What is Docking?

"Predicting the best ways two molecules will interact."

1. Obtain the 3D structures of the two molecules.
2. Locate the best binding site.
3. Determine the best binding modes.

We need to quantify or rank solutions.

We need a scoring function or force field.

The experimentally observed structure may be amongst one of several predicted solutions.

We need a search method.
Defining a Docking

- **Position**
  - $x$, $y$, $z$

- **Orientation**
  - $qx$, $qy$, $qz$, $qw$

- **Torsions**
  - $\tau_1$, $\tau_2$, ..., $\tau_n$

Key aspects of docking...

- **Scoring Functions**
  - What are they?

- **Search Methods**
  - How do they work?
  - Which search method should I use?

- **Dimensionality**
  - What is it?
  - Why is it important?

Scoring Function in AutoDock 4: Motivation

- To improve scoring function
  - improved hydrogen bonding
  - new desolvation energy term & internal desolvation energy
  - larger training set and new weights
- To permit protein sidechain, loop or domain flexibility
  - (new DPF keyword, "flexres")
    - treats protein's moving atoms as part of the non-translating, non-reorienting part of the torsion tree
- To simulate the unbound state of the ligand & protein
  - extended, compact and crystallographic ligand conformations

$$
\Delta G = (V_{\text{bound}} - V_{\text{unbound}}) + V_{\text{desolv}} - V_{\text{desolv}} + (V_{\text{internal}} - V_{\text{internal}} - T \Delta S_{\text{conf}})
$$
AutoDock 4 Scoring Function Terms

\[ \Delta G_{\text{total}} = \Delta G_{\text{elec}} + \Delta G_{\text{vdW}} + \Delta G_{\text{desolv}} + \Delta G_{\text{hbond}} + \Delta G_{\text{sm}} \]

- \( \Delta G_{\text{elec}} = \epsilon_{\text{rep}}^2 \frac{q_i q_j}{r_{ij}} \)
- \( \Delta G_{\text{vdW}} = 6 \pi \varepsilon_0 \frac{\sigma_{\text{vdW}}}{r_{ij}} \)
- \( \Delta G_{\text{desolv}} = \text{Solvation terms for moving atoms} \)
- \( \Delta G_{\text{hbond}} = \text{H-bonding Potential with Goodford Directionality} \)
- \( \Delta G_{\text{sm}} = \text{Number of rotatable bonds} \)

Pairwise terms in AutoDock 4

\[ V = W \sum_i \left( A_i \left( \frac{B_i}{r_{ij}} \right)^6 \right) + W \sum_i \left( B_i \left( \frac{C_i}{r_{ij}} \right)^{12} \right) + W \sum_i \left( D_i \left( \frac{E_i}{r_{ij}} \right)^6 \right) + W \sum_i \left( F_i \left( \frac{G_i}{r_{ij}} \right)^{12} \right) \]

- Desolvation includes terms for all atom types
  - Favorable term for C, A (aliphatic and aromatic carbons)
  - Unfavorable term for O, N
  - Proportional to the absolute value of the charge on the atom
  - Computes the intramolecular desolvation energy for moving atoms
- Calibrated with 188 complexes from LPDB, \( K_i \) from PDB-Bind
  - Standard error (in Kcal/mol):
    - 1.64 (extended)
    - 2.73 (compact)
    - 2.63 (bound)
    - 2.67 (AutoDock 3, bound)
- Improved H-bond directionality

Improved H-bond Directionality

- AutoGrid 3
- AutoGrid 4

More Grids, Visits, and Insights: [AutoGrid](http://autodock.scripps.edu/science/autodock-4-desolvation-free-energy/)
Why Use Grid Maps?

- Saves time:
  Precomputing the interactions on a grid is typically 100 times faster than traditional Molecular Mechanics methods.
  \(O(N)\) calculation becomes \(O(1)\).
- AutoDock uses trilinear interpolation to compute the score of a candidate docked ligand conformation.
- AutoDock needs one map for each atom type in the ligand(s) and moving parts of receptor (if there are any).
- Drawback: The receptor is conformationally rigid (although vdW softened).
- Limits the search space.

