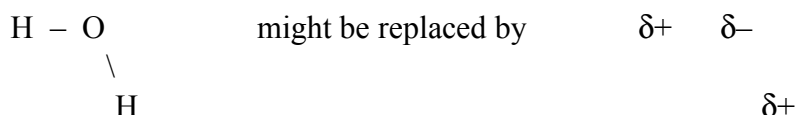


Implicit Solvation Models (D. M. Chipman 11/17/09)

I. Introduction

Solvation can alter the properties of a molecule, e. g. its charge distribution, geometry, vibrational frequencies, electronic transition energies, NMR constants, chemical reactivity, etc. Of particular interest for thermodynamic considerations is the solvation free energy, which is the net energy change upon transferring the molecule from the gas phase into a solvent with which it equilibrates.

An explicit treatment of solvent in an electronic structure calculation would require that many 100s-1000s of solvent molecules surrounding the solute be explicitly included. Also, many such calculations would have to be done to average over thermal fluctuations of the solvent molecules at finite temperature. This is obviously so computationally intensive that the solvent molecules must be treated at a lower level of theory. In fact, they are often treated classically by QM/MM, i.e. quantum mechanical treatment of the solute and molecular mechanical treatment of the solvent. Typically, the MM treatment of the solvent molecules replaces their actual electronic distributions with partial charges, thus only accounting for their electrostatic influence on the solute. For example, water



e. g., TIP3P uses $\delta+ = 0.417$ and $\delta- = -0.834$. These kinds of calculations are generally restricted to research groups that specialize in such things, and good “black box” implementations are not generally available.

Efficient simplified models can implicitly treat the various physical influences of solvent molecules on the solute. These influences are often phenomenologically classified as electrostatic (including induction), cavitation, exchange repulsion, and dispersion attraction. In very accurate theories higher order couplings among these effects may be considered, but that has not yet been done in the context of solvation modeling.

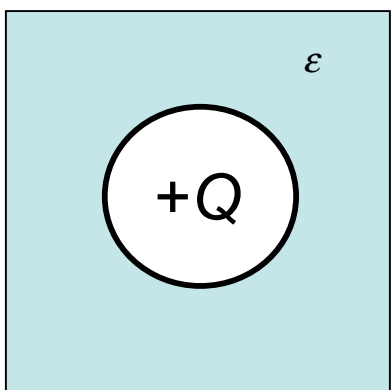
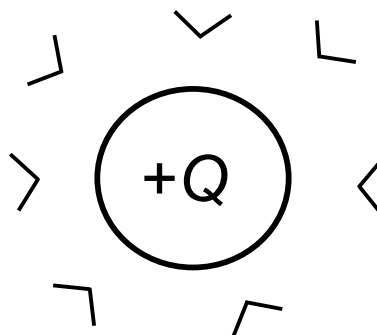
For a polar solute in a polar solvent the electrostatic interactions (including induction) are usually dominant, but the other effects noted above still need to be included for quantitative work. The electrostatic interaction is long range and can be understood classically, while the others are short range and inherently quantum mechanical in origin.

II. Dielectric Continuum

Electrostatic interactions on a solute from solvent are often treated with dielectric continuum models. These have the great advantage that the dielectric continuum response can be formulated to represent the response of a statistically averaged solvent, so that meaningful results can be obtained from a single calculation. These ideas are best introduced by considering a simple example.

II.a. Point charge in a spherical cavity

This might be a crude model for hydration of K^+ or Na^+ . Water molecules will reorient themselves to preferentially point the negative ends of their dipoles toward the + charge of the solute. This tendency is grossly exaggerated in the cartoon at the right. In reality, for any single water molecule there is only a slight average preference that is smaller than its normal thermal fluctuations, but because the electrostatic interaction is of long range ($\sim 1/r$) many solvent molecules are affected and add up to a significant effect.



Let's model this situation by replacing the explicit water molecules with a continuous polarizable medium, as in the shaded region at the left (which actually extends out to infinity). The macroscopic measure of polarizability is the bulk dielectric constant ϵ , here in particular the static value that is appropriate for an equilibrium situation. In vacuum $\epsilon = 1$, in nonpolar solvents $\epsilon \sim 2$, and for water $\epsilon \sim 78$.

