \eta * \Delta Y \quad Z_1^{t+1} = Z_1^t - \eta * \Delta Z$$

$$X_2^{t+1} = X_2^t - \eta * \Delta X \quad Y_2^{t+1} = Y_2^t - \eta * \Delta Y \quad Z_2^{t+1} = Z_2^t - \eta * \Delta Z$$

$$\vdots$$

$$X_N^{t+1} = X_1^t - \eta * \Delta X \quad Y_N^{t+1} = Y_1^t - \eta * \Delta Y \quad Z_N^{t+1} = Z_1^t - \eta * \Delta Z$$

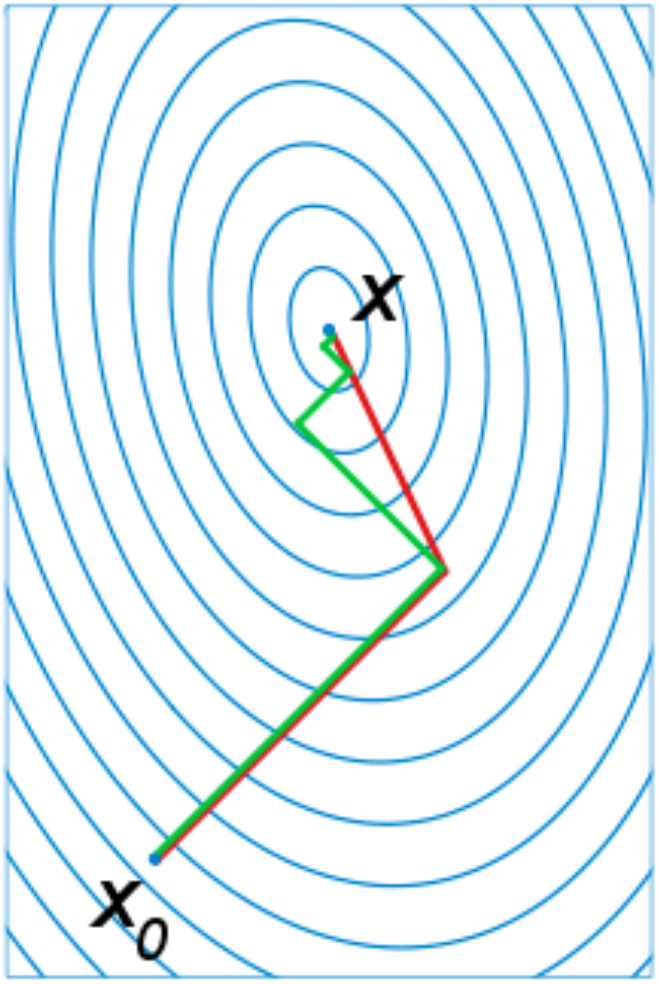
Trieu, Cheng, 2014

Conjugate Gradient Descent

$$x^{t+1} = x^t + \eta d^t$$

$$d^t = -\frac{\partial f^t}{\partial x^t}$$

$$d^t = -\frac{\partial f^t}{\partial x^t} + d^{t-1}$$



A comparison of the convergence of gradient descent with optimal step size (in green) and conjugate vector (in red) for minimizing a quadratic function associated with a given linear system. Conjugate gradient, assuming exact arithmetic, converges in at most *n* steps where *n* is the size of the matrix of the system (here *n*=2).

