

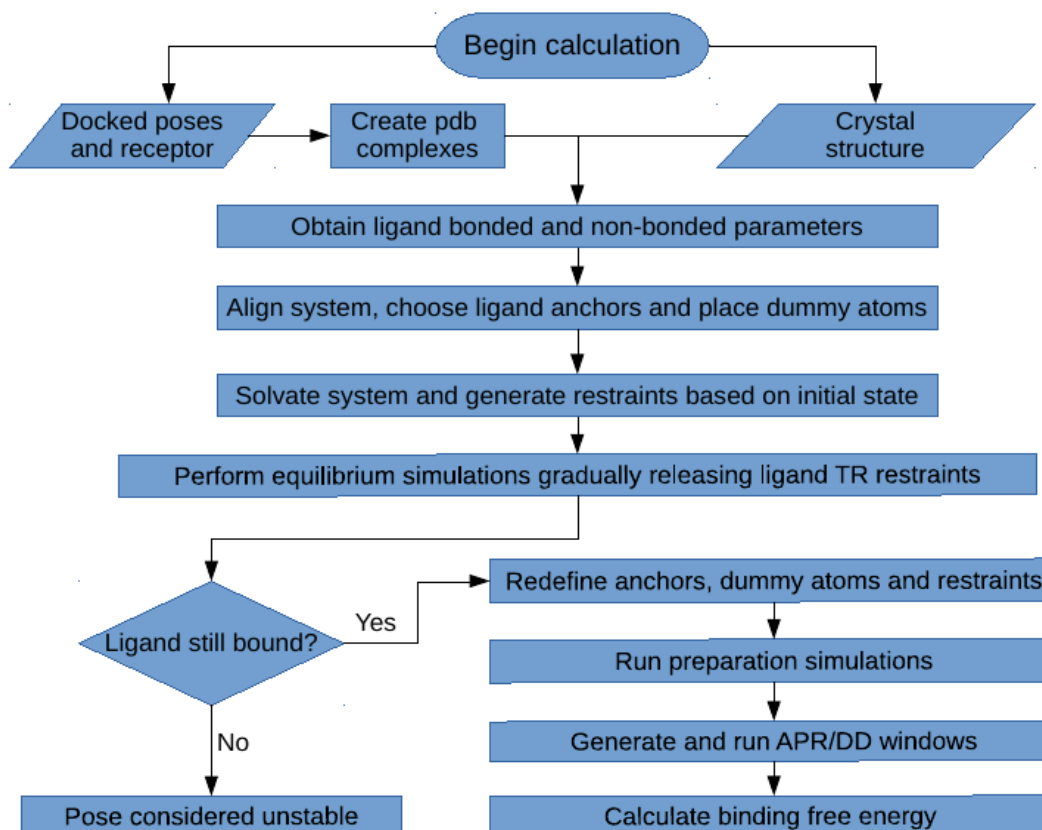
User guide for FEtool.py – v1.0

1. Introduction

The program FEtool.py is designed to fully automate absolute binding free energy calculations, starting only from a crystal structure or a docked complex. The building of the simulation boxes, generation of all the needed parameters, set up of the various simulation windows, running the simulations, and the final free energy analysis are all done without any manual interference. FEtool.py uses the *pmemd.cuda* software from AMBER, which has shown very high performance on Graphics Processing Units (GPUs) at a reduced cost (<http://ambermd.org/gpus16/benchmarks.htm>). We believe that our implementation can be used for high-throughput search of high-affinity ligands to a given receptor, using a rigorous physics-based free energy approach. FEtool.py can also be applied for parameter testing and optimization, as well as the comparison between alchemical (double decoupling -DD) and physical routes (attach-pull-release -APR) for standard binding free energy calculations.

In this user guide we will first describe the workflow of the program, then the various components of the free energy calculation, and how the simulations are analyzed in order to obtain the quantities of interest. All the parameters needed for the program input file, and how they apply to the various calculation steps, will also be described in detail. Finally, we will explain how to add a new protein system to our automated protocol.

2. Workflow



The workflow above shows the equilibration, preparation and calculation protocol. It begins by first building the initial complex, either starting from the docked receptor and ligand files or directly from the receptor-ligand co-crystal structure. After that the parameters are obtained using Antechamber, with the General Amber Force-Field (GAFF) for the bonded and LJ parameters, and the AM1-BCC model for the partial atomic charges. The system is then aligned to a reference structure of a similar protein using the program MUSTANG, so that the ligand anchors and dummy atom coordinates can be automatically assigned.