Setting up the AutoGrid Box

- Macro molecule atoms in the rigid part:
  - center of ligand,
  - center of macromolecule,
  - a picked atom, or
  - typed in x-, y- and z-coordinates.
- Grid point spacing:
  - default is 0.75Å (from 0.2Å to 1.0Å).
  - Number of grid points in each dimension:
    - only give even numbers (from \(2 \times 2 \times 2\) to \(126 \times 126 \times 126\)).
  - AutoGrid adds one point to each dimension.
  - Grid Maps depend on the orientation of the macromolecule.
  - Make sure all the flexible parts of the macromolecule are inside the grid.

To make a molecule/PDB file to show where the gridbox is, use the script makebox:

```
makebox mol.gpf > mol.gpf.dock.pdb
```

Relaxed Complex Method

Lin, J. H.; Benoyam, A. L.; Scherm, J. R., and

Anomalous drug design: accommodating receptor flexibility in molecular modeling; structure guided design in the American Chemical Society.

Lin, J. H.; Benoyam, A. L.; Scherm, J. R., and

AutoDocking: docking of the 5CITEP inhibitor to snapshots of a 2 ns trajectory. Biochimica et Biophysica Acta.

Lin, J. H., Perryman, A. L., and
Scherm, J. R., J. R., and

Docking of the 5CITEP inhibitor to snapshots of a 2 ns trajectory: 5624-5627.

Figure 3. The new preintegration binding conformations in ADT are shown and highlighted in yellow. The ligand in green shown in cDFTB to the orientation similar to the complex in the "rigid" orientation. Residues fully binding both ligand poses are highlighted.
Spectrum of Search: Breadth and Level-of-Detail

**Search Breadth**
- Local
- Molecular Mechanics (MM)
- Intermediate
- Monte Carlo Simulated Annealing (MC/SA)
- Brownian Dynamics
- Molecular Dynamics (MD)
- Global
- Docking

**Level-of-Detail**
- Atom types
- Bond stretching
- Bond-angle bending
- Rotational barrier potentials
- Implicit solvation
- Polarizability
- What's rigid and what's flexible?

Two Kinds of Search

**Systematic**
- Exhaustive
- Deterministic
- Outcome is dependent on granularity of sampling
- Feasible only for low-dimensional problems
- e.g. DOT (6D)

**Stochastic**
- Random
- Outcome varies
- Must repeat the search to improve chances of success
- Feasible for bigger problems
- e.g. AutoDock

Stochastic Search Methods

- Simulated Annealing (SA)*
- Evolutionary Algorithms (EA)
  - Genetic Algorithm (GA)*
- Others
  - Tabu Search (TS)
  - Particle Swarm Optimisation (PSO)
  - Hybrid Global-Local Search Methods
  - Lamarckian GA (LGA)*

*Supported in AutoDock
AutoDock has a Variety of Search Methods

- Global search algorithms:
  - Simulated Annealing (Goodsell et al. 1990)
  - Distributed SA (Morris et al. 1996)
  - Genetic Algorithm (Morris et al. 1998)
- Local search algorithm:
  - Solis & Wets (Morris et al. 1998)
- Hybrid global-local search algorithm:
  - Lamarckian GA (Morris et al. 1998)

How Simulated Annealing Works...

- Ligand starts at a random (or user-specified) position/orientation/confirmation (state).
- Ligand's state undergoes a random change.
- Compare the energy of the new position with that of the last position, if it is:
  - Lower, the move is accepted
  - Higher, the move is accepted if $e_{new} - e_{old} < 0$
  - Otherwise the current move is rejected.
- Cycle ends when we exceed either the number of accepted or rejected moves.
- Annealing temperature is reduced, 0.85 < $T_{new}$ < $T_{old}$
- Rinse and repeat.
- Stops at the maximum number of cycles.

How a Genetic Algorithm Works...

