

# Tutorial: Quantifying Spatially Resolved Hydration Thermodynamics Using Grid Inhomogeneous Solvation Theory [Article v1.0]

Valentin J Hoerschinger<sup>1†</sup>, Franz Waibl<sup>1†</sup>, Vjay Molino<sup>2</sup>, Helmut Carter<sup>2</sup>, Monica L Fernández-Quintero<sup>1</sup>, Steven Ramsey<sup>2</sup>, Daniel R Roe<sup>4</sup>, Klaus R Liedl<sup>1\*</sup>, Michael K Gilson<sup>3\*</sup>, Tom Kurtzman<sup>2\*</sup>

<sup>1</sup>Department of General, Inorganic and Theoretical Chemistry, University of Innsbruck, Austria; <sup>2</sup>Department of Chemistry, Lehman College, The City University of New York, Bronx, New York, USA; <sup>3</sup>Skaggs School of Pharmacy and Pharmaceutical Sciences, University of California, San Diego, USA; <sup>4</sup>Laboratory of Computational Biology, National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Maryland, USA

This LiveCoMS document is maintained online on GitHub at <https://github.com/liedllab/gist-tutorial>; to provide feedback, suggestions, or help improve it, please visit the GitHub repository and participate via the issue tracker.

This version dated 2024-07-10

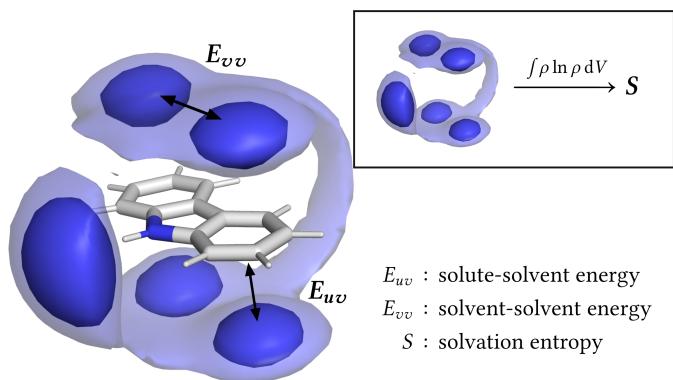
**Abstract** Grid inhomogeneous solvation theory (GIST) is a method to compute the free energy of solvation of a solute molecule on a 3-dimensional grid based on sampling from molecular dynamics (MD) simulations. The high spatial resolution of the GIST output, as well as the decomposition into energy and entropy contributions, allow for highly detailed analyses of solvation around both proteins and small molecules contexts. However, this versatility also comes with a significant entry barrier for new users.

In this tutorial, we aim to guide the reader through the most common steps involved in a GIST analysis using the streptavidin-biotin complex as a demonstrative system. Towards this, Jupyter notebooks and Python packages are provided to simplify the analysis. Furthermore, we discuss the theory of GIST with a focus on practical aspects. We highlight potential pitfalls and show how to avoid technical difficulties. For this tutorial, familiarity with molecular dynamics simulations as well as the AmberTools package [1] is assumed.

**\*For correspondence:**

[klaus.liedl@uibk.ac.at](mailto:klaus.liedl@uibk.ac.at) (KRL); [mgilson@health.ucsd.edu](mailto:mgilson@health.ucsd.edu) (MKG); [thomas.kurtzman@lehman.cuny.edu](mailto:thomas.kurtzman@lehman.cuny.edu) (TK)

<sup>†</sup>These authors contributed equally to this work



**Figure 1.** Schematic showing regions of high water density around a carbazole solute molecule. Based on an MD simulation of solvent around the solute molecule, the energy is computed from the intermolecular interactions of a force field, while the entropy is approximated from the 6-dimensional orientational and solvation solvent distribution  $p$  around the solute molecule. Note that while this depiction focuses on regions of high solvent density, regions with lower density can also contain meaningful contributions to the overall energy and entropy.

## 1 Introduction

Solvation thermodynamics govern many biological and chemical processes involving, e.g., aqueous solutions, hydrophobic effects, or partitioning between different environments. Interactions with water are of special importance as many biological processes occur in an aqueous environment [2]. The free energy of solvation is defined as the reversible work needed to insert a solute molecule into the solvent from gas phase [3]. It is directly linked to the solubility of gases and drives many real-world effects such as hydrophobicity, ligand binding, and protein folding.

Grid inhomogeneous solvation theory (GIST) [4] is a method to compute the free energy of solvation, with applications in the context of drug design and biophysical property description. It computes the solvent density from an MD trajectory and estimates localized entropic and enthalpic contributions on a grid around the solute molecule. Since these contributions are spatially resolved, GIST improves interpretability and offers more detailed insights into the solvation of the investigated solute. A schematic of this is shown in Figure 1. The entropy is computed from orientational and translational distributions of the solvent around the solute molecule, in a first-order approximation. The calculation of higher-order entropy terms is computationally demanding but was realized in recent works [5, 6]. It has been found that solvation free energies of small molecule solutes can be computed at high accuracy using linear scaling factors for the higher-order terms, such as  $\Delta S = 0.6 \Delta S^{1\text{-st-order}}$  for water [7, 8]. Since its initial development, GIST has been used to describe

the thermodynamics of water displacement in protein binding pockets [5, 9–11]. It has been used for a large-scale investigation of the hydration properties of proteins found in SARS-CoV-2 [12]. Furthermore, recent works used GIST to describe biophysical properties of serine proteases [13], macrocycles [14], or antibody fragments [15].

GIST has been implemented on the GPU, substantially improving its performance for large grids [13]. Furthermore, an implementation based on the particle mesh Ewald (PME) [16] method improves both the efficiency and the agreement with popular molecular dynamics engines [7]. Yet further changes allow the inclusion of other rigid solvents than water [8, 17] or the use of salt-water mixtures as solvents [6].

In this tutorial, we aim to give the reader an introduction to GIST and its application to calculate solution thermodynamics properties of interest. While previous publications [9] and tutorials [18] treated how to setup and run GIST calculations in detail, the post-processing was often treated in less detail. While building on these tutorials, we provide an updated guide to calculating solvation properties using GIST to address recent improvements. Furthermore, we aim to establish best practices for the analysis and interpretation of GIST calculations.

### 1.1 Comparison to other methods

A wide range of methods have been devised to compute the free energy of hydration. Data-driven methods include QSPR and UNIFAC [19, 20]. Polarizable continuum models (PCMs) [21, 22] treat the solvent as a homogeneous phase that reacts to the electrostatic potential of the solute molecule [23]. Methods such as MM/PBSA or MM/GBSA [24, 25] combine an implicit treatment of solvent electrostatics with structural sampling of the solute molecule. They can quickly provide results for a large number of structures [26].

On the other hand, explicit solvation methods model the solvent using individual molecules. They are generally more accurate than implicit methods, but require a statistical sampling of the solvent conformations [27, 28]. Molecular dynamics (MD) simulations provide an accurate way of modeling solvent packing in confined areas [29] and general hydrophobic effects [30].

The free energy of solvation can be calculated in a statistically rigorous way using alchemical methods [27, 31, 32] such as free energy perturbation (FEP) [33] or thermodynamic integration (TI) [34]. However, those methods are unable to provide a spatial interpretation of the results. Furthermore, splitting the free energy into enthalpy and entropy contributions is challenging [35].

Methods derived from statistical mechanics bridge this gap by providing three-dimensional resolution. These methods most commonly are based on either the Ornstein-Zernike

(OZ) equation, or [36] inhomogeneous fluid solvation theory (IST) [37]. The most important example of OZ-based methods is the reference interaction site model (RISM) [38] as well as its extension to three dimensions (3D-RISM) [39]. Those methods compute the atomic solvent distributions by self-consistently solving the OZ integral equation to predict solvation thermodynamics.

Methods based on IST use a molecular solvent distribution obtained from an MD simulation to compute the free energy of hydration from its enthalpic and entropic contributions, providing easier interpretability of the resulting distributions. Examples include grid inhomogeneous solvation theory (GIST) [4, 9], WaterMap [40, 41], SSTMap [42], STOW [43] and Solvaware [44]. The main limitation of those methods is that the entropy is approximated through an infinite expansion in terms of the density distribution. Within GIST and other more recent methods, these entropy contributions are calculated via a k-nearest-neighbor (kNN) approach. Due to the high computational effort required to converge the higher order terms, the entropy expansion is usually truncated after the first or, sometimes, the second [5, 8] term, thereby introducing an error. While there are approximations available to deal with those problems, most noteworthy the mutual information expansion (MIE) and Maximum Information Spanning Tree (MIST) approaches, they are not currently implemented in GIST. Recent kNN implementations to calculate solvation entropy further improve phase space sampling by relabeling the solvent molecules in the simulation, treating the solvent molecules as distinguishable [45–48]. For a recent review of kNN methods to calculate entropy in a molecular context, see [49]. Furthermore, IST does not consider the internal degrees of freedom of the solvent. Therefore, IST-based approaches currently can only be used with sufficiently rigid solvents, although a recent paper provides the theory needed to generalize to flexible solvent molecules [50]. Nevertheless, they have been applied on a wide variety of problems involving both small molecules and biological systems as solute molecules.

GIST is an implementation of IST on a three-dimensional grid. Unlike the related method WaterMap [40, 41], it provides solvation thermodynamics on an entire grid, rather than only high-density clusters in a binding pocket. This implies a higher versatility, but also puts more responsibility on the user in terms of correct post-processing. Since the density is computed from an explicit solvent MD simulation, GIST provides an accurate picture of solvation at an atomistic level, even for demanding systems such as drug binding sites in proteins. While the need for MD simulations comes at a large computational cost, GIST is still more efficient than end-state approaches such as TI [34] or FEP [33], with

applications to large systems such as serine proteases [13] or antibody fragments [15]. On the other hand, the first-order approximation means that the solvation entropy is less accurately described than in TI or FEP [6, 7]. Similar to the self-consistent integral theories, GIST only considers a single solute conformation and multiple computations of representative structures are necessary to describe ensemble properties.

## 1.2 Scope

The purpose of this tutorial is to help users run GIST calculations and interpret the results. The tutorial is structured around two examples: a GIST calculation for the small molecule biotin, and a GIST study of biotin-streptavidin binding. Whereas the biotin example gives an introduction to the basics of GIST calculations, the full biotin-streptavidin analysis showcases details and considerations commonly found in more advanced GIST studies. We show how to interpret the three-dimensional contributions of solvation free energy in a binding pocket and around the ligand. Additionally, we compute the binding contribution of the free energy of solvation, which requires accurate post-processing of the GIST outputs to avoid unfavorable summation of bias. In total, we aim to provide a workflow that can be easily adapted to different systems, an introduction to the method and the theory behind it, and an overview of the different implementations of GIST.

Furthermore, we discuss several technical aspects of GIST studies, such as the normalization of voxel values. Additionally, we provide a Python library (`gisttools`) to unify the analysis of GIST data produced by various versions of GIST and make the post-processing of GIST results more accessible. After completing this tutorial, we expect the reader to be able to run their own GIST study.

## 2 Prerequisites

### 2.1 Background knowledge

This tutorial is aimed at users with a solid knowledge of molecular dynamics (MD) simulations.

The user should be able to run MD simulations and analyze the resulting trajectories. The MD simulations presented in this tutorial are run with the Amber simulation engine and analyzed using AmberTools `cpptraj`. For a conceptual overview of running MD simulations with Amber, we recommend reading the Amber manual (<https://ambermd.org/Manuals.php>) [51] and the Amber tutorials (<https://ambermd.org/tutorials>). Previous experience of GIST is not necessary, although we recommend reading the works referenced in section 7.

The presented analyses are run in Python. While no programming experience is necessary to follow the tutorial, a

basic understanding of Python is advantageous to adjust the code towards different requirements and use-cases.

## 2.2 Software/system requirements

The main implementation of GIST is part of the MD analysis software `cpptraj` released with AmberTools [1, 51]. A recent version of `cpptraj` should be used. We recommend using at least version 6.24, which was released with AmberTools24 [1].

The Amber simulation engine is used in this tutorial to run the MD simulations. While Amber is free for non-commercial use, it might not always be available in industrial settings. In that case, other MD engines can be used as long as topologies and trajectories can be produced in a format supported by `cpptraj`. If using GROMACS [52, 53], we propose to prepare the topology with AmberTools [1] and convert it using `acpype.py` [54]. Also note that compressed trajectory formats such as `xtc` might bias the entropy calculation due to the loss of precision for the atom positions. For further reference, the influence of compression on energy calculations was discussed in a recent publication [55].

Furthermore, a recent Python version (3.6 or newer) should be available with the following packages installed:

- `gisttools` (<https://github.com/liedllab/gisttools>, ≥ 0.2)
- `mdtraj` (<https://www.mdtraj.org/>, ≥ 1.9.7) [56]
- `matplotlib` (<https://matplotlib.org/>, ≥ 3.7.0) [57]
- `numpy` (<https://numpy.org/>, ≥ 1.23.5) [58]
- `pandas` (<https://pandas.pydata.org/>, ≥ 1.5.3) [59]

If the reader prefers to skip the MD and GIST calculation, we also provide the GIST output files with this tutorial, such that the post-processing can be done without any expensive calculations. We additionally provide a Jupyter notebook [60, 61] with the presented analyses. For the visualization of three-dimensional contributions we require molecular visualization software that can handle OpenDX files, such as PyMol [62] or VMD [63]. Most of the visualisations and results in this tutorial can also be obtained using the `gistpp` program, which is available from <https://github.com/KurtzmanLab/Gist-Post-Processing> (code and documentation). `Gistpp` can directly manipulate OpenDX files from the GIST output. Its usage and some examples were shown in a previous tutorial on GIST [9].

## 3 Running GIST

To run a GIST analysis, the following is required:

- `cpptraj`.
- A topology of the solute molecule of interest in a solvent box.
- An MD trajectory of that system.