With all the coordinates of the initial system already set, the complex is then placed in a water box with a given ion concentration, and the necessary restraints are applied. An initial equilibration is then performed, with all the receptor restraints activated, and the translational/rotational restraints of the ligand being gradually released in order to find a nearby energy minimum. At the end of this last step, the ligand might still be bound or it might have left the binding site in the case of unstable binding mode. If the latter happens, this pose is considered unstable and no further simulations are performed for this system.

If the ligand is still bound after equilibration, which should usually be the case, then the preparation of the system for the binding free energy calculations is performed. The preparation starts from the last state from equilibrium, reassigning the ligand anchors, repositioning the dummy atoms, solvating/ionizing the system and redefining the restraints. This is necessary since the unrestrained ligand can adopt a different binding mode in the last stage of the equilibration step, which requires a new reference state for the free energy calculations. The preparation simulations may involve the pulling of the ligand from the binding site to bulk, if APR is to be used, or only the simulation of the restrained ligand in the bound state, if only DD is employed.

Starting from the last state of the preparation step, all the necessary simulation windows are now created for the binding free energy calculation. They involve various components for the application/removal of restraints, as well as the pulling/decoupling of the ligand, which are explained in detail in the next section. Once the free energy simulations are concluded, they can be analyzed using the Multistate Bennett Acceptance Ratio (MBAR), Thermodynamic Integration with Gaussian Quadrature (TI), or analytically, depending on the stage and the choice in the input file.

3. Free Energy Components

The FEtool.py expression for the calculated binding free energy is defined as follows:

$$-\Delta G_{bind}^0 = \Delta G_{p,conf,att} + \Delta G_{l,conf,att} + \Delta G_{l,TR,att} + \Delta G_{transfer} + \Delta G_{l,TR,rel} + \Delta G_{l,conf,rel} + \Delta G_{p,conf,rel}$$

In the equation above, the *att* index denotes attachment of restraints in the bound state, and *rel* indicates release of restraints with the ligand in bulk. The *l* and *p* indexes are for ligand and protein (receptor), respectively, *conf* is for conformational restraints and *TR* is for translational/rotational restraints. The $\Delta G_{transfer}$ term is the free energy of transferring of the ligand from the receptor binding site to bulk with all restraints applied, using either a physical reaction coordinate (APR), or an alchemical transformation (DD):

$$\Delta G_{transfer-APR} = \Delta G_{pull} \quad \text{(APR)}$$

$$\Delta G_{transfer-DD} = \Delta G_{dec,elec,site} + \Delta G_{dec,LJ,site} - \Delta G_{dec,elec,bulk} - \Delta G_{dec,LJ,bulk} \quad \text{(DD)}$$

In the case of APR, $\Delta G_{transfer-APR}$ is equal to the pulling free energy of the ligand from the binding site to bulk, which is done using umbrella sampling, as in Ref [1]. For the double decoupling procedure, $\Delta G_{transfer-DD}$ is equal to the sum of four terms, as shown in the equation above. The index *dec* stands for decoupling, *elec* for electrostatic interactions and *LJ* for Lennard-Jones interactions, with these calculations being performed both in the binding site or in bulk.

Table I summarizes all the free energy components from our simulations, with each identified by a letter:

Description	Letter	System	Free Energy Method	Free energy term
Attachment of receptor conformational restraints	a	Complex	MBAR	$\Delta G_{p,conf,att}$
Attachment of ligand conformational restraints	l	Complex	MBAR	$\Delta G_{l,conf,att}$
Attachment of ligand TR restraints	t	Complex	MBAR	$\Delta G_{l,TR,att}$
Pulling stage (umbrella sampling)	u	Complex*	MBAR	ΔG_{pull}
Decoupling of ligand charge interactions (binding site)	e	Complex	MBAR/TI	$\Delta G_{dec,elec,site}$
Decoupling of ligand LJ interactions (binding site)	v	Complex	MBAR/TI	$\Delta G_{dec,LJ,site}$
Decoupling of ligand charge interactions (bulk)	f	Ligand only	MBAR/TI	$\Delta G_{dec,elec,bulk}$
Decoupling of ligand LJ interactions (bulk)	w	Ligand only	MBAR/TI	$\Delta G_{dec,LJ,bulk}$
Release of ligand TR restraints	b	Ligand only	Analytical	$\Delta G_{l,TR,rel}$
Release of ligand conformational restraints	c	Ligand only	MBAR	$\Delta G_{l,conf,rel}$
Release of receptor conformational restraints	r	Receptor only	MBAR	$\Delta G_{p,conf,rel}$

* The receptor and ligand will be physically separated during the pulling simulations

When the calculations are set up, the windows from each free energy component will have their corresponding letter followed by the window number, starting at 0. The number of windows and their properties can be defined in the input file. The letters also identify the free energy output files, which are stored in the ./data folder of each component, after the analysis is performed. More information on the nature of each of the restraints, and the free energy methods we use, can be found in Refs. [1].