- Start with a random population (50-300)
- Genes correspond to state variables
- Perform genetic operations
  - Crossover
    - 1-point crossover, ABCD + abcd $\rightarrow$ Abcd + AbCd
    - 2-point crossover, ABCD + abcd $\rightarrow$ ABcd + Aabcd
    - Arithmetic crossover, ABCD + abcd $\rightarrow$ [(1-ab)ABCd + (1+a)abcd] + [(a-ABCD + abcd), where 0 < a < 1
  - Mutation
    - add or subtract a random amount from randomly selected genes, $A$ $\rightarrow$ $A'$
- Compute the fitness of individuals (energy evaluation)
- Proportional Selection & Elitism
  - If total energy evaluations or maximum generations reached, stop
Lamarck

- Jean-Baptiste-Pierre-Antoine de Monet, Chevalier de Lamarck
- Pioneer French biologist who is best known for his idea that acquired traits are inheritable, an idea now known as Lamarckism, which is controverted by Darwinian theory.

How a Lamarckian GA works

- Lamarckian
  - Phenotypic adaptations of an individual to its environment can be mapped to its genotype & inherited by its offspring.
  - Phenotype: Atomic coordinates
  - Genotype: State variables
  - (1) Local search (LS) modifies the phenotype
  - (2) inverse map phenotype to the genotype
  - Solis and Wets local search
  - Advantage that it does not require gradient information in order to proceed.
- Rik Belew (UCSD) & William Hart (Sandia).

Important Search Parameters

**Simulated Annealing**

- Initial temperature (K): \( T_0 \)
- Temperature reduction factor (K-cycle): \( T^{-1.96} \)
- Termination criteria:
  - accepted moves
  - rejected moves
  - annealing cycles
  - epsilon 50

**Genetic Algorithm & Lamarckian GA**

- Population size: \( \text{ga_pop_size} \)
- Crossover rate: \( \text{ga_crossover_rate} \)
- Mutation rate: \( \text{ga_mutation_rate} 0.02 \)
- Solis & Wets local search (LGA only): \( \text{sw_num} \)
- Termination criteria:
  - num_swaps \( 25000 \) # short
  - num_swaps \( 250000 \) # medium
  - num_swaps \( 2500000 \) # long
  - num_generations \( 27000 \)
Dimensionality of Molecular Docking

- Degrees of Freedom (DOF)
- Position / Translation (3)
- \(x, y, z\)
- Orientation / Quaternion (3)
- \(q_x, q_y, q_z, qw\) (normalized in 4D)
- Rotatable Bonds / Torsions (n)
- \(\tau_1, \tau_2, ..., \tau_n\)
- Dimensionality, \(D = 3 + 3 + n\)

Multidimensional Treasure Hunt...

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Landscape</th>
<th>Divide into</th>
<th>Treasure</th>
<th>Chances</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>1/4</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>1/8</td>
</tr>
</tbody>
</table>

Sampling Hyperspace

- Say we are hunting in \(D\)-dimensional hyperspace...
- We want to evaluate each of the \(D\) dimensions \(N\) times.
- The number of "evals" needed, \(n\), is: \(n = N^D\)
- \(\therefore N = n^{1/D}\)
- For example, if \(n = 10^6\) and...
  - \(D=6\), \(N = (10^6)^{1/6} \approx 10^{0.1667}\) evaluations per dimension
  - \(D=31\), \(N = (10^6)^{1/31} \approx 1.5\) evaluations per dimension
- Clearly, the more dimensions, the tougher it gets.
Next, AutoDock...

- Now for some specifics about AutoDock...

- More information can be found in the User Guide!