In vacuum a point charge of magnitude Q would produce the electrostatic potential $\Phi^{vac}(\vec{r}) = Q/r$, which is just Coulomb's law. In the presence of dielectric we set $\Phi(\vec{r}) = \Phi^{vac}(\vec{r}) + \Phi^{rxn}(\vec{r})$. In present example, solving the equations of electrostatics leads to $\Phi^{rxn}(\vec{r}) = -(\epsilon - 1)Q/\epsilon R$ inside the cavity and $\Phi^{rxn}(\vec{r}) = -(\epsilon - 1)Q/\epsilon r$ outside the cavity, where R is the cavity radius. Thus, the potential is screened (weakened) by the presence of the dielectric. The solute-solvent interaction energy for a point charge is $E = Q\Phi^{rxn}(\vec{r} = 0)$. But note that it takes work to polarize the dielectric. Assuming a linear response of the dielectric to the charge distribution that polarizes it, it can be shown that this work costs exactly half of E . The free energy of solvation is then the remaining half of the interaction energy E , which is

$$\Delta G_{solv} = -\frac{1}{2} \left(\frac{\epsilon - 1}{\epsilon} \right) \frac{Q^2}{R} \quad (\text{Born, 1920}).$$

To summarize, the solute charge distribution polarizes the solvent, creating a nonzero electrostatic potential (the reaction potential, and a corresponding reaction field) in the solvent region with which it has a favorable energy of interaction. Half of this energy is expended as work to polarize the solvent, leaving half available as free energy.

II.b. Multipolar solute in a spherical cavity

Kirkwood (1934) showed that for a point dipole of magnitude μ in a spherical cavity

$$\Delta G_{solv} = -\frac{1}{2} \left(\frac{\epsilon - 1}{\epsilon + 1/2} \right) \frac{\mu^2}{R^3},$$

and that this contribution as well as the Born contribution are the first two terms in an expansion over all possible multipoles $M_{\ell m}$ such that

$$\Delta G_{solv} = -\frac{1}{2} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \left(\frac{\epsilon - 1}{\epsilon + \ell / (\ell + 1)} \right) \frac{|M_{\ell m}|^2}{R^{2\ell+1}}.$$

Onsager (1936) generalized the dipole term to include the effect of solute polarizability α . The solute dipole moment is then $\mu = \mu_0 + \alpha F$ where μ_0 is the permanent solute dipole moment as it exists in the gas phase and αF is the additional solute moment that is induced by the reaction field F evaluated at the location of the point dipole. The result is

$$\Delta G_{solv} = \left[-\frac{1}{2} \left(\frac{\epsilon - 1}{\epsilon + 1/2} \right) \frac{\mu_0^2}{R^3} \right] \left[1 - \left(\frac{\epsilon - 1}{\epsilon + 1/2} \right) \frac{\alpha}{R^3} \right]^{-1}.$$

(However, it is not usually seen in this form. Typically some additional approximation is made for α , such as setting it equal to the molecular volume). This introduces the notion of a self-consistent reaction field (SCRF). The solvent is first polarized by the solute permanent moment μ_0 , which polarizes the solvent producing an initial reaction field that then induces a larger moment in the solute, which in turn further polarizes the solvent. This feedback loop continues until a self-consistent mutual equilibrium is reached where no further polarization of either solute or solvent can occur.

II.c. Multipolar solute in an ellipsoidal cavity

Rinaldi and Rivail (1973 and later) generalized the Kirkwood expansion from the case of a spherical cavity to a general ellipsoidal cavity having three independent semi-axes. But real molecules rarely look much like perfect spheres or ellipses.

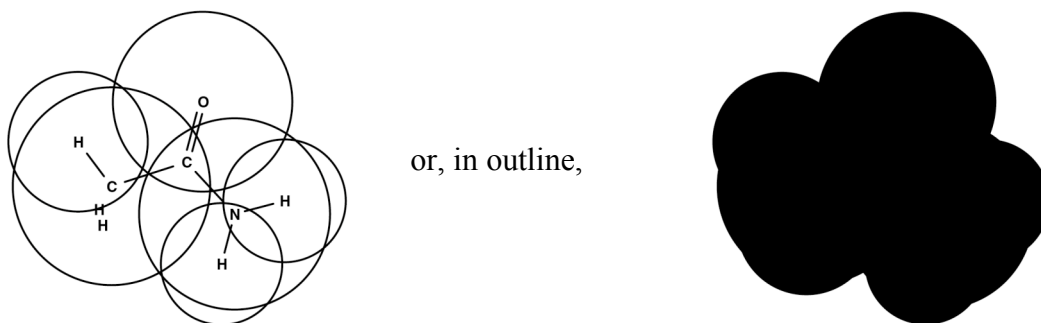
II.d. Multipolar solute in a general cavity

Several groups have treated a multipolar expansion of the solute electrostatic potential in a cavity of general shape. But the potentials of real charge distributions are not always represented well on the cavity by their multipole expansions. It is better to evaluate the actual electrostatic potential directly from the QM wavefunction.

