MANUAL

Minnesota Solvation Database (MNSOL) version 2012

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License for database

Manual

This manual is freely available to all users. See
https://comp.chem.umn.edu/solvation/

Contents

Overview of the Database

This database contains experimental aqueous solvation free energies for 274 neutral solutes (including the water dimer), 112 ionic solutes, and 31 clustered ions containing a single water molecule. The database also contains 2,002 solvation free energies for 322 neutral solutes in 90 different organic solvents, and 87 solvation free energies between water and 11 different organic solvents for 64 neutral solutes. In total, the database contains 2,506 experimental solvation free energies for 520 neutral and ionic solutes. All of the solutes in this database contain at most the following elements: H, C, N, O, F, Si, P, S, Cl, and Br.

Contents of the Database

The Minnesota Solvation Database is available as a tarred and gzipped file named MNSolDatabase2.0.1.tar.gz. To open the file, type the commands

```
gunzip MNSolDatabase2.0.1.tar.gz
tar –xvf MNSolDatabase2.0.1.tar
```

After executing the above commands, a new directory called MNSol2.0.1 will appear. The contents of this directory are as follows:

File or directory name	Brief description
MNSol2.0.1.UsersManual.pdf	this manual
MNSol2.0.1.txt	database file, the contents of which are discussed in detail below
MNSol2.0.1.xls	database file in Microsoft Excel format
solutes.txt	a list of all of the solutes in the database
solutes.xls	the above file in Microsoft Excel format
geometries/	directory containing Cartesian coordinates of all of the solutes in the database

Description of Experimental Values in the Database

The Minnesota Solvation Database contains two types of solvation free energies: absolute solvation free energies and relative solvation free energies between water and various organic solvents. All experimental values in the database are for a temperature of 298 K. The absolute solvation free energies in this database correspond to the following process

$$\text{gas} \longrightarrow \text{liq}$$

where X_{gas} is the solute in the gas phase and X_{liq} is the solute in the dilute liquid phase. The relative solvation free energies correspond to the following process

$$\text{water} \longrightarrow \text{organi}$$

where X_{water} is the solute in the dilute aqueous phase and X_{organic} is the solute in a dilute organic liquid.

Standard States

All of the solvation free energies in this database are tabulated using an ideal gas at a concentration of 1 mol/L dissolving as an ideal solution at a concentration of 1 mol/L as the standard state. This standard state is sometimes referred to as the Ben-Naim standard state, and is usually denoted by the superscript “*”. A commonly used standard state that differs from the one used here is an ideal gas at a concentration of 1 atm dissolving as an ideal solution at a concentration of 1 mol/L. This standard state is usually denoted by the superscript “$\circ$”. The relationship between these two standard states is

$$\Delta\ ^{*}_{\text{gas}\to\text{liq}} = \Delta\ ^{\circ}_{\text{gas}\to\text{liq}} - \Delta\ ^{\circ\to *} \qquad (1)$$

where

$$\Delta\ ^{\circ\to *} = \quad \ln(2446) \qquad (2)$$

At 298 K $\Delta\ ^{\circ\to *}$ equals 1.89 kcal/mol. Thus, eqs 1 and 2 allow one to convert solvation free energies in this database, which use a standard state with a gas phase concentration of 1 mol/L and a liquid phase concentration of 1 mol/L, to a standard state that uses a gas phase concentration of 1 atm and a liquid phase concentration of 1 mol/L.

Aqueous Solvation Free Energies of Neutral Solutes

Most of the aqueous solvation free energies in this database were determined using experimental partition coefficients measured between the gas phase and dilute aqueous solution. The partition coefficient associated with transferring a solute from the gas phase to dilute aqueous solution, $P_{w/a}$, is related to the free energy of this process by

$$\Delta \ {}^{*}_{w/a} = -2.303 \quad \log \ {}_{w/} \tag{3}$$

where the “w/a” denotes transfer from the gas “air” phase, to the dilute aqueous “water” phase. Also, log is the base 10 logarithm. The above notation will be used throughout the remainder of this manual. Example 1 in the “Worked Out Examples” section of this manual shows a sample calculation that uses the above equation.

Some of the aqueous solvation free energies in this database were determined using experimental values of the dimensionless Henry’s Law Constant (HLC), which is the partition coefficient for transferring a solute from dilute aqueous solution to the gas-phase (i.e., $P_{a/w}$). The dimensionless HLC is related to the aqueous solvation free energy according to

$$\Delta \ {}^{*}_{w/a} = 2.303 \quad \log \mathrm{HLC}(-) \tag{4}$$

where the (–) denotes that the HLC is dimensionless.

HLC taken from the PhysProp database are reported in units of atm m^3/mol. These values were converted to dimensionless HLC using the following equation

$$\mathrm{HLC}(-) = \mathrm{HLC}\left(\frac{\mathrm{atm\,m^3}}{\mathrm{mol}}\right) * \left(1.218 \times 10^{4} \ \frac{\mathrm{mol\,K}}{\mathrm{atm\,m^3}}\right) * \left(\frac{1}{\ }\right) \tag{5}$$

where 298 K was used for *T*. See example 2 in the “Worked Out Examples” section for a sample calculation that uses eqs 4 and 5.

The aqueous solvation free energy can also be expressed in terms of the vapor pressure of the solute in equilibrium with its pure liquid (P_{vapor}) and its aqueous solubility in molarity units (S_w). Some of the aqueous solvation free energies in the database were determined using

$$\Delta \ {}^{*}_{w/a} = -2.303 \quad \log\left(\frac{{}_{w} \ \ {}^{\circ}}{{}_{vapor} / \ {}^{\circ}}\right) \tag{6}$$

where $\ ^{\circ}$ is equal to 1 mol/L and $\ ^{\circ}$ is the pressure (24.45 atm) of an ideal gas at 1 molar concentration and 298 K. See example 3 in the “Worked Out Examples” section for a sample calculation that uses eq 6.

Solvation Free Energies of Neutral Solutes in Organic Solvents

Several of the experimental solvation free energies of neutral solutes in organic solvents that are listed in the database were determined using experimental values of partition coefficients measured between the gas phase and dilute organic liquids, i.e.

$$\Delta G^{*}_{\mathrm{o/a}} = -2.303RT\log P_{\mathrm{o/a}} \tag{7}$$

where the "o/a" denotes that the free energy or partition coefficient is for a solute transferring from the gas phase to a dilute organic liquid.

The majority of non-aqueous solvation free energies were determined by combining experimental values for the aqueous solvation free energy with experimental partition coefficients measured between the aqueous phase and different organic solvents, i.e.

$$\Delta G^{*}_{\mathrm{o/a}} = \Delta G^{*}_{\mathrm{w/a}} - 2.303RT\log P_{\mathrm{o/w}} \tag{8}$$

where the "o/w" denotes transfer from water to an organic solvent. (Note that the symbol P_{oct} is often used for the special case in which the partition coefficient is measured between water and 1-octanol). Example 4 in the "Worked Out Examples" section uses eq 8.

The database also contains "self solvation" free energies (e.g., the solvation free energy of chloroform solute in pure liquid chloroform). These solvation free energies were determined using the vapor pressure of the solute in equilibrium with its pure liquid (P_{vapor}) according to

$$\Delta G^{*}_{\mathrm{o/a}} = -2.303RT\log\left(\frac{M_{\mathrm{liq}}/M^{\circ}}{P_{\mathrm{vapor}}/P^{\circ}}\right) \tag{9}$$

where $^{\circ}$ is equal to 1 mol/L, $^{\circ}$ is the pressure (24.45 atm) of an ideal gas at 1 molar concentration and 298 K, and M_{liq} is the molarity of the solute in its pure liquid form, which can be calculated from the density of the solute in its pure liquid state and its molecular weight:

$$\mathrm{liq} = \mathrm{liq}\,\mathrm{MW}_{\mathrm{liq}} \tag{10}$$

Example 5 in the "Worked Out Examples" section uses eqs 9 and 10.