Note that the solute should not move significantly for a GIST calculation, since IST does not take the solute degrees of freedom into account. This is typically achieved by applying restraints on the solute heavy atoms during the MD simulation. GIST analysis can be divided in three steps: defining a region of interest, running GIST using `cpptraj`, and post-processing and analysis. [9]

Identify and define the region of interest

In order to run a GIST analysis, one must define the region where solvent properties will be calculated. This region is defined by a rectangular grid with given position, size, and voxel spacing. The default grid spacing of 0.5 Å provides reasonable discretization for many use-cases. While integrals of GIST quantities over the grid are independent of the voxel size, provided sufficient sampling, individual values converge slower at high resolutions. The grid is defined by parameters of the `gist` command in `cpptraj`. The grid center is defined by its center coordinates `gridcntr`, the voxel number in x, y, and z direction by `griddim`, and the spacing (voxel side-length) in Å by `gridspacn`:

`cpptraj`

```
gist gridcntr <x> <y> <z> griddim <Nx> <Ny> <Nz> gridspacn <val>
```

Additionally, the GIST calculation should usually be preceded by centering the solute molecule in the unit cell and reimaging to account for periodic boundary conditions. Often, the region of interest will be defined as the surrounding of a molecule, for example a ligand in the binding pocket or a whole protein. Using `cpptraj`'s `bounds` command, boundaries can be output to a file. For example, here is the command for a boundary of 10 Å around the ligand LIG:

`cpptraj`

```
bounds :LIG dx 0.5 offset 20 name Grid out bounds.dat
```

Make sure that the `bounds` command is supplied with the exact same trajectory as in the GIST calculation. Any pre-processing steps need to match between the `bounds` command and the `gist` calculation. A helper script called `findcentroid.py` for the same purpose is supplied with this tutorial, and can be used as follows:

Command-line

```
python findcentroid.py -i structure.pdb
```

## Run GIST using cpptraj

GIST is implemented in `cpptraj` which requires the topology and the trajectory of the MD simulation to be analyzed. The command needed to run GIST in `cpptraj` can be written in an input file (e.g `gist.in`) for convenience. The basic command, assuming a grid centered at coordinates ( $x=10.5\text{ \AA}$ ,  $y=20.1\text{ \AA}$ ,  $z=30.1\text{ \AA}$ ) and a grid size of  $30 \times 30 \times 30$  voxels with  $0.5\text{ \AA}$  spacing, is:

```
cpptraj
gist gridcntr 10.5 20.1 30.1 griddim 30 30 30 \
gridspacn 0.50 out gist.dat
```

This command tells `cpptraj` to run a GIST calculation using the specified region and print the output in a file called `gist.dat`. An overview of how to work with `cpptraj` is provided in the program's documentation [64], AMBER tutorials [65] and on the AMBER-hub website [66].

To use OpenMP, MPI or GPU-accelerated (using CUDA) versions of `cpptraj`, a different executable name such as `cpptraj.OMP`, `cpptraj.MPI` or `cpptraj.cuda` is often used. Therefore, make sure to use the right compilation and executable, to get full benefit of the various improvements to GIST as implemented in `cpptraj`. The `gist` action has a large number of options to modify the GIST calculation or its output. A full list is provided at the end of this tutorial or through the `cpptraj` manual. The most important options are summarized in the following table:

**Table 1.** The main options for GIST in `cpptraj`.

Command	Options	Explanation	Default
gridcntr	$<y> <y> <z>$	Coordinates of the grid center in $\text{\AA}$	0 0 0
griddim	$<nx> <ny> <nz>$	Number of voxels per axis	40 40 40
gridspacn	$<dval>$	Grid spacing / voxel dimensions in $\text{\AA}$	0.5
refdens	$<rdval>$	Reference density of the bulk water in molecules/ $\text{\AA}^3$ .	0.0334
temp	$<tval>$	System temperature in Kelvin	300

In GIST, the calculated properties are derived by referencing against the bulk solvent. It is therefore important to set the reference number density  $\rho_0$  according to the solvent model used in your simulation. The solvent-solvent enthalpy  $E_{ww}$  also needs to be referenced, but this is done in the post-processing stage. The calculation of these properties and the need for referencing is discussed in-depth in section 7. Densities and reference energies of typical water models can be found in the `cpptraj` manual. We also provide the densities for water models commonly used with AMBER force fields in

**Table 2.** These densities were calculated from 100 ns MD simulations at 1 bar and 300 K using the Berendsen barostat and the Langevin thermostat. The water boxes were prepared with `tLeap` to a size of  $100\text{ \AA} \times 100\text{ \AA} \times 100\text{ \AA}$  before pressure equilibration.

Due to the different sizes of the boxes, the reference energies used in this tutorial may not align with those specified in the Amber manual. Generally, it is advisable to conduct your own reference calculations, especially for systems that are either very large or very small. The reference values can be extracted from MD trajectories of bulk solvent by calculating the density-weighted average energy per solvent molecule ( $E_{ww,\text{norm}}$ ) and the average solvent density  $\rho_0$ . It is recommended that the size of the reference solvent box closely matches that of the production system. While the impact on the density is not as pronounced, deviations from the production settings can lead to differences of up to 0.005 kcal/mol in the energy per solvent molecule ( $E_{ww,\text{norm}}$ ) for water boxes. These discrepancies, when summing over large grid regions, have the potential to introduce significant errors due to incorrect referencing.

**Table 2.** Reference number density  $\rho_0$  and mean solvent-solvent energy  $E_{ww,\text{norm}}$  for various water models from NPT simulations of  $N_{WAT}$  water solvent molecules at 300 K and 1bar.

Water Model	$\rho_0$ $/\text{\AA}^{-3}$	$E_{ww,\text{norm}}$ $/\text{kcal} \cdot \text{mol}^{-1}$	$N_{WAT}$
TIP3P [67]	0.03287	-9.5398	31795
TIP3PFB [68]	0.03321	-11.7214	32502
TIP4P [69]	0.03316	-9.8583	31218
TIP4PFB [68]	0.03330	-11.8724	31653
TIP4P/Ew [70]	0.03323	-11.0541	31218
TIP5P [71]	0.03285	-9.5989	31382
SPC/E [72]	0.03333	-11.1334	31795
SPC/Eb [73]	0.03358	-11.6966	31795
OPC [74]	0.03330	-12.2456	31842
OPC3 [75]	0.03323	-11.6994	32251

## Postprocessing and Analyzing GIST results

Cpptraj outputs grid quantities in OpenDX (.dx) file format which can be visualized in Pymol or VMD. Aside from thermodynamic quantities, GIST also calculates the number density of each atomic element in the solvent. Here is a list of the most important quantities calculated by GIST:

- [gX] For every element in the main solvent, the number density of atoms found in the voxel, in units of the bulk density. If the same element occurs multiple times, the bulk density is scaled such that the expectation value for the bulk is unity. For water, g<sub>O</sub> and g<sub>H</sub> are produced.
- [Esw] Mean solute-water interaction energy.
- [Eww] Mean water-water interaction energy.
- [PME] (only if PME was used) water PME energy.
- [dTTrans] First order translational entropy.
- [dTSorient] First order orientational entropy.
- [dTSSix] First order entropy for the six-dimensional combined orientation and translation space.
- [dipole] Magnitude of mean dipole moment (polarization).

Several dx files are written by default, such as the energy, entropy, and atomic number densities. All calculated quantities are written to the output file (default `gist-output.dat`) and can be used to generate DX files for other quantities. A full list of all properties in the output is provided at the end of the tutorial in section 8. The output file is organized by voxel and sorted according to their x, y, and z coordinates, describing the center point of the voxel. Energy and entropy quantities are reported in two different ways. The `_dens` quantities are normalized by the voxel volume and can be used to compute integrals. The `_norm` quantities are instead normalized by the solvent number density in the respective voxel averaged over all considered frames, and are useful to visualize local water properties. To convert from a `_norm` quantity  $X_{\text{norm}}^k$  in voxel  $k$  to a `_dens` quantity  $X_{\text{dens}}^k$ , the following equation can be applied:

$$X_{\text{dens}}^k = \frac{X_{\text{norm}}^k}{V^k} \cdot \frac{N_{\text{solvent}}^k}{N_{\text{frames}}} \quad (1)$$

with  $V^k$ , the volume of voxel  $k$ ,  $N_{\text{solvent}}^k$ , the number of solvent molecules in  $k$  over all simulation frames, and  $N_{\text{frames}}$ , the number of frames.

## 4 Tutorial

Here, we aim to guide the reader through a GIST analysis of the streptavidin-biotin complex. The tutorial is structured as follows:

1. Set up and run GIST calculations for a small molecule solute (biotin) and a protein (streptavidin) binding pocket.
2. Compute biotin's free energy of solvation using GIST.
3. Visualize local contributions to  $\Delta G_{\text{solv}}$  in the streptavidin binding pocket and around biotin.
4. Compute the hydration contribution of the biotin, streptavidin and complex to the binding. Combined with the biotin-streptavidin interaction energy, the binding free energy can be estimated.
5. Explore advantages and disadvantages of the GIST method when used to calculate  $\Delta G_{\text{solv}}$

In the first part, we show how to run GIST calculations for small molecule solutes and interpret the output. This provides an example of a simple GIST workflow, without too much details. Afterwards, we apply this to a protein binding pocket and estimate a free energy of ligand binding using an end-states approach based on GIST. In addition, we discuss all steps shown in the first example in further detail.

### 4.1 Streptavidin/Biotin

The streptavidin-biotin complex binding is one of the strongest known non-covalent interactions involving a small molecule. Therefore, the combination of streptavidin and biotin is used routinely as a validation case [76], and the interaction between them has been investigated in detail [77].

In nature, streptavidin occurs as a tetramer, and binds biotin with a binding constant of  $\sim 10^{-14} \text{ M}^{-1}$  [76]. Streptavidin has a so-called flap region, which closes the binding pocket after biotin binding. Here, we will investigate the binding of biotin to a closed streptavidin monomer for simplicity. The binding to the closed conformation of the tetramer has been estimated to have a free energy of  $-26.6 \text{ kcal mol}^{-1}$  [78].

### 4.2 Tutorial data

We will use the crystal structure of streptavidin (PDB code: 1STP [79]) to start our calculations. For the beginners section, we will use the biotin ligand extracted from the crystal structure. For the second part, we will use the whole crystal structure. For the sake of simplicity, you can download prepared and solvated Amber topologies and structures based on 1STP by running

Command-line

```
git clone git@github.com:liedllab/gist-tutorial.git
```

This will download the tutorial files, including both the manuscript and the examples in the `code` folder.

### 4.3 Running GIST for Biotin

In this example, we will be running a simple GIST calculation of the biotin solute molecule to get familiar with the usage of GIST in `cpptraj`.

#### 4.3.1 System preparation

First, extract biotin from the crystal structure and generate a topology and coordinate file compatible with Amber or a simulation package of your choice. The solute molecule should be solvated with a sufficiently large solvent box. For periodic boundary conditions, the size of the solvent box should be large enough for the solvent to behave bulk-like so as to reduce artifacts from solvent-mediated interactions between the periodic images. This corresponds to a distance between solute and box boundary of at least 12 Å for water [7, 8] though we recommend 15 Å or higher. Carefully check the employed force field, protonation state and partial charges. A good starting point for the parametrization and solvation of small molecules is the Amber tutorial 4b (<http://ambermd.org/tutorials/basic/tutorial4b/>).

#### 4.3.2 Equilibration

Equilibrate your solvated biotin in an NVT or NPT ensemble. Even when running the simulation in NVT, it is advisable to include an NPT equilibration step to adjust the box size beforehand. Use enough equilibration time to allow the solvent to relax. A well-tested equilibration protocol can be found in the literature [80].

#### 4.3.3 MD simulation

Now, you can run a restrained MD simulation based on the equilibrated structure of biotin for the subsequent GIST analysis. Restraints should be used during the MD because IST theory is not well-defined for moving solute molecules. We apply a harmonic restraint of  $100 \text{ kcal mol}^{-1} \text{ \AA}^{-2}$  to all heavy atoms to keep the system in place. Note that this is a rather strong restraint. While lower values are possible, make sure that the solute molecule is kept rigid during the simulation. As a minimum value, we recommend  $10 \text{ kcal mol}^{-1} \text{ \AA}^{-2}$  restraints. We run 100 ns of simulation and store the conformations every 100 ps. A simulation length of at least 20 ns is recommended to obtain statistically independent snapshots of the water solvent molecules. An example Amber input file for GIST might look like this:

##### Amber input

```
restrained 100 ns NPT
&cntrl
    ntx=5, irest=1,
```

```
ioutfm=1,
ntb=2, iwrap=1,
ntr=1, restraint_wt=100.0,
restraintmask='!@H=&!WAT',
ntp=1, pres0=1.0, taup=1.0,
ntc=2, ntf=2,
ntt=3, tempi=300.0, temp0=300.0, gamma_ln=2,
nstlim=50000000, dt=0.002,
ntwr=50000, ntwx=5000, ntpi=5000,
/
```

This file will run a 100 ns NPT MD simulation while keeping all atoms except for hydrogens and waters restrained. Note that these are very standard MD settings except for the restraints. Run the MD using `pmemd.cuda`:

##### Command-line

```
pmemd.cuda \
-o \
-i 100ns-npt-restraint.in \
-o md-01.out \
-p solvated.parm7 \
-c EQUIL-DONE.rst \
-x md-01.nc \
-r md-01.ncrst \
-ref EQUIL-DONE.rst
```

#### 4.3.4 GIST analysis

To start our GIST analysis of biotin, we'll first have to decide on the parameters defining the GIST grid during the analysis. We will need a solute structure without water for the analysis of our future GIST results. As we ran our MD simulation with periodic boundaries, we always need to reimagine all molecules to the original box using `cpptraj`'s `autoimage` function. We also recommend that you center the biotin solute molecule to the coordinate origin, as this simplifies the definition of our grid origin later on:

```
cpptraj
parm solvated.parm7
trajin md-01.nc 1 1 1
autoimage !(:WAT) origin
strip :WAT
trajout biotin-centered.pdb
run
```

In this code snippet, the first two lines load the topology and coordinates of the first frame of our MD simulation. In the third line, we reimagine the coordinates to the first box and center the biotin at the origin. Then, we strip all water solvent molecules in the fourth line and write out a pdb file in the fifth line. Finally, we start the analysis with the "run" command.