Spatial restraints used to model trypsin

Type	Basis pdfs[a]	Feature pdfs[b]	Violations[c]	r.m.s.[d]	r.m.s.[e]
Bond lengths	1659	1659	0 (0·1 Å)	0·005 Å	0·005 Å
Bond angles	2250	2250	5 (10°)	2·00°	2·00°
Dihedral angles[f]	919	919	1 (20°)	3·40°	3·40°
van der Waals contacts[g]	531	531	0 (0·2 Å)	0·02 Å	0·02 Å
C^{α}–C^{α} distances	23,538	11,914	26 (1·5 Å)	0·22 Å	0·47 Å
Main-chain N–O distances	7480	3832	19 (1·5 Å)	0·31 Å	0·51 Å
Main-chain Φ dihedral angles	1110	222	2 (20°)	10·8°	21·2°
Main-chain Ψ dihedral angles	1332	222	9 (20°)	10·6°	20·3°
Side-chain χ_1 dihedral angles	528	176	5 (25°)	8·4°	16·8°
Side-chain χ_2 dihedral angles	264	103	3 (25°)	10·2°	13·0°
Side-chain χ_3 dihedral angles	92	32	2 (25°)	11·9°	48·1°
Side-chain χ_4 dihedral angles	48	16	0 (25°)	4·5°	21·9°
Disulphide bridge bonds	6	6	0 (0·1°)	0·007 Å	0·007 Å
Disulphide bridge angles	12	12	0 (10°)	3·7°	3·7°
Disulphide bridge dihedral angles	6	12	0 (20°)	10·0°	12·9°
cis-Peptides[h]	0	0			

Group Formation

- **Group 1**:
- **Group 2**:
- **Group 3**:

Project 1

- Design and develop a template-based protein structure modeling tool
- Assess its performance on a few TBM targets used in CASP12 benchmark

Project Directory

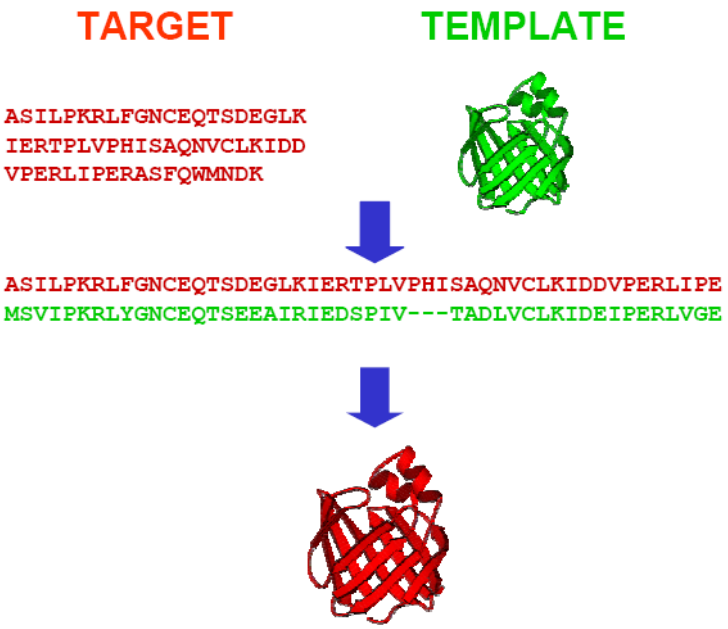
- Project1
- ---- src: source code
- ---- bin: binary
- ---- lib: library
- ---- data: data
- ---- training: training
- ---- test: test cases
- ---- doc: document / references / presentation / report
- ---- other: third-party programs

Discussion of Your Project Plan

- Data preparation & data sharing (cloud computing)
- Algorithm development (initialization, restraints extraction & representation, sampling, optimization): creative, alternative, plural
- Implementation: interface, design, platform, languages, code base / from scratch, task assignment, timeline, progress track
- Evaluation plan (metrics, tools, data, objective, comprehensive, expectation)
- Challenges, Technical Hurdles, Feasibility, Strength, weakness, Risks
- Visualization
- Software Package (installation, test cases)

Useful Tools

- Loop modeling: http://www.math.unm.edu/~vageli/codes/codes.html



- Tools convert between (x,y,z) coordinates and (phi, psi) angles : Rosetta function

- ModLoop a web server for loop modeling based on Modeller

Modeller

- https://salilab.org/modeller/
- A widely used, well-documented template-based modeling tool

MTMG

- A stochastic point cloud sampling method for template-based protein comparative modeling. Scientific Reports, 2016.
- Source code is available: http://sysbio.rnet.missouri.edu/multicom_toolbox/tools.html

Workflow of MTMG

model with weighted average coordinates

RW energy score E_{old}

weighted point cloud

weighted average coordinate

multivariate normal distribution

sample points

sampled points

7.119	8.157	35.950
8.361	7.007	36.605
9.805	11.568	37.554
11.184	11.397	37.138

Yes

Atom clash
Broken chain

No

new model

RW energy score E_{new}

Accept new model?