Aqueous Solvation Free Energies of Ionic Solutes

To determine the aqueous solvation free energies of cations, we used the following thermodynamic cycle

$$\begin{tikzcd}
AH^{+}\text{(gas} \arrow[r, "\Delta\ ^{\circ}_{\text{gas}}(AH^{+})"] \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(AH^{+})"] & A\text{(gas} \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(A)"] & + & H^{+}\text{(gas} \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(H^{+})"] \\
AH^{+}\text{(aq} \arrow[r, "\Delta\ ^{*}_{\text{aq}}(AH^{+})"'] & A\text{(aq} & + & H^{+}\text{(aq}
\end{tikzcd}$$

along with the following equation

$$\Delta\ ^{*}_{\text{aq}} = 2.303\ \ \mathrm{p}\ _{\text{a}} \tag{11}$$

The thermodynamic cycle above and eq 11 yields the following equation for the aqueous solvation free energy of AH^{+}

$$\Delta\ ^{*}_{\text{w/a}}(AH^{+}) = \Delta\ ^{\circ}_{\text{gas}}(AH^{+}) + \Delta\ ^{\circ\rightarrow *} + \Delta\ ^{*}_{\text{w/a}}(A) + \Delta\ ^{*}_{\text{w/a}}(H^{+}) - 2.303\ \ \mathrm{p}\ _{\text{a}}(AH^{+}) \tag{12}$$

where $\Delta\ ^{*}_{\text{w/a}}(A)$ is the aqueous solvation free energy of the neutral species A, $\Delta\ ^{*}_{\text{w/a}}(H^{+})$ is the aqueous solvation free energy of the proton, $\Delta\ ^{\circ}_{\text{gas}}(AH^{+})$ is the gas phase acidity of AH^{+} (which is typically reported as the gas phase basicity of A), equal to $^{\circ}_{\text{gas}}(A) + \ ^{\circ}_{\text{gas}}(H^{+}) - \ ^{\circ}_{\text{gas}}(AH^{+})$, and $\Delta\ ^{\circ\rightarrow *}$ is 1.89 kcal/mol.

For most of the anions in the database, we used the following thermodynamic cycle

$$\begin{tikzcd}
AH\text{ (gas} \arrow[r, "\Delta\ ^{\circ}_{\text{gas}}(AH)"] \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(AH)"] & A^{-}\text{ (gas} \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(A^{-})"] & + & H^{+}\text{(gas} \arrow[d, "\Delta\ ^{*}_{\text{w/a}}(H^{+})"] \\
AH\text{ (aq} \arrow[r, "\Delta\ ^{*}_{\text{aq}}(AH)"'] & A^{-}\text{ (aq} & + & H^{+}\text{(aq}
\end{tikzcd}$$

The thermodynamic cycle above and eq 11 yields the following equation for the aqueous solvation free energy of A^{-}

$$\Delta\ ^{*}_{\text{w/a}}(A^{-}) = -\Delta\ ^{\circ}_{\text{gas}}(AH) - \Delta\ ^{\circ\rightarrow *} + \Delta\ ^{*}_{\text{w/a}}(AH) - \Delta\ ^{*}_{\text{w/a}}(H^{+}) + 2.303\ \ \mathrm{p}\ _{\text{a}}(AH) \tag{13}$$

where $\Delta\ ^{\circ}_{\text{gas}}(AH)$ is the gas phase acidity of AH, equal to $^{\circ}_{\text{gas}}(A^{-}) + \ ^{\circ}_{\text{gas}}(H^{+}) - \ ^{\circ}_{\text{gas}}(AH)$.

In the above equations, we used Zhan and Dixon's (2001) value of −264 kcal/mol for the aqueous solvation free energy of the proton, $\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H}^{+})$. Experimental gas phase basicities of anions and acidities of neutral species were taken from the National Institute of Standards and Technology (NIST) database. Experimental gas-phase basicities of neutral species were taken from the most recent compilation of Hunter and Lias (1998). For neutral species, experimental aqueous solvation free energies were taken from the present database and several additional sources. A large part of the experimental aqueous pK_a data used here was taken from the compilation of Stewart (1985); pK_a data not available in this compilation were taken from several additional sources.

For F^{-}, Cl^{-}, and Br^{-}, we did not use the thermodynamic cycle above. Instead, the aqueous solvation free energies of these ions were taken from Tissandier et al. (1998) and adjusted for a change in the standard state and the value used here for $\Delta G^{*}_{\mathrm{S}}(\mathrm{H}^{+})$.

Examples 6 and 7 in the "Worked Out Examples" section use eqs 12 and 13, respectively.

Aqueous Solvation Free Energies of Clustered Solutes

The database also includes aqueous solvation free energies of clustered solutes containing a single water molecule. For the water dimer, we used the free energy cycle shown below

$$\begin{tikzcd}
\mathrm{H_2O\,(gas)} \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O})"] & + & \mathrm{H_2O\,(gas)} \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O})"] \arrow[r, "\Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.})"] & \mathrm{H_2O\cdot H_2O\,(gas)} \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O\cdot H_2O})"] \\
\mathrm{H_2O\,(aq)} & + & \mathrm{H_2O\,(aq)} \arrow[r, "0"'] & \mathrm{H_2O\cdot H_2O\,(aq)}
\end{tikzcd}$$

which leads to the following equation for the aqueous solvation free energy

$$\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O\cdot H_2O}) = 2\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O}) - \Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.}) + \Delta G^{\circ\rightarrow *} \tag{14}$$

where $\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O})$ is the aqueous solvation free energy of water, and $\Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.})$ is the gas phase binding free energy, which equals $G^{\circ}_{\mathrm{gas}}(\mathrm{H_2O\cdot H_2O}) - 2G^{\circ}_{\mathrm{gas}}(\mathrm{H_2O})$. Substituting experimental values of −6.31 kcal/mol for $\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O})$ and 3.34 kcal/mol for $\Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.})$ into eq 14 gives −14.06 kcal/mol for the aqueous solvation free energy of the water dimer.

The remaining clustered solutes in the database are ionic; for these the following thermodynamic cycle was used

$$\begin{tikzcd}
H_2O(gas) \arrow[d, "\Delta\ {}^{*}_{w/a}(H_2O)"] & + & M^{\pm}(gas \arrow[rr, "\Delta\ {}^{\circ}_{gas}(B.E.)"] \arrow[d, "\Delta\ {}^{*}_{w/a}(M^{\pm})"] & & H_2O\cdot M^{\pm}(gas) \arrow[d, "\Delta\ {}^{*}_{w/a}(H_2O\cdot M^{\pm})"] \\
H_2O(aq) & + & M^{\pm}(aq \arrow[rr, "0"'] & & H_2O\cdot M^{\pm}(aq)
\end{tikzcd}$$

which yields the following equation for the aqueous solvation free energy

$$\Delta\ {}^{*}_{S}(H_2O\cdot M^{\pm}) = \Delta\ {}^{*}_{w/a}(H_2O) + \Delta\ {}^{*}_{w/a}(M^{\pm}) + \Delta\ {}^{\circ}_{gas}(B.E.) + \Delta\ {}^{\circ\rightarrow *} \qquad (15)$$

In the above equation, aqueous solvation free energies of the unclustered ions $\Delta\ {}^{*}_{S}(M^{\pm})$ were taken from the database. When available, experimental values for the gas-phase binding energies were used (NIST database). When experimental values were not available, they were calculated at the B97-1/MG3S level of theory. Example 8 in the “Worked Out Examples” section uses eq 15.

Relative Solvation Free Energies Between Water and Organic Solvents

For many solutes, the experimental data required to determine an absolute solvation free energy between the gas and liquid phase are not available. If one was restricted to considering only absolute solvation free energies, many solutes containing important functionality would not be well represented (or not represented at all) in the database. Thus, *relative* solvation free energies that were determined using experimental partition coefficients measured between water and various solvents (i.e. $P_{o/w}$ values) are also included in the database. The following equation was used to convert experimental partition coefficients into relative solvation free energies

$$\Delta\ {}^{*}_{o/w} = -2.303\ \log\ {}_{o/w} \qquad (16)$$

Uncertainty of Experimental Data

The estimated average uncertainty for solvation free energies of neutral solutes in the data set is 0.2 kcal/mol. The estimated average uncertainty for solvation free energies of ionic solutes is 3 kcal/mol.

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Meot-Ner, M. M.; Lias, S. G. Binding Energies Between Ions and Molecules, and the Thermochemistry of Cluster Ions. In *NIST Chemistry WebBook, NIST Standard Reference Database Number 69*; Linstrom, P. J., Mallard, W. G., Eds.; National Institute of Standards and Technology: Gaithersburg, MD, March 2003.

Description of the Database File

The database is distributed in two different forms: (1) as both a portable spreadsheet file, saved as a tab-delimited text file (MNSol2.0.1.txt) and (2) as a Microsoft Excel spreadsheet (MNSol2.0.1.xls).

Each solvation free energy is one row in the database file, and the pertinent information about each data point is entered in the columns of that row. Below is a listing of the information contained in each of these columns:

Column 1: Database entry number
Column 2: File handle for the Cartesian coordinate file of the solute.
Column 3: Solute name
Columns 4-6: Solute classification numbers. The various solute classes are listed in the "Solute Classification Numbers" section of this manual.
Column 7: Solvent in which the solvation free energy of the solute is listed.
Column 8: The solvation free energy in kcal/mol
Column 9: Description of the type of solvation free energy. Solvation free energies are either absolute "abs" or relative "rel". Absolute solvation free energies are for moving the solute from the gas phase to the solvent listed in column 7. Relative solvation free energies are for moving the solute from water to the solvent listed in column 7.