To decide on a grid size, find the extent (minimum and maximum) of the x-, y-, and z-coordinates of the molecule. To get bulk-like water properties at the grid border, a buffer distance of 15 Å is reasonable for biotin. The grid parameters can be directly calculated using `cpptraj`'s `bound` command:

##### cpptraj

```
parm solvated.parm7
trajin md-01.nc 1 1 1
autoimage !(:WAT) origin
bounds !(:WAT) dx 0.5 offset 30 name MyGrid out bounds.dat
run
```

In the above snippet, we calculate the bounds around the whole protein for a grid with 0.5 Å side-length voxels and a buffer zone of 15.0 Å. Note that the offset is given in terms of number of additional voxels, not length dimension. By varying the atom mask in the `bound` command, it is possible to center the grid on a region of interest, similar to the `findcentroid.py` script.

Now, you can run the actual GIST analysis. Reimage and center the solute molecule as above, to verify that its position matches the grid parameters you decided on. We recommend using either the GPU implementation or MPI-accelerated PME implementation of GIST. While the GPU version is faster when limited CPU resources are available, the PME implementation matches the energy of the Amber MD engine more closely. The MPI implementation [81] scales well over multiple CPU cores and can be combined with either the GPU or PME implementations for maximum efficiency. A speed comparison of the various parallelization implementations is shown in [81].

#### cpptraj

```
parm solvated.parm7
trajin md-01.nc
autoimage !(:WAT) origin
# optionally remove the 'pme' option
gist griddim 100 100 100 out gist.dat \
refdens 0.03287 pme
```

#### 4.3.5 Working with the GIST results

Running the GIST analysis above generates an output data file (`gist.dat`) containing all calculated quantities for each voxel in the grid. Additionally as outlined in section 3, various quantities are written to OpenDX files. To interact with your GIST data, we recommend the `gisttools` library for python3. Open the GIST output with `gisttools`:

#### Python

```
from gisttools.gist import load_gist_file
import matplotlib.pyplot as plt
gist = load_gist_file(
    'gist.dat', struct='solute-centered.pdb',
    eww_ref=-9.539)
print(f'n_frames = {gist.n_frames}')
print(f'rho0 = {gist.rho0}')
```

All information from the output file is now accessible through the `gist` object. If the number of frames of the simulation (`n_frames`) and the reference density (`rho0`) are not provided, they are automatically detected from the GIST data. We will discuss a way to similarly detect the reference energy of the solvent-solvent energy `Eww` in the advanced section.

The GIST data can be accessed and modified from the `gist` object in various ways. `Gisttools` provides access to single or multiple voxels through a `.loc` property similar to the `pandas` library. GIST quantity data for all voxels can be accessed by directly indexing the `gist` object, either by providing a single name or a list of names. Indexing with `.loc` works by providing a voxel index (either a index number or list of numbers) and optionally a column index (column name or list of names). Indices start from 0 and indexing will return a single entry, `pandas series` or `pandas dataframe` depending on the query:

#### Python

```
gist.loc[0, 'population'] # single value
gist.loc[0] # Series
gist.loc[[0,1], ['x', 'y', 'z']] # DataFrame
gist['dTSSix_norm'].head() # Series
gist[['Eww_norm', 'Esw_norm']].head() # DataFrame
```

`Gisttools` also calculates the total enthalpy per voxel (Eall) as a sum of Eww and Esw, and the free energy of solvation (A) by subtracting  $\Delta TSSix$  from Eall.

Information about the grid is stored in the `grid` property of the `gist` object and structural data (supplied as a `pdb` of the solute molecule) is stored as an `mdtraj` trajectory in the `struct` property:

#### Python

```
gist.grid # Grid object
gist.struct # mdtraj.Trajectory object
```

`Gisttools` also provides OpenDX writing capabilities to visualize the calculated or modified GIST data. For visualization, you'll most likely want to write out the density-normalized GIST quantities (`X_dens`):

#### Python

```
gist.save_dx('A_dens', 'A.dx')
```

Section 6 discusses the visualization of OpenDX files.

## 4.4 Applying GIST for the Streptavidin-Biotin complex

In this section we will apply GIST to the full complex and discuss each step of the process in more detail to outline potential pitfalls. We will afterwards introduce advanced analysis workflows which allow you to modify and better visualize the resulting data.

### 4.4.1 System Preparation and Equilibration

If you want to skip this section, run

#### Command-line

```
make equilibration-targets
```

in the code folder. This assumes that you have Python and Amber set up properly and that `pmemd.cuda` is in the PATH.

The choice of initial structure is crucial to the GIST results. Crystal structures may not represent the dominant solution structure for a given target. In our example, we only use a single equilibrated structure. A more sophisticated approach would be to identify several dominant structures in the ensemble and run a separate MD simulation and GIST calculation for each structure. Such dominant structures could either be identified from experimental ensembles or by clustering an unrestrained MD simulation. When starting from an experimental structure, care has to be taken during the preparation step. Make sure to choose a proper protonation state for all titratable moieties. You will need to solvate your structure in a solvent box, which should be large enough to obtain unbiased long-range electrostatics and avoid solvent-mediated interactions of periodic images. A good criterion for validating the box size is to check whether the solvent on the outside of the box behaves bulk-like according to the GIST output. Note that, due to the restraints and finite sampling time, some solvent sites might be inaccessible to the bulk solvent. To investigate such positions, make sure that the number of explicitly placed solvent molecules in such sites matches with experiment or your best guess. For cases where the exact occupation of such sites is unknown, it may be helpful to include grand-canonical Monte Carlo (GCMC) or nonequilibrium candidate Monte Carlo (NCMC) sampling steps in the equilibration or production stage [82, 83]. It is good practice to check your restrained MD simulation or solvent populations obtained by GIST to confirm whether all relevant sites were properly solvated.

When calculating solvation free energy differences between a complex and the corresponding monomers (the dissociated state), there are generally two approaches for dealing with configurational diversity. In the first approach, the ensemble properties of each individual part and the complex are accounted for by running individual MD simulations for each. The second approach assumes sufficient overlap in the conformational space of the dissociated states and the complex. Then, only configurations of the complex are sampled in a single MD simulation of the complex. Calculations for the disassociated states are then run on the extracted structures from the complex configurations. One can choose to sample the complex and dissociated states individually, or to sample only one of them and assume that there is sufficient overlap in the conformations [84, 85].

Here, we do not include any sampling of the conformational states. It is therefore important that the molecular conformations in the complex and dissociated states match exactly. Use the `equilibration.py` script (or your own

procedure) to perform short NVT and NPT equilibration runs on the complex structure. Note that the equilibration script contains unrestrained NPT steps, because restraining two molecules at the same time might interfere with the pressure equilibration. Then, use `cpptraj` to produce biotin and streptavidin structures based on the complex by stripping the respective other molecule like this:

```
cpptraj
parm complex/solvated.parm7
trajin complex/equil/EQUIL-DONE.rst
strip ^2 parmout streptavidin/solvated.parm7
trajout streptavidin/pre-equil.ncrst
```

Adapt the above input file for biotin by striping molecule 1 instead of 2 and replacing the path names in the `strip` and `trajout` commands. Alternatively, we provide a small script named `cpptraj_remove_mol.sh` for this procedure. After that, use `equilibration.py -R` to run short restrained equilibrations (where only the water is allowed to move) on the individual systems. By using restraints, we can ensure that the monomer conformations match the complex.

#### 4.4.2 GIST analysis of Streptavidin-Biotin

To create input bash scripts for the MD simulations and GIST analysis, run the following commands in the code folder:

Command-line

```
make gist-md-inputs
make gist-inputs
```

After running the MD simulations as described in section 4.3.3, proceed with the GIST analysis. For easier post-processing, here we use grids that contain the whole solute molecule and the surrounding solvent. If one is only interested in solvent in the binding site, smaller grids encompassing only the binding site could be used for streptavidin and the complex. While this saves calculation time for the GIST analysis, it complicates the post-processing. Since the GIST analysis is usually less time-demanding than the MD simulation, we recommend using larger grids. Furthermore, we recommend that you center the solute molecule to the coordinate origin to simplify the analysis. Calculate the GIST grid parameters as outlined in the biotin section for the complex and streptavidin and run the GIST analysis.

For larger systems like whole proteins you can usually get away with a smaller buffer region for the GIST grid compared to small molecule solutes. To test whether your grid is large enough, look at solvent properties close to the grid edges, e.g. the solvent-solvent energies. If these correspond to the respective bulk properties, it can be assumed that your grid is large enough to capture all perturbations of the solute on the solvent. Note that a different box-size or number of solvent molecules can skew the bulk properties slightly compared to

the reference values provided above. In that case, checking for convergence of the solvent properties near the grid borders is sufficient. You might want to modify your reference values according to your results, as described in the next section.

#### 4.4.3 Reference Values and Radial Convergence

All GIST quantities should be expressed relative to bulk as outlined in section 7. This is automatically done by `cpptraj` for the entropy, using the bulk density specified by `refdens`. The solute-solvent energy  $E_{sw}$  naturally tends towards zero in bulk. However, the solvent-solvent energy  $E_{ww}$  needs to be referenced.

The Amber manual provides reference densities and energies for several solvents. Furthermore, a large variety of reference values calculated with GPU-GIST are listed in Table 2. However, the exact energy values are different when using PME-GIST, and also depend on the box size. For quantitative analyses, it is recommended to compute an exact reference energy. The most accurate method to compute a reference energy is to run a GIST calculation of the pure solvent using the same energy method (PME/GPU), a similar box size, at the same temperature and pressure and then compute the average solvent-solvent energy per solvent molecule.

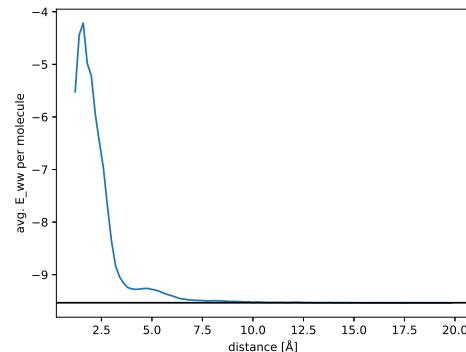
$$E_{ww}^{ref} = \frac{\int E_{ww} dx}{\langle N_{solvent} \rangle} = \frac{\sum_{voxels} E_{ww}^{dens} V_{vox}}{\sum_{voxels} N_{solvent}/N_{frames}} \quad (2)$$

Alternatively, the solvent-solvent energy in a large GIST grid converges to the bulk value at sufficient distance to the solute molecule. Therefore, the reference energy can be obtained by binning the voxels by their distance to the solute molecule, and evaluate Equation 2 within each bin. If this value converges with increasing distance from the solute, it can be used as  $E_{ww}^{ref}$ .

`gisttools` contains functions to facilitate this analysis. There is also a method `detect_reference_value` that automatically tries to find the converged value. Although it has a simple convergence check built-in, it is always recommended to check the convergence by hand. A handy way to check this is to calculate the radial distribution of this GIST property, i.e. a histogram in relation to the distance to the solute. Due to the conceptual similarity with classical radial distribution functions, describing the density of distances between two particle types, this function is exposed to the user as the `rdf` method.

#### Python

```
from gisttools.gist import load_gist_file
import matplotlib.pyplot as plt
gist = load_gist_file(
    'gist.dat', struct='solute-centered.pdb')
bins, eww = gist.rdf(
    'Eww_unref_norm', bins=100, rmax=20.,
```



**Figure 2.** Convergence of  $E_{ww}$  in the complex calculation with increasing distance to the solute molecule (streptavidin-biotin). The horizontal line shows the automatically computed reference energy.

```
normalize='norm')
plt.plot(bins, eww)
eww_auto = gist.detect_reference_value()
plt.axhline(eww_auto, color='k')
plt.gca().set(
    xlabel='distance [Å]', ylabel='E_ww per mol')
plt.show()
```

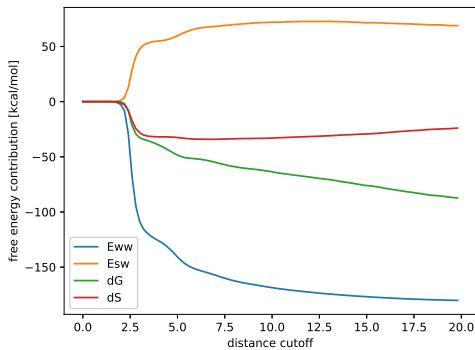
The expected output of this code is shown in Figure 2. After choosing an appropriate reference value, we need to subtract this value from  $E_{ww}$ . Make sure to subtract the reference from the normalized (`_norm`) data. In `gisttools`, this is done simply by setting `gist.eww_ref`. Now, sum all free energy contributions to obtain the spatially resolved  $\Delta G_{solv}$ . In `gisttools`, this is done automatically and can be accessed using the `A_dens` and `A_norm` data rows.

$$\Delta G_{solv}(r) = \Delta E_{ww}(r) + \Delta E_{sw}(r) - T\Delta S^{\text{six}}(r) \quad (3)$$

After that, check whether your free energy contributions become negligible far away from the solute molecule. In a plot like Figure 2 based on the `A_dens` column, the values should tend to zero. However, it is more informative to plot the cumulative free energy contribution against the distance to the solute molecule, to check the convergence (see Figure 3). If the curve flattens out, the converged value is your final  $\Delta G_{solv}$ . If the curve diverges even for large integration distances you might need to tweak the  $E_{ww}$  reference, or introduce a reference value for the entropy.