Simulated annealing

T = # of iterations

If $E_{new} < E_{old}$, accept, d = 1, $E_{old} = E_{new}$

Else if $e^{\frac{E_{old}-E_{new}}{T}} > 0.5$, accept, $E_{old} = E_{new}$

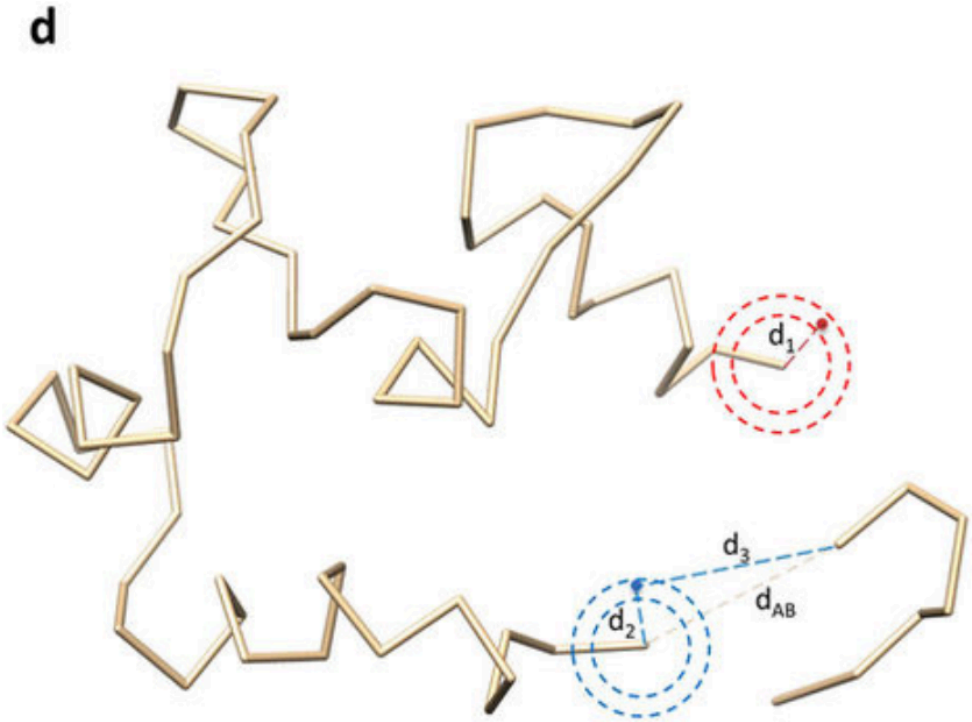
Else reject

$d = (E_{new} - E_{old}) * 0.2 * (1 + \frac{1}{N})^j$ (j = 1, ..., N)