The remaining columns are of interest to developers only:

Columns 10-16: Solvent descriptors for the solvent listed in that row. For water, all solvent descriptors are assigned a value of 1.
Columns 17-26: Total exposed surface area of each atom in the solute, in cal/mol Å^2.
Columns 27-43: Total exposed surface area for the first atom listed, multiplied by the cut-off-tangent (COT) function for that pair of atoms, in cal/mol Å^2. All of these values were obtained using the COT functions as described in Kelly, C. P.; Cramer, C. J.; Truhlar, D. G. *J. Chem. Theory Comput.* **2005**, *1*, 1133., except for OSi, whose COT function is described in Winget, P.; Cramer, C. J.; Truhlar, D. G. *J. Phys. Chem. A*, **2002**, *106*, 5160.
Column 44: Total exposed surface area of all atoms in the solute, in cal/mol Å^2. This value is equal to the sum of columns 17-26.

solvent.dat files

The solvent.dat files in the solutes_by_solvent folder(s) contain, for each solvent, the dielectric constant (DIELEC), index of refraction (SOLN), hydrogen bond acidity (SOLA), hydrogen bond basicity (SOLB), macroscopic surface tension (SOLG), aromaticity (SOLC), and electronegative halogenicity (SOLH). These parameters are explained in the document entitled Minnesota Solvent Descriptor Database (mnsddb.pdf).

Cartesian Coordinate Input Files for Solutes in the Database

The file "solutes" lists all of the solutes in the database. The following information is contained in this file:

Column 1:	Solute number
Column 2:	File handle for the Cartesian coordinate file of the solute.
Column 3:	Name of the solute.
Column 4:	The level of electronic structure theory used to optimize the geometry of each solute in the gas phase. The geometries of all unclustered species have been optimized at the mPW1PW91/MIDI! level of theory in the gas phase. All solute-water clusters have been optimized in the gas phase at the B97-1/MG3S level of theory. The optimized Cartesian coordinates for each of the solutes listed in this file are located in the /geometry directory. In this directory, Cartesian coordinates are listed in units of angstroms.
Columns 5-7:	Solute classification numbers. The various solute classes are listed in the "Solute Classification Numbers" section of this manual.

Citation

If this database is used for published work, the following citation should be given:

Marenich, Aleksandr V; Kelly, Casey P; Thompson, Jason D; Hawkins, Gregory D; Chambers, Candee C; Giesen, David J; Winget, Paul; Cramer, Christopher J; Truhlar, Donald G. (2020). *Minnesota Solvation Database (MNSOL) version 2012*. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/3eks-j059.

The following citation should also be given if the aqueous portion of the database is used:

"SM6: A Density Functional Theory Continuum Solvation Model for Calculating Aqueous Solvation Free Energies of Neutrals, Ions, and Solute-Water Clusters", Kelly, C. P.; Cramer, C. J.; Truhlar, D. G. *J. Chem. Theory. Comput.* **2005**, *1*, 1133.

The following citation should also be given if the organic portion of the database is used:

"New Universal Solvation Model and Comparison of the Accuracy of the SM5.42R, SM5.43R, C-PCM, D-PCM, and IEF-PCM Continuum Solvation Models for Aqueous and Organic Solvation Free Energies and for Vapor Pressures", Thompson, J. D.; Cramer, C. J.; Truhlar, D. G. *J. Phys. Chem. A* **2004**, *108*, 6532.

Version History

MNSol Version 2.0.1 (June 2005)
Authors: Kelly, C. P.; Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

The solvent for entry number 1473 (hydrogen peroxide in cyclohexanone) was incorrectly listed as cyclohexane in version 2.0. Version 2.0.1 correctly lists the solvent as cyclohexanone.

In version 2.0 of the database, the chloroform-water solvation free energy for phenylurea was incorrectly listed as −0.86 kcal/mol. Version 2.0.1 lists the correct value of +0.86 kcal/mol for this free energy.

In version 2.0 of the data base, the absolute solvation free energies of hydrazine in benzene, octanol, diethyl ether, and chloroform were based on an older value of −9.30 kcal/mol for the aqueous solvation free energy of hydrazine (this version and previous versions of the data base correctly list −6.26 kcal/mol for the aqueous solvation free energy of hydrazine). In version 2.0.1, the solvation free energies for hydrazine in the organic solvents above are now correctly computed using a value of −6.26 kcal/mol for the aqueous solvation free energy of hydrazine.

In the geometries directory, *N*-methylaniline is included as a solute twice; once as n012 and another as 0122NMe. The file n012.inp has been removed from this directory, and the listing for n012 has been removed from the files solutes.txt and solutes.xls.

MNSol Version 2.0 (December 2005)
Authors: Kelly, C. P.; Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

This is the second version of the Minnesota Solvation Database. Parts of this database were taken from an earlier database called “Minnesota Solvation Database Version 2003.1” by Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

Solute Classification Numbers

1. H_2, NH_3, and H_2O
    - 1.1 H_2
    - 1.2 NH_3
    - 1.3 H_2O

2. Compounds containing H and/or C and O
    - 2.1. Hydrocarbons
        - 2.1.1. Unbranched alkanes
        - 2.1.2. Branched alkanes
        - 2.1.3. Cycloalkanes
        - 2.1.4. Alkenes
        - 2.1.5. Alkynes
        - 2.1.6. Arenes
    - 2.2. Simple hydroxyl compounds
        - 2.2.1. Alcohols
        - 2.2.2. Phenols
    - 2.3. Ethers
        - 2.4.1. Aldehydes
        - 2.4.2. Ketones
    - 2.5. Carboxylic acids
    - 2.6. Esters
    - 2.7. Lactones
    - 2.8. Peroxides
    - 2.9. Bifunctional H, C, O compounds

3. Compounds containing H and/or C and N
    - 3.1. Aliphatic amines
    - 3.2. Anilines
    - 3.3. Aromatic nitrogen heterocycles
        - 3.3.1. 1 nitrogen in the ring
        - 3.3.2. 2 nitrogens in the ring
    - 3.4. Nitriles
    - 3.5. Hydrazines
    - 3.6. Bifunctional H, C, N compounds

4. Compounds containing H, C, N, and O
    - 4.1. Amides and ureas
        - 4.1.1. Amides
        - 4.1.2. Ureas
    - 4.2. Nitrohydrocarbons
    - 4.3. Bifunctional H, C, N, O compounds

5. Compounds containing H, C, and F
    - 5.1. Fluoroalkanes
    - 5.2. Fluoroarenes

6. Compounds containing H, C, and Cl
    - 6.1. Chloroalkanes
    - 6.2. Chloroalkenes
    - 6.3. Chloroarenes

7. Compounds containing H, C, and Br
    - 7.1. Bromoalkanes
    - 7.2. Bromoalkenes
    - 7.3. Bromoarenes

8. Multihalogen hydrocarbons

9. Halogenated bifunctional compounds, containing at most H, C, N, O, F, Cl, Br
    - 9.1. Bifunctional halogen compounds containing O
    - 9.2. Bifunctional halogen compounds containing N
    - 9.3. Bifunctional halogen compounds containing N and O

10. Compounds containing S, but not P
    - 10.1. Thiols
    - 10.2. Sulfides
    - 10.3. Disulfides
    - 10.4. Sulfur heterocycles
    - 10.5. Non-halogenated sulfur-containing bifunctional compounds
    - 10.6. Halogenated sulfur-containing compounds
    - 10.7. Sulfoxides

11. Phosphorus compounds
    - 11.1. Compounds containing at most H, C, N, O and P
    - 11.2. Nonhalogenated P compounds containing S
    - 11.3. Halogenated P compounds not containing S
    - 11.4. Halogenated P compounds containing S

12. Silicon compounds
    - 12.1. Compounds containing H, C, and Si
    - 12.2. Compounds containing H, C, O, and Si

13. Ionic compounds
    - 13.1. Ions containing only H and C
    - 13.2. Ions containing only H, C and O
    - 13.3. Ions containing only H, C, and N
    - 13.4. Ions containing only H, C, N, and O
    - 13.5. Ions containing S
    - 13.6. Halogenated ions
    - 13.7. Inorganic ions

14. Solute-water clusters
    - 14.1. Neutrals
    - 14.2. Ions

Worked Out Examples

Example 1: Aqueous solvation free energy from the air/water partition coefficient

The experimental aqueous solvation free energy of anisole is listed as -2.45 kcal/mol in the database. This value was determined using an experimental log $P_{w/a}$ value of 1.80, which was taken from Abraham et al. (1990):

$$\Delta \; {}^{*}_{w/a} = -2.303 \quad \log \; {}_{w/}$$

$$\Delta \; {}^{*}_{w/a} = -2.303\left(1.987\times10^{-3}\,\frac{\text{kcal}}{\text{molK}}\right)*(298\text{K})*(-1.80) = -2.45\,\text{kcal/m}$$