#### Python

```
from gisttools.gist import load_gist_file
import matplotlib.pyplot as plt
import numpy as np
# adapt eww_ref according to the used solvent model!
gist = load_gist_file('gist.dat',
    struct='solute-centered.pdb', eww_ref=-9.533)
bins, (dg, esw, eww, s) = gist.rdf(
    ['A_dens', 'Esw_dens', 'Eww_dens', 'dTSSix_dens'],
    bins=100, rmax=20., normalize='none')
```



**Figure 3.** Convergence of  $\Delta G_{\text{solv}}$  and its contributions with increasing distance to the solute molecule. All quantities are cumulative, i.e., summed up to the respective radius. Computed from the biotin calculation.

```
plt.plot(bins, np.cumsum(eww), label='Eww')
plt.plot(bins, np.cumsum(esw), label='Esw')
plt.plot(bins, np.cumsum(dg), label='dG')
plt.plot(bins, np.cumsum(s), label='dS')
plt.legend()
plt.xlabel("distance cutoff [Å]")
plt.ylabel("free energy contribution [kcal/mol]")
```

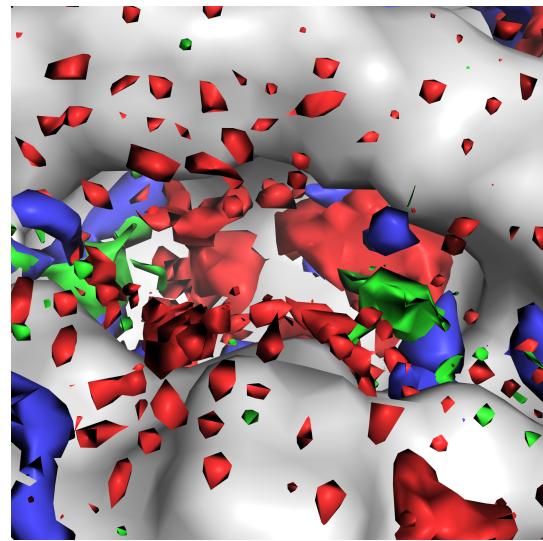
The expected output of this code is shown in Figure 3. Especially the solvent-solvent energy is not perfectly flat, indicating that the reference value is not optimal. Both the entropy and  $E_{sw}$  can be considered converged around 10 Å. While this is not true for  $E_{ww}$ , we will see below that the energy difference upon binding converges more readily than its individual contributions.

#### 4.4.4 Visualizing $\Delta G_{\text{solv}}$

Next, we visualize the 3-dimensional contributions to the free energy of hydration, as well as the entropy and enthalpy contributions. You can use PyMol[62] or VMD[63] to visualize the .dx files from GIST. With `gisttools`, you can create one using e.g., `gist.save_dx('A_dens', 'A_dens.dx')`. It might also be interesting to visualize the average energy of a water solvent molecule at each grid voxel. This quantity is given by  $2E_{ww} + E_{sw}$ . The energy referencing leads to non-zero normalized values where the population is zero. While this is irrelevant for further post-processing, it is advantageous for visualization to set those empty regions to zero. An OpenDX file can be produced using `gisttools` as follows:

Python

```
import gisttools as gt
gist = gt.gist.load_gist_file('gist.dat',
    struct='solute-centered.pdb', eww_ref=-9.533)
gist['E_norm'] = gist['Eww_norm'] * 2 + gist['Esw_norm']
gist.loc[gist['population'] == 0, 'E_norm'] = 0
gist.save_dx('E_norm', 'gist-E-per-mol-norm.dx')
```



**Figure 4.** Free energy contributions in the streptavidin binding pocket. Red: high solvent energy (at +2.5 kcal/mol/molecule). Green: low solvent energy (at -2.5 kcal/mol/molecule). Blue: low solvent entropy  $T\Delta S^{\text{six}}$  (at -2.5 kcal/mol/molecule).

The OpenDX files can then be imported into your molecular viewer of choice. A visualization of entropy and energy contributions to the free energy of solvation of the streptavidin binding pocket is shown in Figure 4. PyMOL input scripts to generate such visualizations are available in the GitHub repository for this tutorial.

#### 4.4.5 Contribution of Hydration to Binding

In the next step, calculate the  $\Delta G_{\text{solv}}$  contributions around biotin in each system (biotin, streptavidin, and complex). Note that our integration region does not fully reach into bulk, and some of the boundary regions are close to streptavidin. Therefore, our results for each system will depend on the exact position of the integration boundary. To avoid inconsistencies, it is important to choose exactly the same integration region for each system. Although we kept the systems rigid, the center of mass might have been shifted during pressure equilibration. Therefore, we align the complex structure to streptavidin and use the shifted biotin coordinates to define the integration region. We recommend using a Jupyter Notebook for the following analyses. Load the files and double check the frame numbers and reference density.

Python

```
import numpy as np
from gisttools.gist import load_gist_file
import matplotlib.pyplot as plt

compl = load_gist_file('complex/gist/gist.dat', \
    struct='complex/gist/solute-centered.pdb')
print(compl.n_frames, compl.rho0)
```

```

biotin = load_gist_file('biotin/gist/gist.dat', \
    struct='biotin/gist/solute-centered.pdb')
print(biotin.n_frames, biotin.rho0)
strept = load_gist_file('streptavidin/gist/gist.dat', \
    struct='streptavidin/gist/solute-centered.pdb')
print(strept.n_frames, strept.rho0)

```

Assign reference energies and check them for plausibility.

Python

```

biotin.eww_ref = biotin.detect_reference_value()
print('Biotin:', biotin.eww_ref)
strept.eww_ref = strept.detect_reference_value()
print('Streptavidin:', strept.eww_ref)
compl.eww_ref = compl.detect_reference_value()
print('Complex:', compl.eww_ref)

```

Subtract a reference entropy from the dTSsix columns.

Python

```

def reference_entropy(gf):
    if 'dTSsix_unref_norm' not in gf.data.columns:
        gf['dTSsix_unref_norm'] = gf['dTSsix_norm']
        gf['dTSsix_unref_dens'] = gf['dTSsix_dens']
    gf['dTSsix_norm'] = gf['dTSsix_unref_norm'] \
        - gf.detect_reference_value('dTSsix_unref_dens')
    gf['dTSsix_dens'] = gf.norm2dens(gf['dTSsix_norm'])
reference_entropy(biotin)
reference_entropy(strept)
reference_entropy(compl)

```

Compute the atom positions that define the integration region. For the streptavidin integral, we align the complex structure onto streptavidin and then use the biotin positions as centers. Note that we use `mdtraj` here, since `gisttools` stores the reference structure as an `mdtraj` Trajectory object. Here, we compute the histogram of the contributions of single properties to assess the convergence.

Python

```

import mdtraj as md
col = 'dTSsix_dens'
def select(traj, sel):
    # Slice a Trajectory by selection mask.
    return traj.atom_slice(traj.top.select(sel))
# we multiply by 10 to convert nm to Angstrom.
biotin_mask = 'resname BTN and not element H'
strept_mask = 'not resname BTN and not resname WAT and not element H'
compl_x = select(compl.struct, biotin_mask).xyz[0] * 10.
biotin_x = select(biotin.struct, biotin_mask).xyz[0]*10.
aligned = compl.struct[:,].superpose(strept.struct, \
    atom_indices=strept.struct.top.select(strept_mask))
aligned = select(aligned, biotin_mask)
strept_x = aligned.xyz[0] * 10.

bins, biotin_rdf = biotin.rdf( \
    col, centers=biotin_x, bins=100, rmax=24)
bins, strept_rdf = strept.rdf( \
    col, centers=strept_x, bins=100, rmax=24)
bins, compl_rdf = compl.rdf( \
    col, centers=compl_x, bins=100, rmax=24)

```

Now, subtract the monomer histograms from the complex, and compute the sum of your property within some cutoff

distance to the solute. If you also visualize the individual histograms, you will notice that the difference converges much better with increasing radius than the single contributions.

Python

```

difference = compl_rdf - biotin_rdf - strept_rdf
cutoff = 12
integral = difference[bins < cutoff].sum()
print('Integral = {}'.format(integral))
plt.plot(bins, np.cumsum(difference))
plt.axvline(cutoff)
plt.xlabel('distance to biotin [\AA]')
plt.ylabel('dG contribution [kcal/mol]')

```

Finally, you can also plot the difference between the complex and monomer contributions against the distance to biotin, using the complex coordinates for the holo structure:

Python

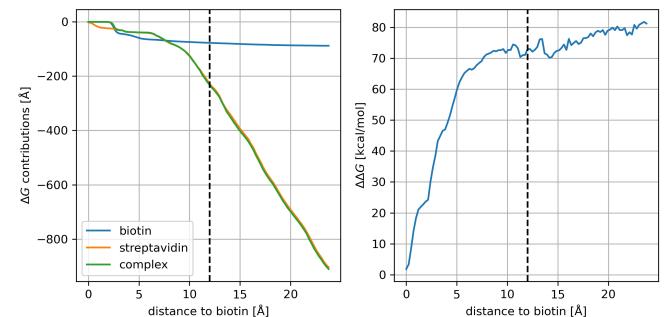
```

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(8, 4))
cutoff = 12
ax1.plot(bins, np.cumsum(biotin_rdf), label='biotin')
ax1.plot(
    bins, np.cumsum(strept_rdf), label='streptavidin')
ax1.plot(bins, np.cumsum(compl_rdf), label='complex')
ax1.legend()
ax1.axvline(cutoff, color='k', linestyle='--')
ax1.set_xlabel('distance to biotin [\AA]')
ax1.set_ylabel('$\Delta G$ contributions [\AA]')
ax1.grid()

difference = compl_rdf - biotin_rdf - strept_rdf
ax2.plot(bins, np.cumsum(difference))
ax2.axvline(cutoff, color='k', linestyle='--')
ax2.set_xlabel('distance to biotin [\AA]')
ax2.set_ylabel('$\Delta \Delta G$ [kcal/mol]')
ax2.grid()
plt.show()

```

The expected result is shown in Figure 5.



**Figure 5.** Left:  $\Delta G_{\text{solv}}$  contributions around the location of biotin in the binding pocket, evaluated in the biotin, streptavidin, and complex systems. Each line represents a cumulative sum plotted against the distance to biotin. Right: The hydration contribution to binding, evaluated as the difference between the lines in the left panel. The vertical dashed line is at 12  $\text{\AA}$  and represents the chosen integration cutoff.

Compute the energy (`Eall`) and entropy (`dTSsix`) contributions separately. To make this easier, `gisttool` includes a

function to integrate in a radius around atom centers:

Python

```
import pandas as pd
centers = {'biotin': biotin_x,
           'strept': strept_x,
           'compl': compl_x}
gist_objs = {'biotin': biotin,
             'strept': strept,
             'compl': compl}
cols = ['Eall_dens', 'dTsix_dens']
rmax = 12
results = {
    name: gist.integrate_around(
        cols, rmax, centers[name])
    for name, gist in gist_objs.items()}
print(pd.DataFrame(results))
```

You will find that the energy disfavors binding, because we do not yet include the interaction energy between biotin and streptavidin. Using the `energy` command in `cpptraj`, you can compute this interaction energy. We recommend using PME in combination with PME-GIST, but not with GPU-GIST to be in line with the different ways the energy is calculated in the two GIST methods. An example `cpptraj` is then:

cpptraj

```
parm solvated.parm7
trajin md-01.nc 1 last 100
energy complex ^1,2 # etype pme
energy strept ^1 # etype pme
energy biotin ^2 # etype pme
go
diff = complex[total] - strept[total] - biotin[total]
writedata energy.dat diff complex[total] \
strept[total] biotin[total]
avg(complex[total])
avg(strept[total])
avg(biotin[total])
avg(diff)
```

It has been shown [7, 8] that the solvation entropy in water is best approximated by 0.6 times the first order entropy provided by GIST. So we also compute the scaled entropy and check the effect on the binding affinity. The expected results are summarized in Table 3.

**Table 3.** Free energy contributions for the monomers and the dimer in  $\text{kcal}\cdot\text{mol}^{-1}$ . “Diff” is calculated as  $E^{\text{internal}} + \Delta E^{\text{GIST}} - \Delta S^{\text{scaled}}$ . “total” is calculated as “complex”–“streptavidin” - “biotin”.

System	$E^{\text{internal}}$	$\Delta E^{\text{GIST}}$	$T\Delta S^{\text{GIST}}$	$T\Delta S^{\text{scaled}}$	Diff
complex	-1303.4	-361.2	-233.1	-139.9	-1524.7
streptavidin	-1180.7	-360.8	-242.4	-145.4	-1396.1
biotin	-24.0	-98.1	-35.1	-21.1	-101.0
total	-98.7	97.7	44.4	26.6	-27.6

Even though streptavidin-biotin is known to be a very stable complex, the free solvation energy ( $\Delta E^{\text{GIST}} - T\Delta S^{\text{scaled}}$ ) favors the dissociation. This is expected: the binding of biotin

to streptavidin is facilitated over a large number of H-bonds and over polar interactions. As such, water favourably solvates both biotin and streptavidin and an energetic penalty is paid when displacing the water during the binding process. In this case, we find that the changes in the energy of solvation and of the internal energy  $\Delta E^{\text{internal}}$  more or less cancel out, indicating that binding is largely entropy-driven in this case. At first, this is surprising, since isothermal titration calorimetry (ITC) of biotin-streptavidin shows strong enthalpic binding contributions [86, 87]. However, we do not take the conformational transition of the streptavidin binding pocket into account.

Prior computational studies suggest a  $\Delta G$  of  $-26.6 \text{ kcal mol}^{-1}$  for the binding of biotin into the closed conformation of streptavidin [78]. This indicates that our result is in good agreement with literature. To improve the agreement with ITC measurements, the conformational changes of the binding pocket should be included.

#### 4.4.6 Further steps

In this tutorial, we obtained a value for the binding of biotin into the closed conformation of the streptavidin binding pocket. To investigate the effect of different conformations on the binding affinity, you can perform molecular dynamics simulations of the complex and/or monomers and perform GIST on multiple cluster representatives. To include the effect of lid closing in the binding process, free energy calculation methods such as umbrella sampling can be used. To speed up the calculation, smaller GIST grids could be used by focusing on the binding pocket, or by rotating the solute molecule by its principal axes to fit the cuboid grid more exactly. However, this should be done *before* the MD simulation, since rotating the trajectory damages the periodic box information.

## 5 Recent developments

In recent years, several updates to the original GIST implementation have been published. The basic functionality of the program, however, has not been changed. In this chapter, we will shortly present each of those updates.