AutoDock / ADT

<table>
<thead>
<tr>
<th>AutoDock &amp; AutoGrid</th>
<th>ADT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>2000</td>
</tr>
<tr>
<td>Number crunching</td>
<td>Visualizing, set-up</td>
</tr>
<tr>
<td>Command-line, awk, shell &amp; Python scripts.</td>
<td>Graphical User Interface.</td>
</tr>
<tr>
<td>Text editors</td>
<td>PMV ++, Python</td>
</tr>
<tr>
<td>C &amp; C++, compiled</td>
<td>GUI-less, self-logging &amp; rescriptable</td>
</tr>
<tr>
<td>Python, interpreted</td>
<td></td>
</tr>
</tbody>
</table>


- AutoDock licenses

- Papers citing AutoDock (source: Science Citation Index Expanded)
Number of Citations for Docking Programs — ISI Web of Science (2005)

Trends in Citations of Docking Programs — ISI Web of Science (2005)

Practical Considerations

- What problem does AutoDock solve?
  - Flexible ligands
  - Rigidity of protein.
- What range of problems is feasible?
  - Depends on the search method:
    - LGA > GA >> SA >> LS
    - SA: can output trajectories, $D < 8$ torsions.
    - LGA: $D < 8$ torsions.
- When is AutoDock not suitable?
  - No 3D structures are available.
  - Modelled structure of poor quality.
  - Too many (32 torsions, 2048 atoms, 22 atom types).
  - Target protein too flexible.
Using AutoDock: Step-by-Step

- Set up ligand PDBQT — using ADT's "Ligand" menu
- OPTIONAL: Set up flexible receptor PDBQT — using ADT's "Flexible Residues" menu
- Set up macromolecule & grid maps — using ADT's "Grid" menu
- Pre-compute AutoGrid maps for all atom types in your set of ligands — using "autogrid4"
- Perform dockings of ligand to target — using "autodock4", and in parallel if possible.
- Visualize AutoDock results — using ADT's "Analyze" menu
- Cluster dockings — using "analysis" DPF command in "autodock4" or ADT's "Analyze" menu for parallel docking results.

AutoDock 4 File Formats

Prepare the Following Input Files
- Ligand PDBQT file
- Rigid Macromolecule PDBQT file
- Flexible Macromolecule PDBQT file ("Flexres")
- AutoGrid Parameter File (GPF)
  - GPF depends on atom types in:
    - Rigid PDBQT file
    - Optional flexible residues PDBQT file
- AutoDock Parameter File (DPF)

Run AutoDock 4
- Macromolecule PDBQT + GPF → Grid Maps, GLG
- Run AutoDock 4
- Grid Maps + Ligand PDBQT + "Flexres PDBQT +"
- DPF → DLF (dockings & clustering)
- Run ADT to Analyze DLG

Things you need to do before using AutoDock 4

Ligand:
- Add all hydrogens, compute Gasteiger charges, and merge non-polar H; also assign AutoDock 4 atom types
- Ensure total charge corresponds to tautomeric state
- Choose torsion tree root & rotatable bonds

Macromolecule:
- Add all hydrogens, compute Gasteiger charges, and merge non-polar H; also assign AutoDock 4 atom types
- Assign Stouten atomic solvation parameters
- Optionally, create a flexible residues PDBQT in addition to the rigid PDBQT file
- Compute AutoGrid maps
Preparing Ligands and Receptors

- AutoDock uses ‘United Atom’ model
  - Reduces number of atoms, speeds up docking
- Need to:
  - Add polar Hs. Remove non-polar Hs.
  - Both Ligand & Macromolecule
  - Replace missing atoms (disorder).
  - Fix hydrogens at chain breaks.
- Need to consider pH:
  - Acidic & Basic residues, Histidines.
  - http://molprobity.biochem.duke.edu/
- Other molecules in receptor:
  - Waters; Cofactors, Metal ions.
  - Molecular Modelling elsewhere.

Atom Types in AutoDock 4

- One-letter or two-letter atom type codes
- More atom types than AD3:
  - 22
- Same atom types in both ligand and receptor
  - http://autodock.scripps.edu/wiki/NewFeatures

Partial Atomic Charges are required for both Ligand and Receptor

- Partial Atomic Charges:
  - Peptides & Proteins, DNA & RNA
    - Gasteiger (PEOE) - AD4 Force Field
  - Organic compounds; Cofactors
    - Gasteiger (PEOE) - AD4 Force Field
    - MOPAC (MNDO, AM1, PM3)
    - Gaussian (6-31G*)
  - Integer total charge per residue.
  - Non-polar hydrogens:
    - Always merge
Carbon Atoms can be either Aliphatic or Aromatic Atom Types