Example 2: Aqueous solvation free energy from the Henry’s Law Constant

The experimental aqueous solvation free energy of benzamide is listed as -10.90 kcal/mol in the database. This value was determined using an experimental HLC of 2.45E-10 atm m^3/mol, which was taken from the PhysProp database:

Part 1:

$$\text{HLC}(-) = \text{HLC}\left(\frac{\text{atm m}^3}{\text{mol}}\right)*\left(1.218\times10^{4}\,\frac{\text{molK}}{\text{atm m}^3}\right)*\left(\frac{1}{\;}\right)$$

$$\text{HLC}(-) = 2.45\times10^{-10}\left(\frac{\text{atm m}^3}{\text{mol}}\right)*\left(1.218\times10^{4}\,\frac{\text{molK}}{\text{atm m}^3}\right)*\left(\frac{1}{298\text{K}}\right) = 1.00\times10^{-8}$$

Part 2:

$$\Delta \; {}^{*}_{w/a} = 2.303 \quad \log \text{HLC}(-)$$

$$\Delta \; {}^{*}_{w/a} = 2.303\left(1.987\times10^{-3}\,\frac{\text{kcal}}{\text{molK}}\right)*(298\text{K})*(-8.00) = -10.90\,\text{kcal/m}$$

Example 3: Aqueous solvation free energy from vapor pressure and solubility

The experimental aqueous solvation free energy of urea is listed as −13.80 kcal/mol in the database. This value was determined using an experimental M_{aq} value of 8.99 mol/L and an experimental P_{vapor} value of 1.579 E-8 atm, which were both taken from the PhysProp database:

$$\Delta \quad {}^{*}_{\mathrm{w/a}} = -2.303 \quad \log\left(\frac{\mathrm{w} \qquad {}^{\circ}}{\mathrm{vapor} / \quad {}^{\circ}}\right)$$

$$\Delta \quad {}^{*}_{\mathrm{w/a}} = -2.303\left(1.987\times 10^{-3}\,\frac{\mathrm{kcal}}{\mathrm{molK}}\right) * (298\,\mathrm{K}) * \log\left(\frac{8.99\,\mathrm{mol/L}/1.0\,\mathrm{mol/L}}{1.579\times 10^{8}\,\mathrm{atm}/24.45\,\mathrm{atm}}\right) = -13.80\,\mathrm{kcal/mo}$$

Example 4: Solvation free energy in an organic liquid from the aqueous solvation free energy and the organic liquid - water partition coefficient

The experimental solvation free energy for phenol in octanol is listed as −8.69 kcal/mol in the database. This value was determined using an experimental value of −6.62 kcal/mol for the aqueous solvation free energy of phenol, which was taken from the database, and an experimental value of 1.52 for log $P_{\mathrm{o/w}}$, which was taken from the MedChem database:

$$\Delta \quad {}^{*}_{\mathrm{o/a}} = \Delta \quad {}^{*}_{\mathrm{w/a}} - 2.303 \quad \log \quad {}_{\mathrm{o/w}}$$

$$\Delta \quad {}^{*}_{\mathrm{o/a}} = -6.62\,\mathrm{kcal/mol} - 2.303\left(1.987\times 10^{-3}\,\frac{\mathrm{kcal}}{\mathrm{molK}}\right) * (298\,\mathrm{K}) * 1.52 = -8.69\,\mathrm{kcal/mo}$$

Example 5: Solvation free energy in an organic liquid from the vapor pressure of the solute over its pure liquid

The experimental self-solvation free energy of carbon tetrachloride (i.e. carbon tetrachloride in carbon tetrachloride) is listed as −4.35 kcal/mol in the database. To calculate the molarity (M_{liq}) of pure carbon tetrachloride, the density of carbon tetrachloride (1.5842 g/mL, which equals 10.30 mol/L) and its molecular weight (153.2 g/mol) were used in eq 10. An experimental value of 0.151 atm was used for the vapor pressure of carbon tetrachloride in equilibrium with its pure liquid (P_{vapor}), which was taken from the *CRC* Handbook:

$$\Delta \quad {}^{*}_{\mathrm{o/a}} = -2.303 \quad \log\left(\frac{\mathrm{liq} \qquad {}^{\circ}}{\mathrm{vapor} / \quad {}^{\circ}}\right)$$

$$\Delta \quad {}^{*}_{\mathrm{o/a}} = -2.303 * \left(1.987\times 10^{-3}\,\frac{\mathrm{kcal}}{\mathrm{molK}}\right) * (298\,\mathrm{K}) \log\left(\frac{10.30\,\mathrm{mol/L} / 1\,\mathrm{mol/L}}{0.151\,\mathrm{atm} / 24.45\,\mathrm{atm}}\right) = -4.35\,\mathrm{kcal/mo}$$

Example 6: Aqueous solvation free energy of methylammonium ($CH_3NH_3^+$)

The experimental aqueous solvation free energy of methylammonium is listed as −75 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta\ {}^{\circ}_{\mathrm{gas}}(\mathrm{A})$	206.6 kcal/mol	NIST
$\Delta\ {}^{\circ\rightarrow *}$	1.9 kcal/mol	–
$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH})$	−4.6 kcal/mol	MNSol1.0
$\mathrm{p}\ {}_{\mathrm{a}}(\mathrm{AH}^+)$	10.6	Stewart (1985)
$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{H}^+)$	−264.0 kcal/mol	Zhan and Dixon (2001)

$$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH}^+) = \Delta\ {}^{\circ}_{\mathrm{gas}}(\mathrm{A}) + \Delta\ {}^{\circ\rightarrow *} + \Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH}) + \Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{H}^+) - 2.303\quad \mathrm{p}\ {}_{\mathrm{a}}(\mathrm{AH}^+)$$

$$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH}^+) = 206.6 + 1.9 - 4.6 - 264.0 - 2.303\quad (10.6) = -75\,\mathrm{kcal/m}$$

Example 7: Aqueous solvation free energy of methoxide ($CH3O^-$)

The experimental aqueous solvation free energy of methoxide is listed as −97 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta\ {}^{\circ}_{\mathrm{gas}}(\mathrm{A})$	375.0 kcal/mol	NIST
$\Delta\ {}^{\circ\rightarrow *}$	1.9 kcal/mol	–
$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH})$	−5.1 kcal/mol	MNSol1.0
$\mathrm{p}\ {}_{\mathrm{a}}(\mathrm{AH}^+)$	15.5	Stewart (1985)
$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{H}^+)$	−264.0 kcal/mol	Zhan and Dixon (2001)

$$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{A}^-) = -\Delta\ {}^{\circ}_{\mathrm{gas}}(\mathrm{A}^-) - \Delta\ {}^{\circ\rightarrow *} + \Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{AH}) - \Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{H}^+) + 2.303\quad \mathrm{p}\ {}_{\mathrm{a}}(\mathrm{AH})$$

$$\Delta\ {}^{*}_{\mathrm{w/a}}(\mathrm{A}^-) = -375.0 - 1.9 - 5.1 + 264.0 + 2.303\quad (15.5) = -97\,\mathrm{kcal/m}$$

Example 8: Aqueous solvation free energy of methoxide + 1H$_2$O [H$_2$O(CH$_3$O)$^-$]

The experimental aqueous solvation free energy of the methoxide-water cluster is listed as −84 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta \ ^{*}_{\mathrm{w/a}}(\mathrm{H_2O})$	−6.3 kcal/mol	MNSol1.0
$\Delta \ ^{*}_{\mathrm{w/a}}(\mathrm{M}^{\pm})$	−97.0 kcal/mol	MNSol1.0
$\Delta \ ^{\circ}_{\mathrm{gas}}(\mathrm{B.E.})$	−17.0 kcal/mol	NIST
$\Delta \ ^{\circ\rightarrow *}$	1.9 kcal/mol	–

$$\Delta \ ^{*}_{\mathrm{S}}(\mathrm{H_2O \cdot M^{\pm}}) = \Delta \ ^{*}_{\mathrm{w/a}}(\mathrm{H_2O}) + \Delta \ ^{*}_{\mathrm{w/a}}(\mathrm{M}^{\pm}) - \Delta \ ^{\circ}_{\mathrm{gas}}(\mathrm{B.E.}) + \Delta \ ^{\circ\rightarrow *} = -84\mathrm{kcal/mc}$$

END OF MANUAL

Contents

Overview of the Database

This database contains experimental aqueous solvation free energies for 274 neutral solutes (including the water dimer), 112 ionic solutes, and 31 clustered ions containing a single water molecule. The database also contains 2,002 solvation free energies for 322 neutral solutes in 90 different organic solvents, and 87 solvation free energies between water and 11 different organic solvents for 64 neutral solutes. In total, the database contains 2,506 experimental solvation free energies for 520 neutral and ionic solutes. All of the solutes in this database contain at most the following elements: H, C, N, O, F, Si, P, S, Cl, and Br.