### 5.1 GPU implementation

In Reference [17], a GPU implementation of the energy calculation was presented, which typically increases the speed by 1–2 orders of magnitude. If `cpptraj` is compiled with GPU support, the energy calculation uses the GPU automatically, without any additional input. However, PME-GIST is not supported on the GPU, and no GPU code will be used when specifying `pme`.

## 5.2 PME implementation

In Reference [7], a PME implementation of the GIST energy was presented. For typical systems, this implementation is slightly slower than GPU-GIST, but much faster than the original CPU code. Furthermore, PME-GIST offers the best agreement between GIST energies and those observed in an classical MD simulation. To run PME-GIST, the `pme` flag to `gist` can be used in `cpptraj`. The output will contain two additional columns: `PME_dens` and `PME_norm`. They contain the potential of solute molecule and solvent evaluated at the solvent positions and divided by two. Furthermore, the `Eww` and `Esw` columns are also computed using PME, and are reported as usual. For typical use cases, we recommend using `Eww` and `Esw` over the `PME` column.

## 5.3 MPI parallelization

The most recent addition to GIST is the MPI parallelization of both energy and entropy calculations [81]. Since the MPI parallelization is orthogonal to the other improvements, it can be used with both PME or GPU accelerated GIST.

## 5.4 GIST with non-water solvents

In references [8, 14, 17], an extension of GIST towards solvents other than water is described. To run a GIST calculation in a solvent other than water, use `solute` with a `cpptraj` selection mask to select the solute molecule. All other molecules will be treated as solvent. If there are multiple solvent species, also use the `solventmols` flag as described in Section 5.5.

The code will automatically choose three atoms per solvent species to define the solvent orientation, and print this selection to the output. Sometimes, however, the automatic selection is not optimal. For instance, in methanol one can either incorporate the C-H bonds or the O-H bond in the selection. The latter is probably more relevant since it can incorporate hydrogen bonding effects. Assuming that the alcohol hydrogen atom is called H1, this could be specified as follows:

`cpptraj`

```
gist gridcntr <x> <y> <z> \
griddim <Nx> <Ny> <Nz> gridspacn <val> \
solute ^1 rigidatoms O1 H1 C1
```

Note that the central atom of the `rigidatoms` selection goes first.

## 5.5 GIST with salt-water mixtures

In [6], an extension of GIST was presented that can use salt-water mixtures as a solvent. This allows treating salting-out effects, although it was shown that the salting-out coefficient is over-predicted by GIST because of the first-order entropy

approximation. Generally, GIST should be able to treat arbitrary solvent mixtures as long as each solvent molecule is sufficiently rigid.

In the `cpptraj` implementation of GIST, the `solute` keyword specifies which components of the system are treated as a solute molecule. Everything else will be treated as solvent. If the solvent contains more than one molecular species, a list of solvent molecule names (i.e., “`solventmols WAT,NA,CL`”) must be specified. For each solvent molecule in this list, densities (e.g., `g_mol_NA`) and energies (e.g., `Eww_mol_NA`) will be computed and written to `.dx` files. Note that, e.g., `Esw_mol_NA` contains the interactions of every “`NA`” solvent molecule with the solute molecule, and `Esw_mol_NA` contains the interactions among “`NA`” solvent molecules as well as their interactions with all other solvents, divided by 2 to account for double counting. The entropy will be computed using only the density of the first solvent molecule.

For instance, a GIST calculation in salt water, including the first-order water entropy, can be run as follows:

`cpptraj`

```
gist gridcntr <x> <y> <z> \
griddim <Nx> <Ny> <Nz> gridspacn <val> \
solute !(:WAT,NA,CL) solventmols WAT,NA,CL
```

The current implementation of the entropy calculation in `cpptraj` requires at least 3 atoms in the main solvent. Note that the calculation of the reference value is complicated by the introduction of additional solvents. For an overview of how to correctly handle such calculations, refer to reference [6]. Additionally, to compute the first-order entropy of the ions, as well as an approximate second order entropy, Python code is available on <https://github.com/liedllab/second-disorder>.

## 6 Visualization

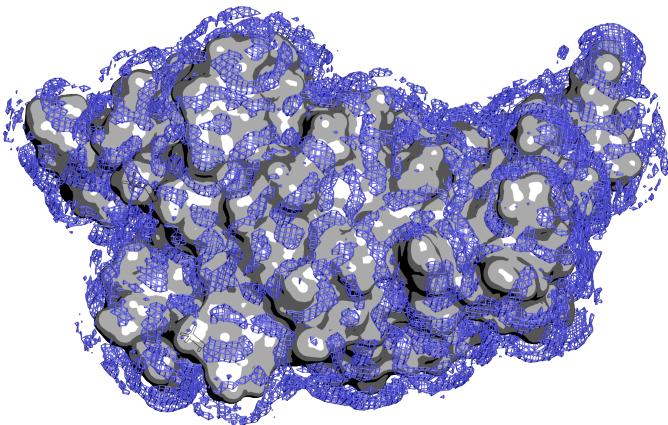
### 6.1 Visualizing DX files

A minimal PyMOL input to visualize a `dx` file is shown here. This loads an input structure from a file named `streptavidin.pdb` and visualizes the oxygen density at an isolevel of 2 (i.e., twice the reference density). The expected output is shown in Figure 6.

`Pymol`

```
load output/streptavidin/gist.pdb, streptavidin
as surface
color gray70, streptavidin
load output/streptavidin/gist-g0.dx, g0
isomesh g0_high, g0, 2
color slate, g0_high
```

A more sophisticated visualization, including the energy, entropy, and free energy of removing a single water solvent molecule, is found in Figure 7.



**Figure 6.** Oxygen density around streptavidin at an isolevel of twice the reference density (i.e., bulk)

## 6.2 Solvent Accessible Surface (SAS)

The solvent accessible surface (SAS) represents the interface between regions that are occupied by the solute molecule, and those which can be accessed by the solvent. GIST provides a very natural way of creating a SAS using an isosurface of the oxygen density  $g_0$ . At a very low isovalue, an isosurface of the water's oxygen or hydrogen shows areas the water can reach, essentially creating a SAS. Here, the SAS was generated from a simulation of water around streptavidin without biotin, leaving the binding site solvent-accessible. The expected output is shown in Figure 8.

Pymol

```
load ../gist.pdb
load ../gist-g0.dx
isomesh sas, gist-g0, 0.1
```

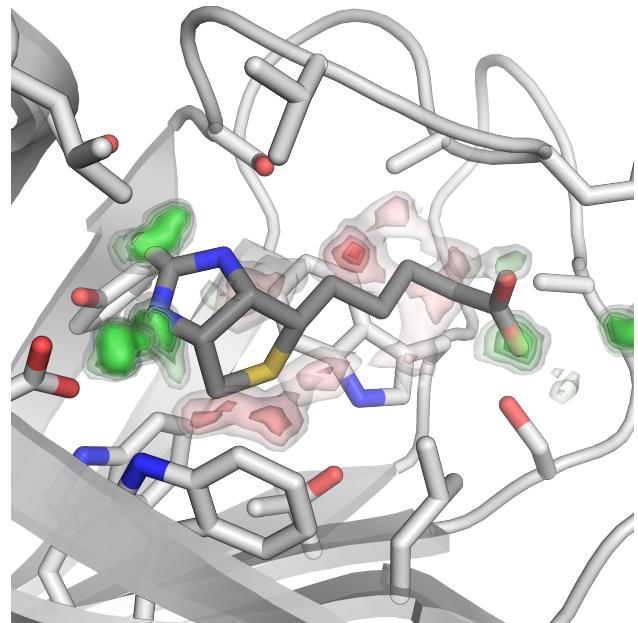
## 6.3 Defining the binding pocket

Specific regions in a protein can be defined to calculate the thermodynamic quantities for that region. This is significant specially when calculating the properties of water that will be expelled when a ligand binds to the protein.

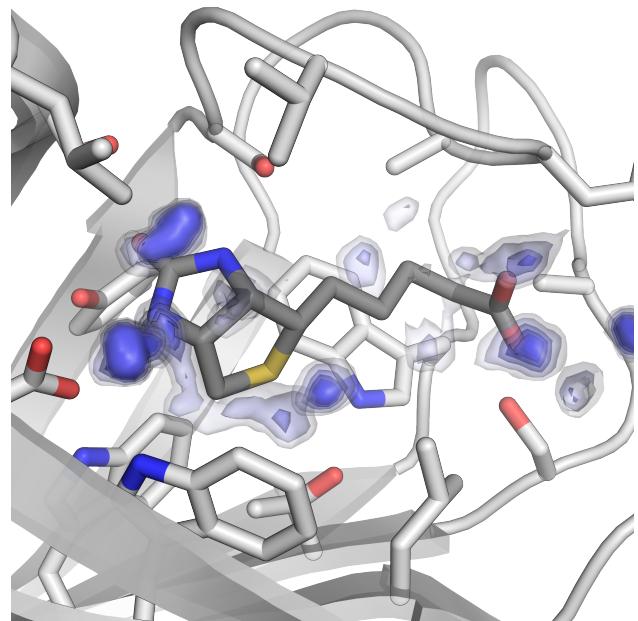
For example, voxels that are located within the binding pocket can be defined using a ligand solute molecule and a distance criteria. In section 4.4.5, we show how to integrate over regions such as the binding pocket. To visualize the considered region, we can create a OpenDX file where we set the considered voxels to 1 and all others to 0. Here, we show what this would look like for a radius of 3.5 Å around the heavy atoms of biotin.

Python

```
import gisttools as gt
def select(traj, sel):
    """
    Slice a Trajectory by selection mask.
    """
    pass
```

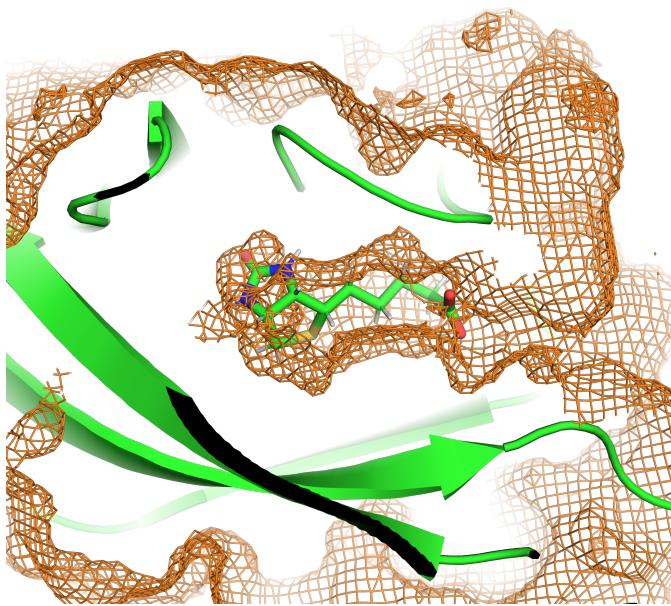


(a) GIST solvent energy (based on  $E_{sw} + 2E_{ww}$ ).

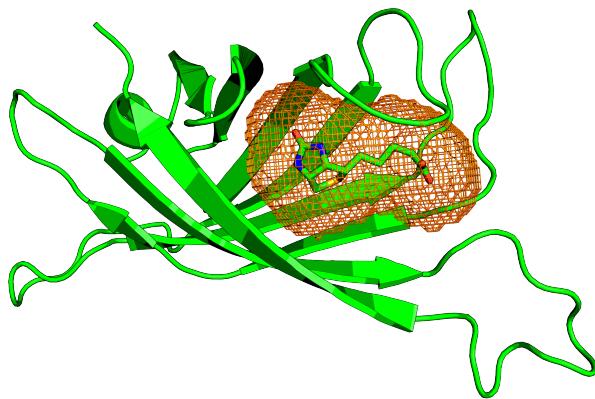


(b) GIST solvent entropy

**Figure 7.** Biotin in the streptavidin binding pocket, with isosurfaces based on the GIST calculation on the holo structure. Isolevels shown are  $(\pm) 0.25, 0.5, 1.0, 1.5, 2.0, 2.5$ , and  $3.0 \text{ kcal mol}^{-1} \text{ Å}^{-3}$ , except for the positive energy, where they are divided by two to visually account for its overall lower density. The negative solvent energy is shown in green, positive solvent energy in red and negative entropy in blue. Only voxels within 4 Å of biotin are shown.



**Figure 8.** SAS for streptavidin focused on the binding pocket



**Figure 9.** Volume of streptavidin defined around 3.5 Å of biotin.

```

    return traj.atom_slice(traj.top.select(sel))
### Load GIST data
compl = gt.gist.load_gist_file(
    'complex/gist/gistoutlong.dat',
    struct='complex/gist/gist_nowat.pdb')
### Define ligand atoms and find voxels around them
rmax = 3.5
biotin_mask = 'resname BTN and not element H'
btn = select(compl.struct, biotin_mask).xyz[0] * 10.
ind, _, _ = compl.distance_to_spheres(btn, rmax)

### Set voxels within 3.5Å of biotin to 1, write out dx file
compl.loc[ind, 'BP'] = 1
compl.save_dx('BP', 'binding_pocket.dx')

```

## 7 Theory

GIST is an implementation of inhomogeneous fluid solvation theory (IST) [37] that discretizes the free energy of solvation  $\Delta G_{\text{solv}}$  on a three-dimensional grid. It was first devised by Nguyen et al. [4] and its implementation in `cpptraj` was thoroughly described by Ramsey et al. [9]. Here, we only provide a short overview of the theory behind GIST. For more technical information (such as implementation details), we recommend one of the more recent publications on developments in GIST [7, 17, 81].

### 7.1 Solvation Entropy

IST expresses the free energy of solvation in terms of the solvent density in a coordinate system defined by the solute molecule. The solute molecule is kept fixed in space, following the standard solvation process established by Ben-Naim [3].