4. Input file

Various options concerning the creation of the systems, simulations and analysis, can be chosen in the input file:

calc_type: Accepts the options “dock” or “crystal”, for a receptor ligand pair of pdb files, or a complex co-crystal structure, respectively. The system initial pdb files should be located in the ./all-poses folder.

celpp_receptor: Sets the name of the receptor, followed by `_docked`. For example, choose “hiTanimoto-5uf0_5uez” for a receptor file called `hiTanimoto-5uf0_5uez_docked.pdb`. The naming is based on the CELPP challenge procedure. For a crystal structure, put the four letter identifier for the structure, for example “5uf0” for the `5uf0.pdb` crystal structure.

poses_list: The list of poses that will be used for the calculations. The list should be placed in brackets and separated by commas. Ex: “[0,1,2,3,4]”. This parameter is not used for crystal structure calculations.

ligand_name: The residue name for the ligand. This is arbitrary for docked poses (Ex: “DOK”), but is necessary if starting the calculations from a crystal structure. In that case, put the three letter ligand identifier in this option. Ex: “89J” for the `5uf0` crystal structure.

H1, H2 and H3: These define the anchor atoms of the receptor, which have to be determined beforehand. The original protein sequence numbering should be used here, using AMBER masks to define each atom. Ex: “:403@CA” for the CA atom of residue 403.

fe_type: Designates which components are to be included in the free energy calculations. For example, if all the APR and DD calculations are to be performed, choose “all” for this option. If only double decoupling with restraints will be performed, choose “dd-rest”, and if only APR choose “pmf-rest”. The “custom” option allows to choose any combination of components, using the `components` option below.

components: If the option custom is set in the option above, choose the components you want to calculate, using a list of letters separated by spaces inside a bracket. Ex: “[c l t a]”.

release_eq: The weights for the gradual release of the restraints in the equilibrium stage, going from 100 (fully restrained) to 0 (unrestrained). Each option will be a new simulation, and they are performed in sequence. Use a list of letters separated by spaces inside a bracket to define these weights. Ex: “[5.00 2.50 1.00 0.00]”. A single 0.00 inside the brackets (Ex: “[0.00]”) will run just one equilibrium simulation without any ligand restraints.

attach_apr: List of weights for the spring constant of each window during the attaching/releasing of restraints using MBAR (components a, l, t, c and r). The total number of windows for each of these components will be the size of the array. Ex: “[0.00 2.00 4.00 16.00 64.00 100.00]” for a total of 6 windows.

translate_apr: Windows for the umbrella sampling (pulling) procedure of APR, identified by the letter u. It starts from 0.00 (bound state) until the desired reference distance between the receptor and the ligand in the unbound state. The number of windows is the size of the array. Ex: “[0.00 1.00 2.00 3.00 4.00 5.00]” for a total of 6 windows, ending 5.00 Å away from the initial reference distance.

lambdas: Lambda values for the double decoupling procedure, going from 0.00 to 1.00. Ex: For a 12-point Gaussian quadrature, choose “[0.00922 0.04794 0.11505 0.20634 0.31608 0.43738 0.56262 0.68392 0.79366 0.88495 0.95206 0.99078]” for the lambda array values.

pull_ligand: Choice to pull the ligand from the binding site or not during preparation. This is needed for the APR method, but not needed for double decoupling. Choose “yes” or “no” for this option.

pull_spacing: The interval between each ligand position during the preparation simulations, if the option above is set to yes. The final distance is the last value in the `translate_apr` array. Ex: “0.1” for a pulling interval of 0.1 Å.

`rec_distance_force`: Distance spring constant for the receptor rigid body restraints, identified as R2 in Ref. [1]. Use units of kcal/mol.Å².

`rec_angle_force`: Angle and torsion angle spring constants for the receptor rigid body restraints, identified as A3, A4, T4, T5 and T6 in Ref. [1]. Use units of kcal/mol.rad². Both `rec_distance_force` and `rec_angle_force` only keep the system in the lab frame, and are fully activated at all times during simulations of the complex.