Contents of the Database

The Minnesota Solvation Database is available as a tarred and gzipped file named MNSolDatabase2.0.1.tar.gz. To open the file, type the commands

```
gunzip MNSolDatabase2.0.1.tar.gz
tar –xvf MNSolDatabase2.0.1.tar
```

After executing the above commands, a new directory called MNSol2.0.1 will appear. The contents of this directory are as follows:

File or directory name	Brief description
MNSol2.0.1.UsersManual.pdf	this manual
MNSol2.0.1.txt	database file, the contents of which are discussed in detail below
MNSol2.0.1.xls	database file in Microsoft Excel format
solutes.txt	a list of all of the solutes in the database
solutes.xls	the above file in Microsoft Excel format
geometries/	directory containing Cartesian coordinates of all of the solutes in the database

Description of Experimental Values in the Database

The Minnesota Solvation Database contains two types of solvation free energies: absolute solvation free energies and relative solvation free energies between water and various organic solvents. All experimental values in the database are for a temperature of 298 K. The absolute solvation free energies in this database correspond to the following process

$$X_{\text{gas}} \longrightarrow X_{\text{liq}}$$

where X_{gas} is the solute in the gas phase and X_{liq} is the solute in the dilute liquid phase. The relative solvation free energies correspond to the following process

$$X_{\text{water}} \longrightarrow X_{\text{organic}}$$

where X_{water} is the solute in the dilute aqueous phase and X_{organic} is the solute in a dilute organic liquid.

Standard States

All of the solvation free energies in this database are tabulated using an ideal gas at a concentration of 1 mol/L dissolving as an ideal solution at a concentration of 1 mol/L as the standard state. This standard state is sometimes referred to as the Ben-Naim standard state, and is usually denoted by the superscript "*". A commonly used standard state that differs from the one used here is an ideal gas at a concentration of 1 atm dissolving as an ideal solution at a concentration of 1 mol/L. This standard state is usually denoted by the superscript "○". The relationship between these two standard states is

$$\Delta G^{*}_{\text{gas}\rightarrow\text{liq}} = \Delta G^{\circ}_{\text{gas}\rightarrow\text{liq}} - \Delta G^{\circ\rightarrow *} \tag{1}$$

where

$$\Delta G^{\circ\rightarrow *} = RT\ln(24.46) \tag{2}$$

At 298 K $\Delta G^{\circ\rightarrow *}$ equals 1.89 kcal/mol. Thus, eqs 1 and 2 allow one to convert solvation free energies in this database, which use a standard state with a gas phase concentration of 1 mol/L and a liquid phase concentration of 1 mol/L, to a standard state that uses a gas phase concentration of 1 atm and a liquid phase concentration of 1 mol/L.

Aqueous Solvation Free Energies of Neutral Solutes

Most of the aqueous solvation free energies in this database were determined using experimental partition coefficients measured between the gas phase and dilute aqueous solution. The partition coefficient associated with transferring a solute from the gas phase to dilute aqueous solution, $P_{\mathrm{w/a}}$, is related to the free energy of this process by

$$\Delta G^{*}_{\mathrm{w/a}} = -2.303RT\log P_{\mathrm{w/a}} \tag{3}$$

where the "w/a" denotes transfer from the gas "air" phase, to the dilute aqueous "water" phase. Also, log is the base 10 logarithm. The above notation will be used throughout the remainder of this manual. Example 1 in the "Worked Out Examples" section of this manual shows a sample calculation that uses the above equation.

Some of the aqueous solvation free energies in this database were determined using experimental values of the dimensionless Henry's Law Constant (HLC), which is the partition coefficient for transferring a solute from dilute aqueous solution to the gas-phase (i.e., $P_{\mathrm{a/w}}$). The dimensionless HLC is related to the aqueous solvation free energy according to

$$\Delta G^{*}_{\mathrm{w/a}} = 2.303RT\log \mathrm{HLC}(-) \tag{4}$$

where the (–) denotes that the HLC is dimensionless.

HLC taken from the PhysProp database are reported in units of atm m^3/mol. These values were converted to dimensionless HLC using the following equation

$$\mathrm{HLC}(-) = \mathrm{HLC}\left(\frac{\mathrm{atm\,m^3}}{\mathrm{mol}}\right) * \left(1.218\times 10^4\ \frac{\mathrm{mol\,K}}{\mathrm{atm\,m^3}}\right) * \left(\frac{1}{T}\right) \tag{5}$$

where 298 K was used for T. See example 2 in the "Worked Out Examples" section for a sample calculation that uses eqs 4 and 5.

The aqueous solvation free energy can also be expressed in terms of the vapor pressure of the solute in equilibrium with its pure liquid (P_{vapor}) and its aqueous solubility in molarity units (S_{w}). Some of the aqueous solvation free energies in the database were determined using

$$\Delta G^{*}_{\mathrm{w/a}} = -2.303RT\log\left(\frac{S_{\mathrm{w}}/M^{\circ}}{P_{\mathrm{vapor}}/P^{\circ}}\right) \tag{6}$$

where M° is equal to 1 mol/L and P° is the pressure (24.45 atm) of an ideal gas at 1 molar concentration and 298 K. See example 3 in the "Worked Out Examples" section for a sample calculation that uses eq 6.

Solvation Free Energies of Neutral Solutes in Organic Solvents

Several of the experimental solvation free energies of neutral solutes in organic solvents that are listed in the database were determined using experimental values of partition coefficients measured between the gas phase and dilute organic liquids, i.e.

$$\Delta G^{*}_{\text{o/a}} = -2.303RT\log P_{\text{o/a}} \tag{7}$$

where the "o/a" denotes that the free energy or partition coefficient is for a solute transferring from the gas phase to a dilute organic liquid.

The majority of non-aqueous solvation free energies were determined by combining experimental values for the aqueous solvation free energy with experimental partition coefficients measured between the aqueous phase and different organic solvents, i.e.

$$\Delta G^{*}_{\text{o/a}} = \Delta G^{*}_{\text{w/a}} - 2.303RT\log P_{\text{o/w}} \tag{8}$$

where the "o/w" denotes transfer from water to an organic solvent. (Note that the symbol P_{oct} is often used for the special case in which the partition coefficient is measured between water and 1-octanol). Example 4 in the "Worked Out Examples" section uses eq 8.

The database also contains "self solvation" free energies (e.g., the solvation free energy of chloroform solute in pure liquid chloroform). These solvation free energies were determined using the vapor pressure of the solute in equilibrium with its pure liquid (P_{vapor}) according to

$$\Delta G^{*}_{\text{o/a}} = -2.303RT\log\left(\frac{M_{\text{liq}}/M^{\circ}}{P_{\text{vapor}}/P^{\circ}}\right) \tag{9}$$

where M° is equal to 1 mol/L, P° is the pressure (24.45 atm) of an ideal gas at 1 molar concentration and 298 K, and M_{liq} is the molarity of the solute in its pure liquid form, which can be calculated from the density of the solute in its pure liquid state and its molecular weight:

$$M_{\text{liq}} = \rho_{\text{liq}}\text{MW}_{\text{liq}} \tag{10}$$

Example 5 in the "Worked Out Examples" section uses eqs 9 and 10.

Aqueous Solvation Free Energies of Ionic Solutes

To determine the aqueous solvation free energies of cations, we used the following thermodynamic cycle

$$\begin{tikzcd}
\mathrm{AH^+\,(gas)} \arrow[r, "\Delta G^\circ_{\mathrm{gas}}(\mathrm{AH^+})"] \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{AH^+})"] & \mathrm{A(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{A})"] & + & \mathrm{H^+(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{H^+})"] \\
\mathrm{AH^+\,(aq)} \arrow[r, "\Delta G^*_{\mathrm{aq}}(\mathrm{AH^+})"'] & \mathrm{A\,(aq)} & + & \mathrm{H^+(aq)}
\end{tikzcd}$$

along with the following equation

$$\Delta G^*_{\mathrm{aq}} = 2.303RT\,\mathrm{p}K_{\mathrm{a}} \tag{11}$$

The thermodynamic cycle above and eq 11 yields the following equation for the aqueous solvation free energy of AH^+

$$\Delta G^*_{\mathrm{w/a}}(\mathrm{AH^+}) = \Delta G^\circ_{\mathrm{gas}}(\mathrm{AH^+}) + \Delta G^{\circ\rightarrow *} + \Delta G^*_{\mathrm{w/a}}(\mathrm{A}) + \Delta G^*_{\mathrm{w/a}}(\mathrm{H^+}) - 2.303RT\,\mathrm{p}K_{\mathrm{a}}(\mathrm{AH^+}) \tag{12}$$

where $\Delta G^*_{\mathrm{w/a}}(\mathrm{A})$ is the aqueous solvation free energy of the neutral species A, $\Delta G^*_{\mathrm{w/a}}(\mathrm{H^+})$ is the aqueous solvation free energy of the proton, $\Delta G^\circ_{\mathrm{gas}}(\mathrm{AH^+})$ is the gas phase acidity of AH^+ (which is typically reported as the gas phase basicity of A), equal to $G^\circ_{\mathrm{gas}}(\mathrm{A}) + G^\circ_{\mathrm{gas}}(\mathrm{H^+}) - G^\circ_{\mathrm{gas}}(\mathrm{AH^+})$, and $\Delta G^{\circ\rightarrow *}$ is 1.89 kcal/mol.