The entropy can be approximated as an infinite expansion of correlations of increasing order. In a slightly simplified view, the first order is the log solvent density  $\ln(g_{sw}(\mathbf{r}, \omega))$  at each position  $\mathbf{r}$  and orientation  $\omega$ . The first-order entropy omits all solvent-solvent (and higher) correlations, while the solute-solvent correlation is taken into account because the coordinates are relative to the solute. Thus, it is called the solute-water entropy  $S_{sw}$ . The solvent density is expressed relative to the bulk density  $\rho^0$ . The entropy integral is also normalized by  $8\pi^2$ , which is the volume of the orientational space. In bulk or at a high distance to the solute molecule, the quantity  $g_{sw}(\mathbf{r}, \omega)$  approaches one, which leads to zero first-order entropy. Therefore, no reference entropy is needed unless there is a numeric bias, e.g., when the MD frames are statistically dependent because the time between them is insufficient.

$$\Delta S_{\text{solv}} \approx \Delta S_{sw} \equiv -R \frac{\rho^0}{8\pi^2} \int g_{sw}(\mathbf{r}, \omega) \ln g_{sw}(\mathbf{r}, \omega) d\mathbf{r} d\omega \quad (4)$$

#### 7.1.1 Entropy Calculations in `cpptraj`

In `cpptraj`, the calculation of solvation entropy is handled by two methods.

In the first method, the solvation entropy is broken down into translational and orientational contributions.

$$\Delta S_{\text{solv}} = \Delta S_{trans} + \Delta S_{orient} \quad (5)$$

This is exact assuming that the distribution of the orientation  $\omega$  is constant within a voxel  $k$ , but might converge slower than computing the entropy from the combined space (see below). The second method directly calculates the solvation entropy by evaluating the six-dimensional integral (3 for position and 3 for orientation).

A first nearest neighbor (NN) approach is used to evaluate the entropy based on the orientational and translational distributions. The distributions are computed relative to a homogeneous distribution of solvent molecules, given a bulk density  $\rho^0$ . The average entropy contributions per solvent molecule in voxel  $k$  are calculated as

$$S_k^{trans} = -R \left( \gamma + \frac{1}{N_k} \sum_{i=1}^{N_k} \ln g_{NN,i}(\mathbf{r}) \right), \quad (6)$$

$$S_k^{orient} = -R \left( \gamma + \frac{1}{N_k} \sum_{i=1}^{N_k} \ln g_{NN,i}(\omega) \right), \quad (7)$$

and

$$S_k^{six} = -R \left( \gamma + \frac{1}{N_k} \sum_{i=1}^{N_k} \ln g_{NN,i}(\mathbf{r}, \omega) \right), \quad (8)$$

where  $N_k$  is the number of water solvent molecules found in voxel  $k$ ,  $\gamma$  is Euler's constant accounting for the bias of the naive entropy estimator, and  $g_{NN}$  is the nearest neighbor estimate of the density.

## 7.2 Solvation Energy

The solvation energy is calculated from the water-water and water-solute interactions from the force field.

$$\Delta E_{solv} = \Delta E_{sw} + \Delta E_{ww} \quad (9)$$

The solute-solvent energy  $E_{sw}$  can be expressed in terms of the solvent density and the potential  $U_{sw}(\mathbf{r}, \omega)$  induced by the solute molecule. In practice,  $E_{sw}$  is computed as the expectation value  $\langle \cdot \rangle$  of the pairwise force field energy  $U_{ij}$  between all solvent molecules in voxel  $k$  and all solute atoms.

$$\Delta E_{sw}(\mathbf{r}) \equiv \frac{1}{8\pi^2} \int g_{sw}(\omega | \mathbf{r}) U_{sw}(\mathbf{r}, \omega) d\omega$$

$$\Delta E_{sw,k} = \left\langle \sum_i^{\text{solvent}, k} \sum_j^{\text{solute}} U_{ij} \right\rangle \quad (10)$$

To localize  $E_{sw}$  on the three-dimensional grid, every energy term is assigned to the voxel  $k$  holding the solvent, and the expectation value in Equation 10 is computed per voxel. Similar to the entropy integrals, the solute-water solvation energy decays with increasing distance to the solute molecule. Hence, it can be approximated by local spatial integrals. The solvent-solvent energy  $E_{ww}$  is computed similarly. It can also be expressed in terms of density functions, but is practically computed as a sum over solvent-solvent interactions per voxel  $k$ . In contrast to  $E_{sw}$ ,  $E_{ww}$  does not tend to zero in bulk. Therefore, a reference corresponding to the average energy of a bulk water solvent molecule needs to be subtracted. The referenced solvent-solvent energy will be denoted as  $E_{ww}^{\text{corr}}$ .

$$\begin{aligned} \Delta E_{ww}^{\text{corr}}(\mathbf{r}) &\equiv \left( \frac{1}{8\pi^2} \right)^2 \rho^0 \int g_{sw}(\omega | \mathbf{r}) \\ &\times [g_{sw}(\mathbf{r}', \omega') - g_{ww}^0(\mathbf{r}, \omega, \mathbf{r}', \omega')] \\ &\times U_{ww}(\mathbf{r}, \omega, \mathbf{r}', \omega') d\omega d\mathbf{r}' d\omega' \end{aligned} \quad (11)$$

$$\Delta E_{ww,k}^{\text{corr}} = \frac{1}{N_k} \left\langle \sum_i^{\text{solvent}, k} \sum_{j \neq i}^{\text{solvent}} U_{ij} \right\rangle - \langle E_{ww}^{\text{bulk}} \rangle$$

### 7.2.1 Interpreting the energy values

When computing the total  $E_{ww}$  of the system, double-counting of interactions must be avoided. The total solvent-solvent energy of the system is as follows:

$$\Delta E_{ww}^R = \sum_k^{\text{voxels}} \frac{E_{ww,k}^{\text{corr}}}{2} \quad (12)$$

However, when water is replaced from a small region  $R$  of interest, such as a single water solvent molecule, almost all interactions are with water solvent molecules outside of this region. Therefore, there is no double counting, and the full solvent-solvent energy should be used.

$$\Delta E_{ww}^R = \sum_k^{\text{voxels in } R} E_{ww,k}^{\text{corr}} \quad (13)$$

When the region  $R$  comprises more than one solvent molecule, interactions within this region are double-counted while interactions to the outside are not. This could be solved using the solvent-solvent energy between each pair of voxels  $E_{ww,k,l}$ :

$$\Delta E_{ww}^R = 2 \left( \sum_k^{\text{voxels in } R} E_{ww,k}^{\text{corr}} - \sum_k^{\text{voxels in } R} \sum_l^{\text{voxels in } R \setminus k} E_{ww,k,l} \right) \quad (14)$$

While this is supported by the standard GIST implementation (using the `do_eij` flag), it is rarely done due to the large size of the  $E_{ww,k,l}$  matrix. Integrating GIST values over the whole grid corresponds to a process where all the solvent is removed into bulk. However, when integrating over a small region, this process is less well-defined, since it is unclear to what extent the remaining solvent would reorganize. This depends on the local environment and on *what* the solvent would be replaced by. Therefore, the effect of reorganization must be judged for each case individually. One way to treat reorganization is an end-state approach as shown in the tutorial: all states before and after solvent reorganization are considered. In the tutorial, this corresponds to the solvation of biotin and streptavidin separated (initial states) and in complex (end-state). Note that all solvent contributions need to be considered to get thermodynamically accurate results

in such a case. In practice this therefore requires the integration over the whole grid or at least all voxels with solvent properties different from bulk (i.e. setting a large cutoff).

### 7.2.2 PME energy

In the original version of GIST, the energies are calculated based on the the minimum image convention. In PME-GIST, the electrostatic energy  $E_{\text{elec}}$  is calculated using the particle mesh Ewald (PME) method, which yields energies that are highly consistent with the Amber MD engine [7]. The Lennard-Jones part  $E_{\text{lj}}$  is computed separately in direct space.

$$E_{\text{total}} = E_{\text{elec}} + E_{\text{lj}} \quad (15)$$

During the electrostatics calculation, the system is treated as periodic and the energy is split into a short-range term  $E_{\text{dir}}$ , which is calculated in direct space using a distance cutoff, and a long-range term  $E_{\text{rec}}$ , which is calculated in reciprocal space. Additionally, there is a correction term  $E_{\text{self}}$  (called  $E_{\text{corr}}$  in the original publication [7]), which corrects for the self-interaction of each solvent molecule in the reciprocal term.

$$E_{\text{elec}} = E_{\text{dir}} + E_{\text{rec}} + E_{\text{self}} \quad (16)$$

The short-range Lennard-Jones contribution is computed in the direct space using a distance cutoff. Furthermore, a long-range correction term is computed that accounts for the contributions above this cutoff assuming a homogeneous distribution of particles.

$$E_{\text{lj}} = E_{\text{lj, short}} + E_{\text{lj, corr}} \quad (17)$$

## 8 Checklists and Cheat Sheets

### SIMULATION SETTINGS

**Each number denotes the minimum setting, with the optimum in brackets.**

- Simulation time: 10 ns to 20 ns (100 ns)
- Number of analyzed frames: 10 000 (100 000)
- Restraints: minimum 10 kcal mol<sup>-1</sup> Å<sup>-2</sup> on solute heavy atoms. (typically 100 kcal mol<sup>-1</sup> Å<sup>-2</sup>)

### CHOOSING AN ENERGY METHOD

- CPU: slow, most general (can write out  $E_{ij}$  matrices)
- CPU, PME: highly consistent with Amber MD, fast
- GPU, direct space: fastest for a single CPU core

All methods profit from MPI-parallelization. PME with multiple CPU cores (>4) is usually the fastest method.

### OBTAINING ABSOLUTE ΔG<sub>solv</sub>

- Check the radial convergence (see Fig. 3)
- Choose a sufficient distance cutoff
- Choose an optimal  $E_{\text{ww}}$  reference value
- Tweak simulation length and number of frames to obtain smooth free energy contributions and unbiased (i.e., zero) bulk entropy.
- If necessary, subtract an entropy reference

### HANDLING CONVERGENCE PROBLEMS

- Insufficient sampling leads to high noise in the results. Use higher numbers of frames.
- Correlation between frames leads to negative entropy in bulk. Increase simulation time and/or reduce the number of frames.

## THE CPPTRAJ GIST ACTION

### Options

Various flags and options can be provided when running a GIST calculation in cpptraj. A list of possible and required options is provided here:

#### I/O Options

name <dataset name>	Name for output datasets in cpptraj.
prefix <prefix>	Output file name prefix. Default is 'gist'.
ext <extension>	Output grid file name extension. Default is '.dx'.
out <file>	Name of the main GIST output file. If not specified set to '<prefix>-output.dat'.
info <file>	Name of main GIST info file. If not specified info is written to standard output.
floatfmt <fmt>	Format for floating point values in GIST output file. Options are 'double', 'scientific' or 'general'. Default chooses 'fixed' or 'scientific' automatically.
floatwidth <val>	Width of floating point values in GIST output file. Default is no width restriction.
floatprec <val>	Precision of floating point values in GIST output file. Default is the system default.
intwidth <val>	Width of integer point values in GIST output file. Default is no width restriction.
doeij	Output the triangular matrix representing the water-water interactions between pairs of voxels. Not supported with PME or GPU GIST.

#### Grid Options

gridcntr <xval> <yval> <zval>	Coordinates in Å of the center of the grid. Default is 0.0, 0.0, 0.0.
griddim <xval> <yval> <zval>	Grid dimensions in voxels along each coordinate axis. Default is 40, 40, 40.
gridspacn <val>	Grid spacing (linear dimension of each voxel) in Angstroms. Default is 0.5 Å.
rmsfit <mask>	If specified, grid will be rotated and translated to follow the atoms selected by mask.

#### GIST Calculation Options

skipE	Skip all the energy calculations (cannot be specified with 'doeij')
skipS	Skip all the entropy calculations.
refdens <val>	Reference density of bulk solvent, used in computing $g_O, g_H$ , and the translational entropy. Default is 0.0334 molecules/Å <sup>3</sup> .
temp <val>	Temperature of the input trajectory.
noimage	Disable distance imaging in energy calculation.
neighborcut <val>	Cutoff in Å for determining solvent O-O neighbors. Default is 3.5 Å.
oldnnvolume	Use the old reference volume for the nearest neighbor entropy.
nnsearchlayers <val>	Layers of neighboring voxels considered in nearest neighbor search. Higher values may improve entropy convergence for little sampling or fine grid spacings, but increase the calculation time. Default is 1.

#### PME Options

nopme	Do not use particle mesh Ewald for the non-bonded calculation. This is set on default.
pme	Use particle mesh Ewald for the non-bonded electrostatics calculation. The van der Waals energy will be calculated using a long-range correction for periodicity.
cut <val>	Direct space cutoff for pme. Default is 3.5 Å.
dsumtol <val>	Direct sum tolerance used to determine Ewald coefficient. Default is 0.00001.
ewcoeff <val>	Ewald coefficient in 1/Å.
erfcdx <val>	Spacing to use for the ERFC splines. Default is 0.0002 Å.
skinnb	Used to determine pairlist atoms (added to cut, so pairlist cutoff is cut + skinnb); included in order to maintain consistency with results from sander.
ljswidth <val>	If specified, use a force-switching form for the Lennard-Jones calculation from <cutoff>-<val> to <cutoff>.
order <val>	Spline order for charges.
nfft <nfft1>,<nfft2>,<nfft3>	Explicitly set the number of FFT grid points in each dimension. Will be determined automatically if not specified.

## THE CPPTRAJ GIST ACTION

### Further Options

#### Solvent Options

solute <mask>	Selection mask for the solute. All other molecules will be solvent. If this is omitted, the standard solute/solvent assignment will be used.
solventmols <mols>	Comma-separated list of solvent molecules residue names. Energies will be computed per solvent molecule. For the entropy, only the first solvent will be used. Use this for calculations with more than one solvent of interest, e.g. for ions.
rigidatoms <c> <a1> <a2>	Specifies the molecular orientation for the entropy calculation from a central atom and two additional atoms, e.g. O H1 H2 for water. By default, a simple heuristic will be used. Use this option if the automatically chosen atoms are collinear or do not represent the orientation well.
nocom	Do not use the center of mass to define the molecular position. Instead, use the first atom in rigidatoms. Use this flag to restore the behavior of old GIST runs.