`rec_dihcf_force`: Final spring constant for the protein conformational dihedral restraints, if this option is activated (see `rec_bb` variable). The nature of these restraints, and how they are implemented, are explained in Ref. [1]. Use units of kcal/mol.rad².

`rec_discf_force`: Final spring constant for the protein conformational distance restraints between the anchor atoms. Use units of kcal/mol.Å².

`lig_distance_force`, `lig_angle_force`, `lig_dihcf_force` and `lig_discf_force`: Final spring constants for the ligand restraints, defined the same way as the receptor above. The value of `lig_distance_force` also designates the spring constant used during the pulling simulations. The nature of the ligand conformational restraints, and how they are implemented, are explained in Ref. [1].

`water_model`: The water model used in the calculations. Supported options are “TIP3P”, “TIP4PEW” and “SPCE”.

`num_waters`: Number of waters used in the simulations of the complex and the *apo* protein.

`buffer_x` and `buffer_y`: Options for the water padding in the x and y axes of the system, remembering that the pulling is done along the z coordinate. The dependent variable is the padding in the z-axis, so make sure you have enough waters to cover the complex and allow the pulling of the ligand.

`lig_box`: Water padding in the three Cartesian axes for the box with only the ligand in it.

`neutralize_only`: Option to add ions only to neutralize the system, or to also include a chosen ion molar concentration. Accepts options “yes” or “no”.

`cation` and `anion`: Cation and anion species to be used, accepts all ions supported by the Joung and Cheatham monovalent ion parameters Ref [2]. Ex: “Na+” and “Cl-”.

`num_cations`: Number of cations to be added after neutralization, for the desired ion concentration, for simulations of the complex and the *apo* protein. The number of anions is the dependent variable, since the systems are always neutral.

`num_cations_ligbox`: Number of cations to be added after neutralization, for the desired ion concentration, for the smaller ligand box.

`hmr`: Use hydrogen mass repartitioning with a 4 fs time step, if set to “yes”. If set to “no”, the simulations do not use hmr, and use a 2 fs time step.

`temperature`: Temperature of the simulated systems, in Kelvin.

`eq_steps1`: Number of steps for each simulation of the gradual release of restraints, during the equilibration procedure.

`eq_steps2`: Number of steps for the last simulation of the equilibration procedure, in which the ligand is unrestrained.

`prep_steps1`: Number of steps for the first simulation of the preparation step, in which the ligand is fully restrained in the bound state.

`prep_steps2`: Number of steps for each of the pulling simulations, during the preparation procedure. The distance separation of each of these steps is defined in the `pull_spacing` option.

`[component]_steps1`: Number of steps of equilibration, for each window of the various components of the free energy calculation, with the component letters shown in Table I. No data is collected during this simulation.

`[component]_steps2`: Number of steps for the production stage of each window of the various components of the free energy calculation, in which data is collected.

`rec_bb`: Choice to use or not protein (receptor) backbone dihedral restraints, accepting “yes” or “no”.

`bb_start` and `bb_end`: Residue range of the protein backbone dihedral restraints, using the original protein sequence numbering.

`l1_x`: distance in the x axis between the first protein anchor atom H1 and the center of the “strike zone” for the search of the ligand first anchor L1. More details on this procedure can be found in Ref. []

`l1_y`: Same as the previous one, but for the y axis distance.

`l1_z`: Minimum distance between the first protein anchor atom H1 and the first ligand anchor L1, in the z axis.

`l1_range`: Size of the “strike zone” for the first ligand anchor atom search, which is a square with sides having twice the value of this parameter ($2 \times l1_range$).

`min_adis` and `max_adis`: Minimum and maximum distance between the ligand anchors.

`dd_type`: Type of integration method for the decoupling components of the binding free energy calculation (e, v, f and w). If “TI” is chosen, Gaussian quadrature is applied, if “MBAR” is chosen, the latter is used to calculate these components. Remember that the lambda values have to be suitable for either type of integration method.

`weights`: Weights for Gaussian quadrature calculations, in case the TI option is chosen above. These values must correspond to the values chosen in the `lambdas` array, for the procedure to be applied correctly. In the case of a 12-point Gaussian quadrature, write “[0.02359 0.05347 0.08004 0.10158 0.11675 0.12457 0.12457 0.11675 0.10158 0.08004 0.05347 0.02359]” for this variable.

`blocks`: Number of blocks for block data analysis. This separates the simulation data in blocks and provides the results for each, so the temporal variation and convergence of the results can be assessed.

5. Adding a new protein system