For most of the anions in the database, we used the following thermodynamic cycle

$$\begin{tikzcd}
\mathrm{AH\,(gas)} \arrow[r, "\Delta G^\circ_{\mathrm{gas}}(\mathrm{AH})"] \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{AH})"] & \mathrm{A^-\,(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{A^-})"] & + & \mathrm{H^+(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{H^+})"] \\
\mathrm{AH\,(aq)} \arrow[r, "\Delta G^*_{\mathrm{aq}}(\mathrm{AH})"'] & \mathrm{A^-\,(aq)} & + & \mathrm{H^+(aq)}
\end{tikzcd}$$

The thermodynamic cycle above and eq 11 yields the following equation for the aqueous solvation free energy of A^-

$$\Delta G^*_{\mathrm{w/a}}(\mathrm{A^-}) = -\Delta G^\circ_{\mathrm{gas}}(\mathrm{AH}) - \Delta G^{\circ\rightarrow *} + \Delta G^*_{\mathrm{w/a}}(\mathrm{AH}) - \Delta G^*_{\mathrm{w/a}}(\mathrm{H^+}) + 2.303RT\,\mathrm{p}K_{\mathrm{a}}(\mathrm{AH}) \tag{13}$$

where $\Delta G^\circ_{\mathrm{gas}}(\mathrm{AH})$ is the gas phase acidity of AH, equal to $G^\circ_{\mathrm{gas}}(\mathrm{A^-}) + G^\circ_{\mathrm{gas}}(\mathrm{H^+}) - G^\circ_{\mathrm{gas}}(\mathrm{AH})$.

In the above equations, we used Zhan and Dixon's (2001) value of −264 kcal/mol for the aqueous solvation free energy of the proton, $\Delta G^*_{\mathrm{w/a}}(\mathrm{H}^+)$. Experimental gas phase basicities of anions and acidities of neutral species were taken from the National Institute of Standards and Technology (NIST) database. Experimental gas-phase basicities of neutral species were taken from the most recent compilation of Hunter and Lias (1998). For neutral species, experimental aqueous solvation free energies were taken from the present database and several additional sources. A large part of the experimental aqueous $\mathrm{p}K_\mathrm{a}$ data used here was taken from the compilation of Stewart (1985); $\mathrm{p}K_\mathrm{a}$ data not available in this compilation were taken from several additional sources.

For F^-, Cl^-, and Br^-, we did not use the thermodynamic cycle above. Instead, the aqueous solvation free energies of these ions were taken from Tissandier et al. (1998) and adjusted for a change in the standard state and the value used here for $\Delta G^*_\mathrm{S}(\mathrm{H}^+)$.

Examples 6 and 7 in the "Worked Out Examples" section use eqs 12 and 13, respectively.

Aqueous Solvation Free Energies of Clustered Solutes

The database also includes aqueous solvation free energies of clustered solutes containing a single water molecule. For the water dimer, we used the free energy cycle shown below

$$\begin{tikzcd}
\mathrm{H_2O(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O})"] & + & \mathrm{H_2O(gas)} \arrow[r, "\Delta G^\circ_{\mathrm{gas}}(\mathrm{B.E.})"] \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O})"] & \mathrm{H_2O\cdot H_2O(gas)} \arrow[d, "\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O\cdot H_2O})"] \\
\mathrm{H_2O(aq)} & + & \mathrm{H_2O(aq)} \arrow[r, "0"'] & \mathrm{H_2O\cdot H_2O(aq)}
\end{tikzcd}$$

which leads to the following equation for the aqueous solvation free energy

$$\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O\ \cdot H_2O}) = 2\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O}) - \Delta G^\circ_{\mathrm{gas}}(\mathrm{B.E.}) + \Delta G^{\circ\to *} \tag{14}$$

where $\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O})$ is the aqueous solvation free energy of water, and $\Delta G^\circ_{\mathrm{gas}}(\mathrm{B.E.})$ is the gas phase binding free energy, which equals $G^\circ_{\mathrm{gas}}(\mathrm{H_2O\cdot H_2O}) - 2\,G^\circ_{\mathrm{gas}}(\mathrm{H_2O})$. Substituting experimental values of −6.31 kcal/mol for $\Delta G^*_{\mathrm{w/a}}(\mathrm{H_2O})$ and 3.34 kcal/mol for $\Delta G^\circ_{\mathrm{gas}}(\mathrm{B.E.})$ into eq 14 gives −14.06 kcal/mol for the aqueous solvation free energy of the water dimer.

The remaining clustered solutes in the database are ionic; for these the following thermodynamic cycle was used

$$\begin{tikzcd}
\mathrm{H_2O\,(gas)} \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O})"] & + & \mathrm{M^{\pm}\,(gas)} \arrow[r, "\Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.})"] \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{M^{\pm}})"] & \mathrm{H_2O\cdot M^{\pm}\,(gas)} \arrow[d, "\Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O\cdot M^{\pm}})"] \\
\mathrm{H_2O\,(aq)} & + & \mathrm{M^{\pm}\,(aq)} \arrow[r, "0"'] & \mathrm{H_2O\cdot M^{\pm}\,(aq)}
\end{tikzcd}$$

which yields the following equation for the aqueous solvation free energy

$$\Delta G^{*}_{\mathrm{S}}(\mathrm{H_2O\cdot M^{\pm}}) = \Delta G^{*}_{\mathrm{w/a}}(\mathrm{H_2O}) + \Delta G^{*}_{\mathrm{w/a}}(\mathrm{M^{\pm}}) + \Delta G^{\circ}_{\mathrm{gas}}(\mathrm{B.E.}) + \Delta G^{\circ\rightarrow *} \tag{15}$$

In the above equation, aqueous solvation free energies of the unclustered ions $\Delta G^{*}_{\mathrm{S}}(\mathrm{M^{\pm}})$ were taken from the database. When available, experimental values for the gas-phase binding energies were used (NIST database). When experimental values were not available, they were calculated at the B97-1/MG3S level of theory. Example 8 in the “Worked Out Examples” section uses eq 15.

Relative Solvation Free Energies Between Water and Organic Solvents

For many solutes, the experimental data required to determine an absolute solvation free energy between the gas and liquid phase are not available. If one was restricted to considering only absolute solvation free energies, many solutes containing important functionality would not be well represented (or not represented at all) in the database. Thus, *relative* solvation free energies that were determined using experimental partition coefficients measured between water and various solvents (i.e. $P_{\mathrm{o/w}}$ values) are also included in the database. The following equation was used to convert experimental partition coefficients into relative solvation free energies

$$\Delta G^{*}_{\mathrm{o/w}} = -2.303RT\log P_{\mathrm{o/w}} \tag{16}$$

Uncertainty of Experimental Data

The estimated average uncertainty for solvation free energies of neutral solutes in the data set is 0.2 kcal/mol. The estimated average uncertainty for solvation free energies of ionic solutes is 3 kcal/mol.

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Description of the Database File

The database is distributed in two different forms: (1) as both a portable spreadsheet file, saved as a tab-delimited text file (MNSol2.0.1.txt) and (2) as a Microsoft Excel spreadsheet (MNSol2.0.1.xls).

Each solvation free energy is one row in the database file, and the pertinent information about each data point is entered in the columns of that row. Below is a listing of the information contained in each of these columns:

Column 1:	Database entry number
Column 2:	File handle for the Cartesian coordinate file of the solute.
Column 3:	Solute name
Columns 4-6:	Solute classification numbers. The various solute classes are listed in the “Solute Classification Numbers” section of this manual.
Column 7:	Solvent in which the solvation free energy of the solute is listed.
Column 8:	The solvation free energy in kcal/mol
Column 9:	Description of the type of solvation free energy. Solvation free energies are either absolute “abs” or relative “rel”. Absolute solvation free energies are for moving the solute from the gas phase to the solvent listed in column 7. Relative solvation free energies are for moving the solute from water to the solvent listed in column 7.