#### Order Calculation Options

doorder	Calculate the water order parameter [reference] for each voxel
nopl	Do not use pair list for order calculation
plcut <val>	Pair list cutoff for order calculation. Default is 10 Å

### Output

GIST calculations write a variety of data sorted by voxel into an outputfile specified by the 'out' keyword. Some of the output data is also automatically written to 'open data explorer' (.dx) files for convenient visualisation in software such as VMD or PyMOL. Note that some columns will be written out both with '\_norm' and '\_dens' suffixes, referring to normalization by solvent molecule or voxel volume respectively. The following columns can be found in the output file:

Name	Keyword	Description
index		Voxel indices
x, y, z		Coordinates of the voxel centers
pop		Population of solvent in voxel over entire simulation
gX		For every element in the main solvent, the number density of atoms found in the voxel, in units of the bulk density. If the same element occurs multiple times, the bulk density is scaled accordingly.
g_mol_Y	[solventmols]	Density of every solvent species Y. Scaled by rho0.
Esw		Mean solute-solvent interaction energy.
Eww		Mean solvent-solvent interaction energy.
Esw_mol_Y	[solventmols]	Mean solute-solvent interaction energy for solvent species Y.
Eww_mol_Y	[solventmols]	Mean solvent-solvent interaction energy for solvent species Y.
PME	[pme]	Solvent PME energy.
U_PME	[pme]	Solvent PME energy.
dTTrans		First order translational entropy.
dTSorient		First order orientational entropy.
order		(if doorder was specified) Average Tetrahedral Order Parameter.
dipolex		x-component of the mean solvent dipole moment density
dipoley		y-component of the mean solvent dipole moment density
dipolez		z-component of the mean solvent dipole moment density
dipole		Magnitude of mean dipole moment density (polarization).
neighbor		Mean number of solvent molecules neighboring the solvent molecules found in this voxel.
order		Average tetrahedral order parameter

## Author Contributions

All authors were involved in reviewing and editing the original manuscript.

VJH and FW conceptualized the research and co-wrote the initial draft.

VM contributed the original drafts of sections 7 and 6.

HC helped with code curation and validation.

MLFQ helped with conceptualization and gave writing input for the initial draft.

SR and DR contributed technical input.

KRL, MKG and TK were involved with conceptualization, funding acquisition, project management and supervision.

For a more detailed description of author contributions, see the GitHub issue tracking and changelog at <https://github.com/liedllab/gist-tutorial>.

## Potentially Conflicting Interests

MKG has an equity interest in and is a cofounder and scientific advisor of VeraChem LLC.

## Funding Information

### Author Information

#### ORCID:

Valentin J Hoerschinger: [0000-0002-4469-3238](https://orcid.org/0000-0002-4469-3238)

Franz Waibl: [0000-0003-0527-0803](https://orcid.org/0000-0003-0527-0803)

Vjay Molino:

Helmut Carter: [0000-0003-0273-4107](https://orcid.org/0000-0003-0273-4107)

Monica L Fernández-Quintero: [0000-0002-6811-6283](https://orcid.org/0000-0002-6811-6283)

Steven Ramsey: [0000-0001-7441-3228](https://orcid.org/0000-0001-7441-3228)

Daniel R Roe: [0000-0002-5834-2447](https://orcid.org/0000-0002-5834-2447)

Klaus R Liedl: [0000-0002-0985-2299](https://orcid.org/0000-0002-0985-2299)

Michael K Gilson: [0000-0002-3375-1738](https://orcid.org/0000-0002-3375-1738)

Tom Kurtzman: [0000-0003-0900-772X](https://orcid.org/0000-0003-0900-772X)

## References

- [1] Case DA, Aktulga HM, Belfon K, Cerutti DS, Cisneros GA, Cruzeiro VWD, Forouzesh N, Giese TJ, Götz AW, Gohlke H, Izadi S, Kasavajhala K, Kaymak MC, King E, Kurtzman T, Lee TS, Li P, Liu J, Luchko T, Luo R, et al. AmberTools. *Journal of Chemical Information and Modeling*. 2023; 63(20):6183–6191. <https://doi.org/10.1021/acs.jcim.3c01153>, pMID: 37805934.
- [2] Privalov PL, Crane-Robinson C. Role of water in the formation of macromolecular structures. *Eur Biophys J*. 2016; 46(3):203–224. <https://doi.org/10.1007/s00249-016-1161-y>.
- [3] Ben-Naim A. Solvation Thermodynamics. New York, NY: Springer US; 1987. <https://doi.org/10.1007/978-1-4757-6550-2>.
- [4] Nguyen CN, Kurtzman Young T, Gilson MK. Grid inhomogeneous solvation theory: Hydration structure and thermodynamics of the miniature receptor cucurbit[7]uril. *J Chem Phys*. 2012; 137(4):044101. <https://doi.org/10.1063/1.4733951>.
- [5] Nguyen CN, Kurtzman T, Gilson MK. Spatial Decomposition of Translational Water-Water Correlation Entropy in Binding Pockets. *J Chem Theory Comput*. 2015; 12(1):414–429. <https://doi.org/10.1021/acs.jctc.5b00939>.
- [6] Waibl F, Kraml J, Fernández-Quintero ML, Loeffler JR, Liedl KR. Explicit solvation thermodynamics in ionic solution: Extending grid inhomogeneous solvation theory to solvation free energy of salt-water mixtures. *J Comput Aided Mol Des*. 2022; 36(2):101–116. <https://doi.org/10.1007/s10822-021-00429-y>.
- [7] Chen L, Cruz A, Roe DR, Simmonett AC, Wickstrom L, Deng N, Kurtzman T. Thermodynamic Decomposition of Solvation Free Energies with Particle Mesh Ewald and Long-Range Lennard-Jones Interactions in Grid Inhomogeneous Solvation Theory. *J Chem Theory Comput*. 2021; 17(5):2714–2724. <https://doi.org/10.1021/acs.jctc.0c01185>.
- [8] Waibl F, Kraml J, Hoerschinger VJ, Hofer F, Kamenik AS, Fernández-Quintero ML, Liedl KR. Grid inhomogeneous solvation theory for cross-solvation in rigid solvents. *J Chem Phys*. 2022; 156(20):204101. <https://doi.org/10.1063/5.0087549>.
- [9] Ramsey S, Nguyen C, Salomon-Ferrer R, Walker RC, Gilson MK, Kurtzman T. Solvation thermodynamic mapping of molecular surfaces in AmberTools: Gist. *J Comput Chem*. 2016; 37(21):2029–2037. <https://doi.org/10.1002/jcc.24417>.
- [10] Baliaus TE, Fischer M, Stein RM, Adler TB, Nguyen CN, Cruz A, Gilson MK, Kurtzman T, Shoichet BK. Testing inhomogeneous solvation theory in structure-based ligand discovery. *Proc Natl Acad Sci U S A*. 2017; 114(33):E6839–E6846. <https://doi.org/10.1073/pnas.1703287114>.
- [11] Hüfner-Wulsdorf T, Klebe G. Protein-ligand complex solvation thermodynamics: Development, parameterization, and testing of GIST-based solvent functionals. *J Chem Inf Model*. 2020; 60(3):1409–1423. <https://doi.org/10.1021/acs.jcim.9b01109>.
- [12] Olson B, Cruz A, Chen L, Ghattas M, Ji Y, Huang K, Ayoub S Jr, Luchko T, McKay DJ, Kurtzman T. An online repository of solvation thermodynamic and structural maps of SARS-CoV-2 targets. *J Comput Aided Mol Des*. 2020; 34(12):1219–1228. <https://doi.org/10.1007/s10822-020-00341-x>.
- [13] Kraml J, Kamenik AS, Waibl F, Schauperl M, Liedl KR. Solvation Free Energy as a Measure of Hydrophobicity: Application to Serine Protease Binding Interfaces. *J Chem Theory Comput*. 2019; 15(11):5872–5882. <https://doi.org/10.1021/acs.jctc.9b00742>.
- [14] Kamenik AS, Kraml J, Hofer F, Waibl F, Quoika PK, Kahler U, Schauperl M, Liedl KR. Macrocyclic Cell Permeability Measured by Solvation Free Energies in Polar and Apolar Environments. *J Chem Inf Model*. 2020; 60(7):3508–3517. <https://doi.org/10.1021/acs.jcim.0c00280>.
- [15] Waibl F, Fernández-Quintero ML, Kamenik AS, Kraml J, Hofer F, Kettenberger H, Georges G, Liedl KR. Conformational ensembles of antibodies determine their hydrophobicity. *Biophys J*. 2021; 120(1):143–157. <https://doi.org/10.1016/j.bpj.2020.11.010>.
- [16] Darden T, York D, Pedersen L. Particle mesh Ewald: An  $n \cdot \log(n)$  method for Ewald sums in large systems. *J Chem Phys*. 1993; 98(12):10089–10092. <https://doi.org/10.1063/1.464397>.

- [17] Kraml J, Hofer F, Kamenik AS, Waibl F, Kahler U, Schauperl M, Liedl KR. Solvation Thermodynamics in Different Solvents: Water-chloroform Partition Coefficients from Grid Inhomogeneous Solvation Theory. *J Chem Inf Model.* 2020; 60(8):3843–3853. <https://doi.org/10.1021/acs.jcim.0c00289>.
- [18] Salomon R, Nguyen C, Ramsey S, Gough JD, Walker R, Kurtzman T, AMBER Tutorials: 25. Analysis of water thermodynamics using Grid Inhomogeneous Solvation Theory of Factor Xa active site; <https://ambermd.org/tutorials/advanced/tutorial25/>.
- [19] Borhani TN, García-Muñoz S, Vanesa Luciani C, Galindo A, Adjiman CS. Hybrid QSPR models for the prediction of the free energy of solvation of organic solute/solvent pairs. *Phys Chem Chem Phys.* 2019; 21(25):13706–13720. <https://doi.org/10.1039/c8cp07562j>.
- [20] Fredenslund A, Jones RL, Prausnitz JM. Group-contribution estimation of activity coefficients in non-ideal liquid mixtures. *AIChE J.* 1975; 21(6):1086–1099. <https://doi.org/10.1002/aic.690210607>.
- [21] Miertuš S, Scrocco E, Tomasi J. Electrostatic interaction of a solute with a continuum. A direct utilization of AB initio molecular potentials for the prevision of solvent effects. *Chem Phys.* 1981; 55(1):117–129. [https://doi.org/10.1016/0301-0104\(81\)85090-2](https://doi.org/10.1016/0301-0104(81)85090-2).
- [22] Klamt A, Schüürmann G. COSMO: A new approach to dielectric screening in solvents with explicit expressions for the screening energy and its gradient. *J Chem Soc, Perkin Trans 2.* 1993; (5):799–805. <https://doi.org/10.1039/p29930000799>.
- [23] Mennucci B. Continuum Solvation Models: What Else Can We Learn from Them? *The Journal of Physical Chemistry Letters.* 2010; 1(10):1666–1674. <https://doi.org/10.1021/jz100506s>.
- [24] Sitkoff D, Sharp KA, Honig B. Accurate Calculation of Hydration Free Energies Using Macroscopic Solvent Models. *J Phys Chem.* 1994; 98(7):1978–1988. <https://doi.org/10.1021/j100058a043>.
- [25] Kollman PA, Massova I, Reyes C, Kuhn B, Huo S, Chong L, Lee M, Lee T, Duan Y, Wang W, Donini O, Cieplak P, Srinivasan J, Case DA, Cheatham TE. Calculating Structures and Free Energies of Complex Molecules: Combining Molecular Mechanics and Continuum Models. *Accounts Chem Res.* 2000; 33(12):889–897. <https://doi.org/10.1021/ar000033j>.
- [26] Genheden S, Ryde U. The MM/PBSA and MM/G-BSA methods to estimate ligand-binding affinities. *Expert Opin Drug Discovery.* 2015; 10(5):449–461. <https://doi.org/10.1517/17460441.2015.1032936>.
- [27] Liu S, Cao S, Hoang K, Young KL, Paluch AS, Mobley DL. Using MD Simulations To Calculate How Solvents Modulate Solubility. *J Chem Theory Comput.* 2016; 12(4):1930–1941. <https://doi.org/10.1021/acs.jctc.5b00934>.
- [28] Swails JM, York DM, Roitberg AE. Constant pH Replica Exchange Molecular Dynamics in Explicit Solvent Using Discrete Protonation States: Implementation, Testing, and Validation. *J Chem Theory Comput.* 2014; 10(3):1341–1352. <https://doi.org/10.1021/ct401042b>.
- [29] Haider K, Wickstrom L, Ramsey S, Gilson MK, Kurtzman T. Enthalpic Breakdown of Water Structure on Protein Active-Site Surfaces. *The Journal of Physical Chemistry B.* 2016; 120(34):8743–8756. <https://doi.org/10.1021/acs.jpcb.6b01094>.
- [30] Pratt LR, Chaudhari MI, Rempe SB. Statistical Analyses of Hydrophobic Interactions: A Mini-Review. *The Journal of Physical Chemistry B.* 2016; 120(27):6455–6460. <https://doi.org/10.1021/acs.jpcb.6b04082>.
- [31] Mobley DL, Bayly CI, Cooper MD, Shirts MR, Dill KA. Small Molecule Hydration Free Energies in Explicit Solvent: An Extensive Test of Fixed-Charge Atomistic Simulations. *J Chem Theory Comput.* 2009; 5(2):350–358. <https://doi.org/10.1021/ct800409d>.
- [32] Mobley DL, Guthrie JP. FreeSolv: A database of experimental and calculated hydration free energies, with input files. *J Comput Aided Mol Des.* 2014; 28(7):711–720. <https://doi.org/10.1007/s10822-014-9747-x>.
- [33] Zwanzig RW. High-Temperature Equation of State by a Perturbation Method. I. Nonpolar Gases. *J Chem Phys.* 1954; 22(8):1420–1426. <https://doi.org/10.1063/1.1740409>.
- [34] Kirkwood JG. Statistical Mechanics of Fluid Mixtures. *J Chem Phys.* 1935; 3(5):300–313. <https://doi.org/10.1063/1.1749657>.
- [35] Peter C, Oostenbrink C, van Dorp A, van Gunsteren WF. Estimating entropies from molecular dynamics simulations. *J Chem Phys.* 2004; 120(6):2652–2661. <https://doi.org/10.1063/1.1636153>.
- [36] Hansen JP, McDonald IR. Theory of Simple Liquids. 4 ed. San Diego, CA: Elsevier; 2013. <https://doi.org/10.1016/c2010-0-66723-x>.
- [37] Lazaridis T. Inhomogeneous Fluid Approach to Solvation Thermodynamics. I. Theory. *The Journal of Physical Chemistry B.* 1998; 102(18):3531–3541. <https://doi.org/10.1021/jp9723574>.
- [38] Chandler D, Andersen HC. Optimized Cluster Expansions for Classical Fluids. II. Theory of Molecular Liquids. *J Chem Phys.* 1972; 57(5):1930–1937. <https://doi.org/10.1063/1.1678513>.
- [39] Kovalenko A, Hirata F. Three-dimensional density profiles of water in contact with a solute of arbitrary shape: A RISM approach. *Chem Phys Lett.* 1998; 290(1-3):237–244. [https://doi.org/10.1016/s0009-2614\(98\)00471-0](https://doi.org/10.1016/s0009-2614(98)00471-0).
- [40] Young T, Abel R, Kim B, Berne BJ, Friesner RA. Motifs for molecular recognition exploiting hydrophobic enclosure in protein-ligand binding. *Proc Natl Acad Sci.* 2007; 104(3):808–813. <https://doi.org/10.1073/pnas.0610202104>.
- [41] Abel R, Young T, Farid R, Berne BJ, Friesner RA. Role of the Active-Site Solvent in the Thermodynamics of Factor Xa Ligand Binding. *JACS.* 2008; 130(9):2817–2831. <https://doi.org/10.1021/ja0771033>.
- [42] Haider K, Cruz A, Ramsey S, Gilson MK, Kurtzman T. Solvation Structure and Thermodynamic Mapping (SSTMap): An Open-Source, Flexible Package for the Analysis of Water in Molecular Dynamics Trajectories. *J Chem Theory Comput.* 2017; 14(1):418–425. <https://doi.org/10.1021/acs.jctc.7b00592>.