- Solvation Free Energy
  - Based on a partial-charge-dependent variant of Stouten method.
  - Treats aliphatic ($\text{C}^\text{A}$) and aromatic ($\text{A}^\text{A}$) carbons differently.
- Need to rename ligand aromatic $\text{C}^\text{A}$ to $\text{A}^\text{A}$.
- ADT determines if ligand is a peptide:
  - If so, uses a look-up dictionary.
  - If not, inspects geometry of $\text{C}^\text{A}$s in rings. Renames $\text{C}^\text{A}$s if flat enough.
  - Can adjust planarity criterion (15° detects more rings than default 7.5°).

Defining Ligand Flexibility

- Set Root of Torsion Tree:
  - By interactively picking, or
  - Automatically.
  - Smallest/largest sub-tree.
- Interactively Pick Rotatable Bonds:
  - No leaves;
  - No bonds in rings;
  - Can freeze:
    - Peptide/amide/selected/all;
  - Can set the number of active torsions that move either the most or the fewest atoms

Setting Up Your Environment

- At TSRI:
  - Modify .cshrc:
    - Change PATH & stacksize:
      - source PATH /mgl/prog/archives/bin/tcr/python:/path)
      - $PATH stacksize unlimited
  - ADT Tutorial, every time you open a Shell or Terminal, type:
    - % source /tsri/python/share/bin/initadtcsh
  - To start AutoDockTools, type:
    - % adt
- Web:
  - http://autodock.scripps.edu
  - http://mgltools.scripps.edu
Choose the Docking Algorithm

- SA.dpf — Simulated Annealing
- GA.dpf — Genetic Algorithm
- LS.dpf — Local Search
  - Solis-Wets (SW)
  - Pseudo Solis-Wets (pSW)
- GALS.dpf — Genetic Algorithm with Local Search, i.e. Lamarckian GA

Run AutoGrid

- Check: Enough disk space?
  - Maps are ASCII, but can be ~2-8MB!
- Start AutoGrid from the Shell:
  - \% autogrid4 mol.gpf
  - \% autogrid4 -p mol.gpf -l mol.glg &
  - Follow the log file using:
    - \% tail -f mol.glg
    - Type <Ctrl>-C to break out of the ’tail’ command
- Wait for “Successful Completion” before starting AutoDock

Run AutoDock

- Do a test docking, ~ 25,000 evals
- Do a full docking, if test is OK, ~ 250,000 to 50,000,000 evals
- From the Shell:
  - \% autodock4 -p yourFile.dpf -l yourFile.dlg &
  - Expected time? Size of docking log?
  - Distributed computation
    - At TSRI, Linux Clusters
      - \% submit.py stem 20
      - \% recluster.py stem 20 during 3.5
Analyzing AutoDock Results

- In ADT, you can:
  - Read & view a single DLG, or
  - Read & view many DLG results files in a single directory
  - Re-cluster docking results by conformation & view these
- Outside ADT, you can re-cluster several DLGs
  - Useful in distributed docking
    - `recluster.py stem 20 (during|end) 3.5`

Viewing Conformational Clusters by RMSD

- List the RMSD tolerances
  - Separated by spaces
- Histogram of conformational clusters
  - Number in cluster versus lowest energy in that cluster
- Picking a cluster
  - Makes a list of the conformations in that cluster
  - Set these to be the current sequence for states player.

Advanced Topics

- Stochastic search methods rely on random numbers
- Random Number Generator, RNG
Random number generator

- RNG needs a seed or seeds.
  - Different seeds lead to different sequences of random numbers.
- SA and GA use different RNGs.
  - SA needs 1 seed.
  - GA & LGA need 2 seeds.
- A seed can be:
  - A long integer, say "314159", or
  - "time" = number of seconds since 1970 Jan 1, or
  - "pid" = UNIX process ID of this job.

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- Ruth Huey
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- Chris Rosin
- Max Chang
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- Many patient ADT users