The remaining columns are of interest to developers only:

Columns 10-16:	Solvent descriptors for the solvent listed in that row. For water, all solvent descriptors are assigned a value of 1.
Columns 17-26:	Total exposed surface area of each atom in the solute, in cal/mol Å^2.
Columns 27-43:	Total exposed surface area for the first atom listed, multiplied by the cut-off-tangent (COT) function for that pair of atoms, in cal/mol Å^2. All of these values were obtained using the COT functions as described in Kelly, C. P.; Cramer, C. J.; Truhlar, D. G. *J. Chem. Theory Comput.* **2005**, *1*, 1133., except for OSi, whose COT function is described in Winget, P.; Cramer, C. J.; Truhlar, D. G. *J. Phys. Chem. A*, **2002**, *106*, 5160.
Column 44:	Total exposed surface area of all atoms in the solute, in cal/mol Å^2. This value is equal to the sum of columns 17-26.

solvent.dat files

The solvent.dat files in the solutes_by_solvent folder(s) contain, for each solvent, the dielectric constant (DIELEC), index of refraction (SOLN), hydrogen bond acidity (SOLA), hydrogen bond basicity (SOLB), macroscopic surface tension (SOLG), aromaticity (SOLC), and electronegative halogenicity (SOLH). These parameters are explained in the document entitled Minnesota Solvent Descriptor Database (mnsddb.pdf).

Cartesian Coordinate Input Files for Solutes in the Database

The file “solutes” lists all of the solutes in the database. The following information is contained in this file:

Column 1:	Solute number
Column 2:	File handle for the Cartesian coordinate file of the solute.
Column 3:	Name of the solute.
Column 4:	The level of electronic structure theory used to optimize the geometry of each solute in the gas phase. The geometries of all unclustered species have been optimized at the mPW1PW91/MIDI! level of theory in the gas phase. All solute-water clusters have been optimized in the gas phase at the B97-1/MG3S level of theory. The optimized Cartesian coordinates for each of the solutes listed in this file are located in the /geometry directory. In this directory, Cartesian coordinates are listed in units of angstroms.
Columns 5-7:	Solute classification numbers. The various solute classes are listed in the “Solute Classification Numbers” section of this manual.

Citation

If this database is used for published work, the following citation should be given:

Marenich, Aleksandr V; Kelly, Casey P; Thompson, Jason D; Hawkins, Gregory D; Chambers, Candee C; Giesen, David J; Winget, Paul; Cramer, Christopher J; Truhlar, Donald G. (2020). *Minnesota Solvation Database (MNSOL) version 2012*. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/3eks-j059.

The following citation should also be given if the aqueous portion of the database is used:

“SM6: A Density Functional Theory Continuum Solvation Model for Calculating Aqueous Solvation Free Energies of Neutrals, Ions, and Solute-Water Clusters”, Kelly, C. P.; Cramer, C. J.; Truhlar, D. G. *J. Chem. Theory. Comput.* **2005**, *1*, 1133.

The following citation should also be given if the organic portion of the database is used:

“New Universal Solvation Model and Comparison of the Accuracy of the SM5.42R, SM5.43R, C-PCM, D-PCM, and IEF-PCM Continuum Solvation Models for Aqueous and Organic Solvation Free Energies and for Vapor Pressures”, Thompson, J. D.; Cramer, C. J.; Truhlar, D. G. *J. Phys. Chem. A* **2004**, *108*, 6532.

Version History

MNSol Version 2.0.1 (June 2005)
Authors: Kelly, C. P.; Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

The solvent for entry number 1473 (hydrogen peroxide in cyclohexanone) was incorrectly listed as cyclohexane in version 2.0. Version 2.0.1 correctly lists the solvent as cyclohexanone.

In version 2.0 of the database, the chloroform-water solvation free energy for phenylurea was incorrectly listed as –0.86 kcal/mol. Version 2.0.1 lists the correct value of +0.86 kcal/mol for this free energy.

In version 2.0 of the data base, the absolute solvation free energies of hydrazine in benzene, octanol, diethyl ether, and chloroform were based on an older value of –9.30 kcal/mol for the aqueous solvation free energy of hydrazine (this version and previous versions of the data base correctly list –6.26 kcal/mol for the aqueous solvation free energy of hydrazine). In version 2.0.1, the solvation free energies for hydrazine in the organic solvents above are now correctly computed using a value of –6.26 kcal/mol for the aqueous solvation free energy of hydrazine.

In the geometries directory, *N*-methylaniline is included as a solute twice; once as n012 and another as 0122NMe. The file n012.inp has been removed from this directory, and the listing for n012 has been removed from the files solutes.txt and solutes.xls.

MNSol Version 2.0 (December 2005)
Authors: Kelly, C. P.; Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

This is the second version of the Minnesota Solvation Database. Parts of this database were taken from an earlier database called "Minnesota Solvation Database Version 2003.1" by Thompson, J. D.; Hawkins, G. D.; Chambers, C. C.; Giesen, D. G.; Winget, P.; Cramer, C. J.; Truhlar, D. G.

Solute Classification Numbers

1. H_2, NH_3, and H_2O
    - 1.1 H_2
    - 1.2 NH_3
    - 1.3 H_2O

2. Compounds containing H and/or C and O
    - 2.1. Hydrocarbons
        - 2.1.1. Unbranched alkanes
        - 2.1.2. Branched alkanes
        - 2.1.3. Cycloalkanes
        - 2.1.4. Alkenes
        - 2.1.5. Alkynes
        - 2.1.6. Arenes
    - 2.2. Simple hydroxyl compounds
        - 2.2.1. Alcohols
        - 2.2.2. Phenols
    - 2.3. Ethers
        - 2.4.1. Aldehydes
        - 2.4.2. Ketones
    - 2.5. Carboxylic acids
    - 2.6. Esters
    - 2.7. Lactones
    - 2.8. Peroxides
    - 2.9. Bifunctional H, C, O compounds

3. Compounds containing H and/or C and N
    - 3.1. Aliphatic amines
    - 3.2. Anilines
    - 3.3. Aromatic nitrogen heterocycles
        - 3.3.1. 1 nitrogen in the ring
        - 3.3.2. 2 nitrogens in the ring
    - 3.4. Nitriles
    - 3.5. Hydrazines
    - 3.6. Bifunctional H, C, N compounds

4. Compounds containing H, C, N, and O
    - 4.1. Amides and ureas
        - 4.1.1. Amides
        - 4.1.2. Ureas
    - 4.2. Nitrohydrocarbons
    - 4.3. Bifunctional H, C, N, O compounds

5. Compounds containing H, C, and F
    5.1. Fluoroalkanes
    5.2. Fluoroarenes

6. Compounds containing H, C, and Cl
    6.1. Chloroalkanes
    6.2. Chloroalkenes
    6.3. Chloroarenes

7. Compounds containing H, C, and Br
    7.1. Bromoalkanes
    7.2. Bromoalkenes
    7.3. Bromoarenes

8. Multihalogen hydrocarbons

9. Halogenated bifunctional compounds, containing at most H, C, N, O, F, Cl, Br
    9.1. Bifunctional halogen compounds containing O
    9.2. Bifunctional halogen compounds containing N
    9.3. Bifunctional halogen compounds containing N and O

10. Compounds containing S, but not P
    10.1. Thiols
    10.2. Sulfides
    10.3. Disulfides
    10.4. Sulfur heterocycles
    10.5. Non-halogenated sulfur-containing bifunctional compounds
    10.6. Halogenated sulfur-containing compounds
    10.7. Sulfoxides

11. Phosphorus compounds
    11.1. Compounds containing at most H, C, N, O and P
    11.2. Nonhalogenated P compounds containing S
    11.3. Halogenated P compounds not containing S
    11.4. Halogenated P compounds containing S

12. Silicon compounds
    12.1. Compounds containing H, C, and Si
    12.2. Compounds containing H, C, O, and Si

13. Ionic compounds
    - 13.1. Ions containing only H and C
    - 13.2. Ions containing only H, C and O
    - 13.3. Ions containing only H, C, and N
    - 13.4. Ions containing only H, C, N, and O
    - 13.5. Ions containing S
    - 13.6. Halogenated ions
    - 13.7. Inorganic ions

14. Solute-water clusters
    - 14.1. Neutrals
    - 14.2. Ions

Worked Out Examples

Example 1: Aqueous solvation free energy from the air/water partition coefficient

The experimental aqueous solvation free energy of anisole is listed as -2.45 kcal/mol in the database. This value was determined using an experimental log $P_{\mathrm{w/a}}$ value of 1.80, which was taken from Abraham et al. (1990):

$$\Delta G^{*}_{\mathrm{w/a}} = -2.303RT\log P_{\mathrm{w/a}}$$

$$\Delta G^{*}_{\mathrm{w/a}} = -2.303\left(1.987\times10^{-3}\ \frac{\mathrm{kcal}}{\mathrm{mol\,K}}\right)*\left(298\ \mathrm{K}\right)*\left(-1.80\right) = -2.45\ \mathrm{kcal/mol}$$