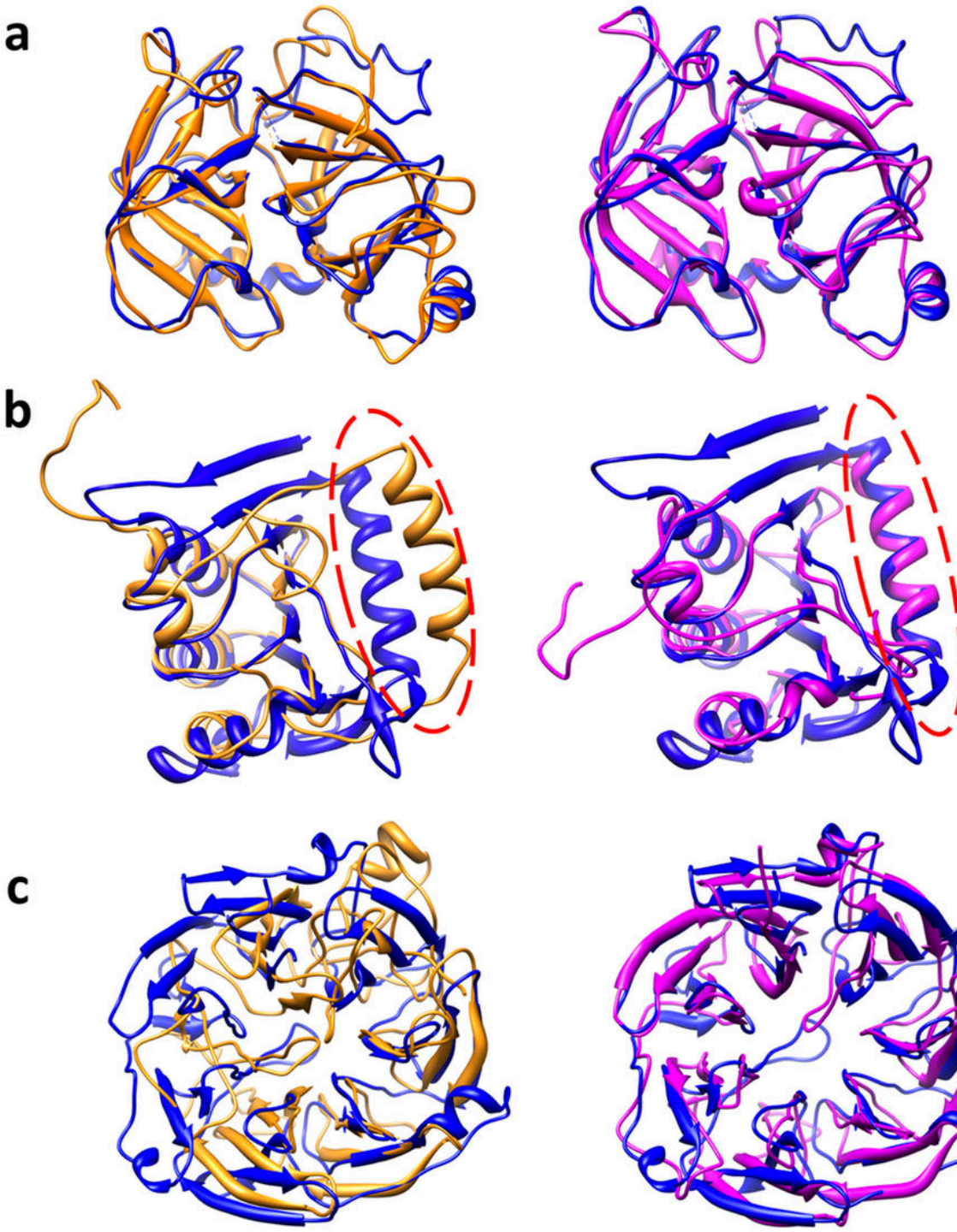
T = T - d

Can model unaligned loops

Handle Gaps

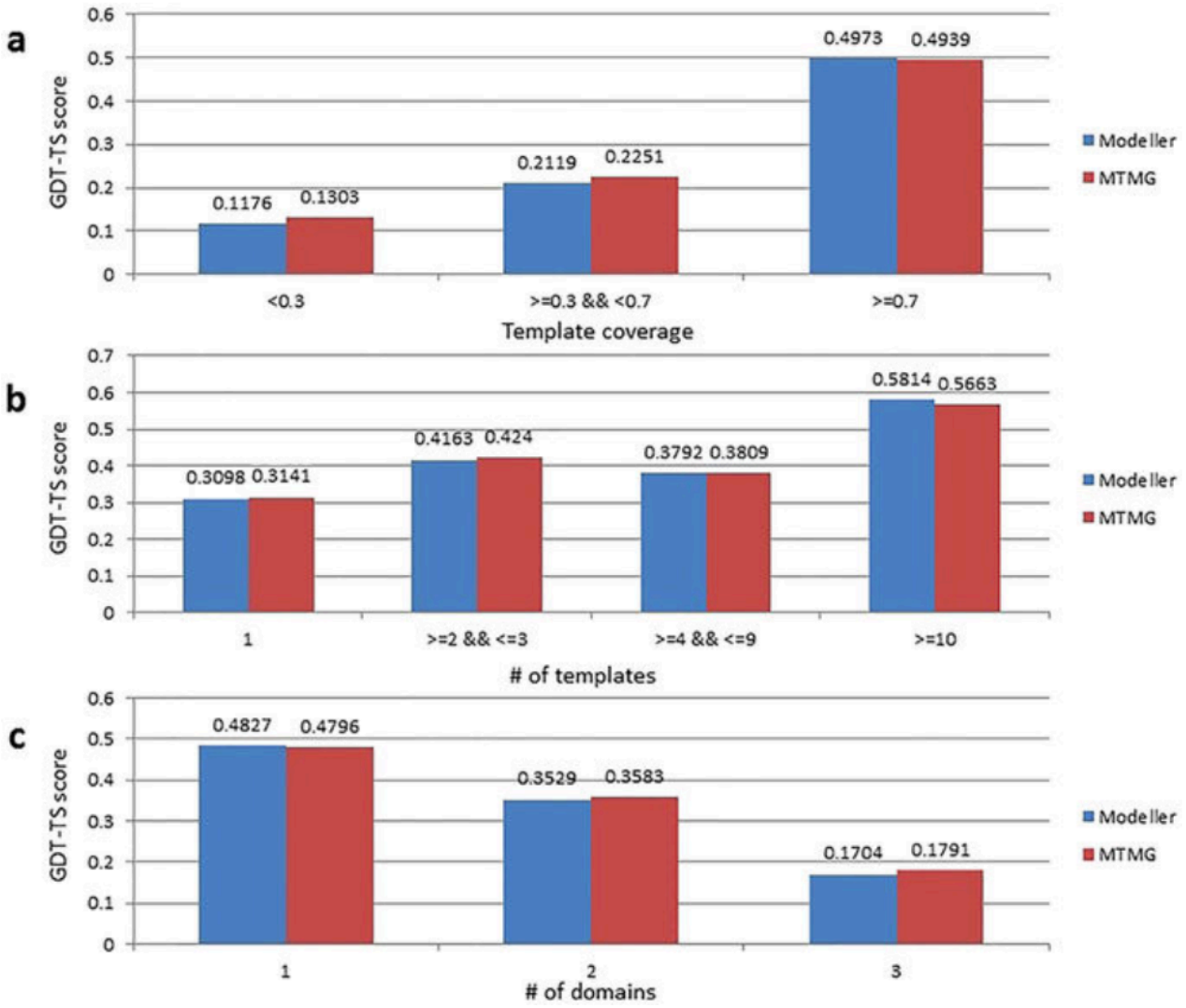


Sampling points for gaps. The radius of the outside circle is 4.5 Å, and the radius of the inner circle is 3.5 Å. The sampling algorithm randomly samples point between the two circles. In the region circled by red, the gap is at the N-terminal. The distance d1 between an accepted sampled point and the first covered residue is between 3.5 Å and 4.5 Å. In the region circled by blue, the three-residue gap is in the middle, and the distance between the two ends of the gap (dAB) is 8.2 Å. The distance d2 between an accepted sampled point and the last covered residue before the gap is between 3.5 Å and 4.5 Å. The distance d3 between an accepted sampled point and the first covered residue after the gap is between 4.1 Å and 11.4 Å.



Three examples illustrating (a) the successful template weighting and combination, (b) the successful template superposition, and (c) the successful domain division and combination of our method. The models predicted by Modeller (gold) and MTMG (purple) were superposed with the native structure (blue).

Figure 5: Comparison of GDT-TS score between the MTMG models and the Modeller models from three aspects on CASP11 targets.



(a) MTMG performed better than Modeller on targets with <0.7 template coverage. **(b)** MTMG performs better than Modeller on targets covered by <10 templates. **(c)** MTMG performs better than Modeller on targets containing multiple domains.

Key Milestones of the Project

- Class discussion (Feb. 7)
- Presentation of your plan on Feb. 14
- Presentation of your results on Feb. 26