- [43] Li Z, Lazaridis T. Computing the thermodynamic contributions of interfacial water. *Methods Mol Biol.* 2012; 819:393–404. [https://doi.org/10.1007/978-1-61779-465-0\\_24](https://doi.org/10.1007/978-1-61779-465-0_24).
- [44] Huggins DJ. Studying the role of cooperative hydration in stabilizing folded protein states. *J Struct Biol.* 2016; 196(3):394–406. <https://doi.org/10.1016/j.jsb.2016.09.003>.
- [45] Reinhard F, Grubmueller H. Estimation of absolute solvent and solvation shell entropies via permutation reduction. *The Journal of chemical physics.* 2007; 126(1).
- [46] Heinz LP, Grubmueller H. Computing spatially resolved rotational hydration entropies from atomistic simulations. *Journal of chemical theory and computation.* 2019; 16(1):108–118.
- [47] Heinz LP, Grubmueller H. Permut-Spatially Resolved Hydration Entropies from Atomistic Simulations. *Biophysical Journal.* 2021; 120(3):290a.
- [48] Fogolari F, Esposito G. Optimal relabeling of water molecules and single-molecule entropy estimation. *Biophysica.* 2021; 1(3):279–296.
- [49] Fogolari F, Borelli R, Dovier A, Esposito G. The k th nearest neighbor method for estimation of entropy changes from molecular ensembles. *Wiley Interdisciplinary Reviews: Computational Molecular Science.* 2024; 14(1):e1691.
- [50] Gilson MK, Kurtzman T. Free Energy Density of a Fluid and Its Role in Solvation and Binding. *Journal of Chemical Theory and Computation.* 2024; 20(7):2871–2887. <https://doi.org/10.1021/acs.jctc.3c01173>, pMID: 38536144.
- [51] Case DA, Aktulga HM, Belfon K, Ben-Shalom IY, Berryman JT, Brozell SR, Cerutti DS, Cheatham TEI, Cisneros GA, Cruzeiro VWD, Darden TA, Forouzesh N, Giambasu G, Ghazimirsaeed M, Giambaşu K, Giese T, Gilson MK, Gohlke H, Goetz AW, Harris R, et al. Amber 2024. . 2024; .
- [52] Abraham MJ, Murtola T, Schulz R, Páll S, Smith JC, Hess B, Lindahl E. GROMACS: High performance molecular simulations through multi-level parallelism from laptops to supercomputers. *SoftwareX.* 2015; 1-2:19–25. <https://doi.org/10.1016/j.softx.2015.06.001>.
- [53] Pronk S, Páll S, Schulz R, Larsson P, Bjelkmar P, Apostolov R, Shirts MR, Smith JC, Kasson PM, van der Spoel D, Hess B, Lindahl E. GROMACS 4.5: A high-throughput and highly parallel open source molecular simulation toolkit. *Method Biochem Anal.* 2013; 29(7):845–854. <https://doi.org/10.1093/bioinformatics/btt055>.
- [54] Sousa da Silva AW, Vranken WF. ACPYPE - AnteChamber PYthon Parser interfacE. *BMC Research Notes.* 2012; 5(1):367. <https://doi.org/10.1186/1756-0500-5-367>.
- [55] Roe DR, Brooks BR. Quantifying the effects of lossy compression on energies calculated from molecular dynamics trajectories. *Protein Science.* 2022; 31(12):e4511. <https://doi.org/https://doi.org/10.1002/pro.4511>.
- [56] McGibbon RT, Beauchamp KA, Harrigan MP, Klein C, Swails JM, Hernández CX, Schwantes CR, Wang LP, Lane TJ, Pande VS. MDTraj: A Modern Open Library for the Analysis of Molecular Dynamics Trajectories. *Biophys J.* 2015; 109(8):1528–1532. <https://doi.org/10.1016/j.bpj.2015.08.015>.
- [57] Hunter JD. Matplotlib: A 2D graphics environment. *Computing in Science & Engineering.* 2007; 9(3):90–95. <https://doi.org/10.1109/MCSE.2007.55>.
- [58] Harris CR, Millman KJ, van der Walt SJ, Gommers R, Virtanen P, Cournapeau D, Wieser E, Taylor J, Berg S, Smith NJ, Kern R, Picus M, Hoyer S, van Kerkwijk MH, Brett M, Haldane A, del Río JF, Wiebe M, Peterson P, Gérard-Marchant P, et al. Array programming with NumPy. *Nature.* 2020; 585(7825):357–362. <https://doi.org/10.1038/s41586-020-2649-2>.
- [59] pandas development team T, pandas-dev/pandas: Pandas. Zenodo; 2023. <https://doi.org/10.5281/zenodo.8239932>, if you use this software, please cite it as below.
- [60] Jupyter P, Bussonnier M, Forde J, Freeman J, Granger B, Head T, Holdgraf C, Kelley K, Nalvarte G, Osherooff A, Pacer M, Panda Y, Perez F, Ragan-Kelley B, Willing C. Binder 2.0 - Reproducible, interactive, sharable environments for science at scale. In: Loizides F, Schmidt B, editors. *Proceedings of the Python in Science Conference SciPy;* 2018. p. 87–90. <https://doi.org/10.25080/majora-4af1f417-011>.
- [61] Granger BE, Perez F. Jupyter: Thinking and Storytelling With Code and Data. *Computing in Science & Engineering.* 2021; 23(2):7–14. <https://doi.org/10.1109/mcse.2021.3059263>.
- [62] Schrodinger L. The PyMOL Molecular Graphics System, Version 1.8; 2015.
- [63] Humphrey W, Dalke A, Schulten K. VMD: Visual molecular dynamics. *J Mol Graphics.* 1996; 14(1):33–38. [https://doi.org/10.1016/0263-7855\(96\)00018-5](https://doi.org/10.1016/0263-7855(96)00018-5).
- [64] Roe DR, CPPTRAJ Documentation: <https://jenkins.jasonswails.com/job/amber-github/job/cpptraj/job/master/lastSuccessfulBuild/artifact/doc/CpptrajManual.pdf>.
- [65] Roe DR, Authors V, AMBER Tutorials: 4. Trajectory Analysis; <https://ambermd.org/tutorials/TrajectoryAnalysis.php>.
- [66] Bergonzo C, Alviz-Amador AA, Roe DR, Love O, Winkler L, Galindo-Murillo R, Cheatham III TE, AMBER-Hub;. <https://amberhub.chpc.utah.edu>.
- [67] Jorgensen WL, Chandrasekhar J, Madura JD, Impey RW, Klein ML. Comparison of simple potential functions for simulating liquid water. *J Chem Phys.* 1983; 79(2):926–935. <https://doi.org/10.1063/1.445869>.
- [68] Wang LP, Martinez TJ, Pande VS. Building force fields: An automatic, systematic, and reproducible approach. *J Phys Chem Lett.* 2014; 5(11):1885–1891. <https://doi.org/10.1021/jz500737m>.
- [69] Jorgensen WL, Madura JD. Temperature and size dependence for Monte Carlo simulations of TIP4P water. *Mol Phys.* 1985; 56(6):1381–1392. <https://doi.org/10.1080/00268978500103111>.
- [70] Horn HW, Swope WC, Pitera JW, Madura JD, Dick TJ, Hura GL, Head-Gordon T. Development of an improved four-site water model for biomolecular simulations: TIP4P-Ew. *J Chem Phys.* 2004; 120(20):9665–9678. <https://doi.org/10.1063/1.1683075>.

- [71] Mahoney MW, Jorgensen WL. A five-site model for liquid water and the reproduction of the density anomaly by rigid, nonpolarizable potential functions. *J Chem Phys.* 2000; 112(20):8910–8922. <https://doi.org/10.1063/1.481505>.
- [72] Berendsen HJC, Grigera JR, Straatsma TP. The missing term in effective pair potentials. *J Phys Chem.* 1987; 91(24):6269–6271. <https://doi.org/10.1021/j100308a038>.
- [73] Takemura K, Kitao A. Water model tuning for improved reproduction of rotational diffusion and NMR spectral density. *J Phys Chem B.* 2012; 116(22):6279–6287. <https://doi.org/10.1021/jp301100g>.
- [74] Izadi S, Anandakrishnan R, Onufriev AV. Building water models: A different approach. *J Phys Chem Lett.* 2014; 5(21):3863–3871. <https://doi.org/10.1021/jz501780a>.
- [75] Izadi S, Onufriev AV. Accuracy limit of rigid 3-point water models. *J Chem Phys.* 2016; 145(7):074501. <https://doi.org/10.1063/1.4960175>.
- [76] Dundas CM, Demonte D, Park S. Streptavidin-biotin technology: Improvements and innovations in chemical and biological applications. *Appl Microbiol Biot.* 2013; 97(21):9343–9353. <https://doi.org/10.1007/s00253-013-5232-z>.
- [77] McConnell DB. Biotin's Lessons in Drug Design. *J Med Chem.* 2021; 64(22):16319–16327. <https://doi.org/10.1021/acs.jmedchem.1c00975>.
- [78] Bansal N, Zheng Z, Song LF, Pei J, Merz KM. The Role of the Active Site Flap in Streptavidin/Biotin Complex Formation. *JACS.* 2018; 140(16):5434–5446. <https://doi.org/10.1021/jacs.8b00743>.
- [79] Weber PC, Ohlendorf DH, Wendoloski JJ, Salemme FR. Structural Origins of High-Affinity Biotin Binding to Streptavidin. *Science.* 1989; 243(4887):85–88. <https://doi.org/10.1126/science.2911722>.
- [80] Roe DR, Brooks BR. A protocol for preparing explicitly solvated systems for stable molecular dynamics simulations. *J Chem Phys.* 2020; 153(5):054123. <https://doi.org/10.1063/5.0013849>.
- [81] Roe DR, Brooks BR. MPI-parallelization of the grid inhomogeneous solvation theory calculation. *Journal of Computational Chemistry.* 2024; 45(10):633–637. <https://doi.org/https://doi.org/10.1002/jcc.27278>.
- [82] Ge Y, Wych DC, Samways ML, Wall ME, Essex JW, Mobley DL. Enhancing Sampling of Water Rehydration on Ligand Binding: A Comparison of Techniques. *Journal of Chemical Theory and Computation.* 2022; 18(3):1359–1381. <https://doi.org/10.1021/acs.jctc.1c00590>, pMID: 35148093.
- [83] Melling OJ, Samways ML, Ge Y, Mobley DL, Essex JW. Enhanced Grand Canonical Sampling of Occluded Water Sites Using Nonequilibrium Candidate Monte Carlo. *Journal of Chemical Theory and Computation.* 2023; 19(3):1050–1062. <https://doi.org/10.1021/acs.jctc.2c00823>, pMID: 36692215.
- [84] Genheden S, Ryde U. Comparison of end-point continuum-solvation methods for the calculation of protein-ligand binding free energies. *Proteins: Structure, Function, and Bioinformatics.* 2012; 80(5):1326–1342. <https://doi.org/https://doi.org/10.1002/prot.24029>.
- [85] Wang E, Sun H, Wang J, Wang Z, Liu H, Zhang JZH, Hou T. End-Point Binding Free Energy Calculation with MM/PBSA and MM/GBSA: Strategies and Applications in Drug Design. *Chemical Reviews.* 2019; 119(16):9478–9508. <https://doi.org/10.1021/acs.chemrev.9b00055>, pMID: 31244000.
- [86] Mpye KL, Gildenhuys S, Mosebi S. The effects of temperature on streptavidin-biotin binding using affinity isothermal titration calorimetry. *AIMS Biophysics.* 2020; 7(4):236–247. <https://doi.org/10.3934/biophys.2020018>.
- [87] Hyre DE. Cooperative hydrogen bond interactions in the streptavidin-biotin system. *Protein Sci.* 2006; 15(3):459–467. <https://doi.org/10.1110/ps.051970306>.