Example 2: Aqueous solvation free energy from the Henry's Law Constant

The experimental aqueous solvation free energy of benzamide is listed as -10.90 kcal/mol in the database. This value was determined using an experimental HLC of 2.45E-10 atm m^3/mol, which was taken from the PhysProp database:

Part 1:

$$\mathrm{HLC}(-) = \mathrm{HLC}\left(\frac{\mathrm{atm\,m^3}}{\mathrm{mol}}\right)*\left(1.218\times10^{4}\ \frac{\mathrm{mol\,K}}{\mathrm{atm\,m^3}}\right)*\left(\frac{1}{T}\right)$$

$$\mathrm{HLC}(-) = 2.45\times10^{-10}\left(\frac{\mathrm{atm\,m^3}}{\mathrm{mol}}\right)*\left(1.218\times10^{4}\ \frac{\mathrm{mol\,K}}{\mathrm{atm\,m^3}}\right)*\left(\frac{1}{298\ \mathrm{K}}\right) = 1.00\times10^{-8}$$

Part 2:

$$\Delta G^{*}_{\mathrm{w/a}} = 2.303RT\log\mathrm{HLC}(-)$$

$$\Delta G^{*}_{\mathrm{w/a}} = 2.303\left(1.987\times10^{-3}\ \frac{\mathrm{kcal}}{\mathrm{mol\,K}}\right)*\left(298\ \mathrm{K}\right)*\left(-8.00\right) = -10.90\ \mathrm{kcal/mol}$$

Example 3: Aqueous solvation free energy from vapor pressure and solubility

The experimental aqueous solvation free energy of urea is listed as −13.80 kcal/mol in the database. This value was determined using an experimental M_{aq} value of 8.99 mol/L and an experimental P_{vapor} value of 1.579 E-8 atm, which were both taken from the PhysProp database:

$$\Delta G^*_{\mathrm{w/a}} = -2.303RT\log\left(\frac{S_{\mathrm{w}}/M^\circ}{P_{\mathrm{vapor}}/P^\circ}\right)$$

$$\Delta G^*_{\mathrm{w/a}} = -2.303\left(1.987\times10^{-3}\ \frac{\mathrm{kcal}}{\mathrm{mol\,K}}\right)*\left(298\ \mathrm{K}\right)*\log\left(\frac{8.99\ \mathrm{mol/L}\ /1.0\ \mathrm{mol/L}}{1.579\times10^{-8}\ \mathrm{atm}/\ 24.45\ \mathrm{atm}}\right) = -13.80\ \mathrm{kcal/mol}$$

Example 4: Solvation free energy in an organic liquid from the aqueous solvation free energy and the organic liquid - water partition coefficient

The experimental solvation free energy for phenol in octanol is listed as −8.69 kcal/mol in the database. This value was determined using an experimental value of −6.62 kcal/mol for the aqueous solvation free energy of phenol, which was taken from the database, and an experimental value of 1.52 for log $P_{\mathrm{o/w}}$, which was taken from the MedChem database:

$$\Delta G^*_{\mathrm{o/a}} = \Delta G^*_{\mathrm{w/a}} - 2.303RT\log P_{\mathrm{o/w}}$$

$$\Delta G^*_{\mathrm{o/a}} = -6.62\ \mathrm{kcal/mol} - 2.303\left(1.987\times10^{-3}\ \frac{\mathrm{kcal}}{\mathrm{mol\,K}}\right)*(298\ \mathrm{K})*1.52 = -8.69\ \mathrm{kcal/mol}$$

Example 5: Solvation free energy in an organic liquid from the vapor pressure of the solute over its pure liquid

The experimental self-solvation free energy of carbon tetrachloride (i.e. carbon tetrachloride in carbon tetrachloride) is listed as −4.35 kcal/mol in the database. To calculate the molarity (M_{liq}) of pure carbon tetrachloride, the density of carbon tetrachloride (1.5842 g/mL, which equals 10.30 mol/L) and its molecular weight (153.2 g/mol) were used in eq 10. An experimental value of 0.151 atm was used for the vapor pressure of carbon tetrachloride in equilibrium with its pure liquid (P_{vapor}), which was taken from the *CRC* Handbook:

$$\Delta G^*_{\mathrm{o/a}} = -2.303RT\log\left(\frac{M_{\mathrm{liq}}/M^\circ}{P_{\mathrm{vapor}}/P^\circ}\right)$$

$$\Delta G^*_{\mathrm{o/a}} = -2.303*\left(1.987\times10^{-3}\ \frac{\mathrm{kcal}}{\mathrm{mol\,K}}\right)*\left(298\ \mathrm{K}\right)\log\left(\frac{10.30\ \mathrm{mol/L}\ /1\ \mathrm{mol/L}}{0.151\ \mathrm{atm}\ /24.45\ \mathrm{atm}}\right) = -4.35\ \mathrm{kcal/mol}$$

Example 6: Aqueous solvation free energy of methylammonium ($CH_3NH_3^+$)

The experimental aqueous solvation free energy of methylammonium is listed as −75 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta G^\circ_{\text{gas}}(\text{A})$	206.6 kcal/mol	NIST
$\Delta G^{\circ\rightarrow *}$	1.9 kcal/mol	–
$\Delta G^*_{\text{w/a}}(\text{AH})$	−4.6 kcal/mol	MNSol1.0
$\text{p}K_\text{a}(\text{AH}^+)$	10.6	Stewart (1985)
$\Delta G^*_{\text{w/a}}(\text{H}^+)$	−264.0 kcal/mol	Zhan and Dixon (2001)

$$\Delta G^*_{\text{w/a}}(\text{AH}^+) = \Delta G^\circ_{\text{gas}}(\text{A}) + \Delta G^{\circ\rightarrow *} + \Delta G^*_{\text{w/a}}(\text{AH}) + \Delta G^*_{\text{w/a}}(\text{H}^+) - 2.303RT\,\text{p}K_\text{a}(\text{AH}^+)$$

$$\Delta G^*_{\text{w/a}}(\text{AH}^+) = 206.6 + 1.9 - 4.6 - 264.0 - 2.303RT(10.6) = -75 \text{ kcal/mol}$$

Example 7: Aqueous solvation free energy of methoxide (CH3O$^-$)

The experimental aqueous solvation free energy of methoxide is listed as −97 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta G^\circ_{\text{gas}}(\text{A})$	375.0 kcal/mol	NIST
$\Delta G^{\circ\rightarrow *}$	1.9 kcal/mol	–
$\Delta G^*_{\text{w/a}}(\text{AH})$	−5.1 kcal/mol	MNSol1.0
$\text{p}K_\text{a}(\text{AH}^+)$	15.5	Stewart (1985)
$\Delta G^*_{\text{w/a}}(\text{H}^+)$	−264.0 kcal/mol	Zhan and Dixon (2001)

$$\Delta G^*_{\text{w/a}}(\text{A}^-) = -\Delta G^\circ_{\text{gas}}(\text{A}^-) - \Delta G^{\circ\rightarrow *} + \Delta G^*_{\text{w/a}}(\text{AH}) - \Delta G^*_{\text{w/a}}(\text{H}^+) + 2.303RT\,\text{p}K_\text{a}(\text{AH})$$

$$\Delta G^*_{\text{w/a}}(\text{A}^-) = -375.0 - 1.9 - 5.1 + 264.0 + 2.303RT(15.5) = -97 \text{ kcal/mol}$$

Example 8: Aqueous solvation free energy of methoxide + 1H_2O [$H_2O(CH_3O)^-$]

The experimental aqueous solvation free energy of the methoxide-water cluster is listed as −84 kcal/mol in the database. This value was determined using the data shown below:

	Experimental Value	Ref.
$\Delta G^*_{\text{w/a}}(H_2O)$	−6.3 kcal/mol	MNSol1.0
$\Delta G^*_{\text{w/a}}(M^\pm)$	−97.0 kcal/mol	MNSol1.0
$\Delta G^\circ_{\text{gas}}(\text{B.E.})$	−17.0 kcal/mol	NIST
$\Delta G^{\circ\rightarrow *}$	1.9 kcal/mol	−

$$\Delta G^*_{\text{S}}(H_2O\cdot M^\pm) = \Delta G^*_{\text{w/a}}(H_2O) + \Delta G^*_{\text{w/a}}(M^\pm) - \Delta G^\circ_{\text{gas}}(\text{B.E.}) + \Delta G^{\circ\rightarrow *} = -84 \text{ kcal/mol}$$

END OF MANUAL