III. Cavities

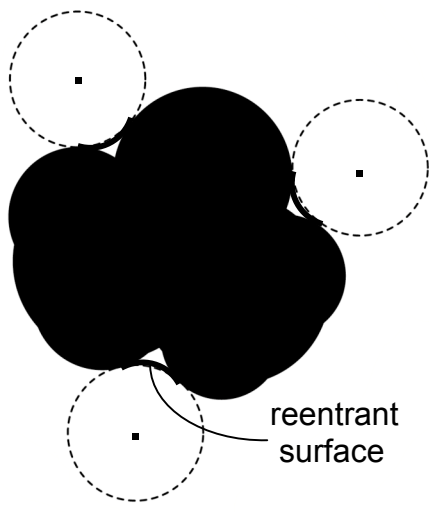
All implicit solvation models require some definition of the size and shape of a cavity that excludes solvent and into which the solute can be inserted. This aspect is widely underappreciated, and in fact the results of practical calculations can often depend more on the choice of cavity than on the choice of interaction energy models.

Many workers base the cavity on a union of atomic spheres, or some refinement of that idea. Spheres are drawn about the solute atoms and the cavity is their union. For example,



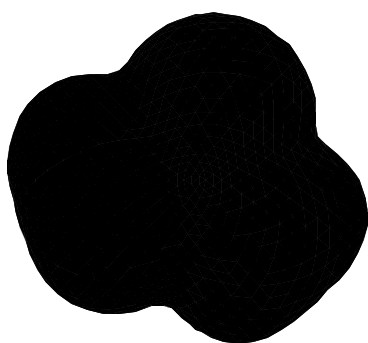
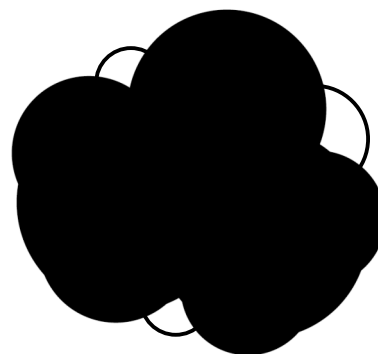
The radii of the atoms are parameters, often taken as the Bondi van der Waals radii increased by 20%. A problem with this is the sharp corners, where in principle electric fields become infinite which can lead to numerical problems in solving the requisite equations. Also, small crevices where atoms join are unphysical regions because real solvent molecules are too big to access there.

The solvent accessible surface (SAS) rolls a probe sphere (of radius about that of a solvent molecule) over the solute spheres, tracing out the surface defined by the center of the rolling probe. This removes the inaccessible crevices.



The solvent excluded surface (SES) traces out the inward facing part of the probe. The reentrant surfaces remove the inaccessible crevices and also smooth out the cavity.

The GePol construction found in the Gaussian program instead partially fills in the crevices with small additional spheres, by a somewhat arbitrary algorithm. The reason is that a certain correction term in the implementation requires that all spheres be concave. This can play havoc with geometry optimizations, because additional spheres can randomly appear or disappear as the geometry changes, leading to discontinuities in the energy gradient that guides the optimization. This problem is said to be fixed in G09.



An isodensity surface traces out a contour of constant solute electron density. It has the advantage of being automatically smooth, and the feature that the shape is determined naturally by the solute molecule. As the electronic structure changes, so does the surface in response. There is then only one parameter to be specified, which determines the overall size of the cavity. A typical value is $\rho_0 = -0.001 |e/a_0^3$ or thereabouts.

Some workers prefer the flexibility of having many parameters, namely the atomic radii, to work with. The radii may be adjusted until the dielectric continuum calculation gives good agreement with experiment for a training set of solute molecules. This effectively brings in all the untreated nonelectrostatic interactions through the back door, because they affect the values of the best fit parameters. Good predictions can then often be made for other similar solutes. But this procedure can fail badly for other dissimilar solutes, and models of this kind should be regarded with caution.

For example, the radii in the Gaussian program are fitted to a small set of experimental data on some neutral solute molecules. Poor results can then be expected for charged solutes (unless the charge is highly delocalized), and probably also for transition states, radicals, excited states, etc.

IV. Models for electrostatic solvation energy

IV.a. Generalized Born Approximation (GBA) (Still et al 1990 , and many others)

Recall that the Born result for a point charge in a spherical cavity is

$$\Delta G_{solv} = -\frac{1}{2} \left(\frac{\epsilon - 1}{\epsilon} \right) \frac{Q^2}{R} \quad .$$

In the GBA the electrostatic part of the potential is approximated as that due to point charges q_k located on each atom of the solute. There can be lots of cleverness in finding q_k values that give a reasonable representation of the true electrostatic potential of the solute molecule. By analogy to the Born result, it is then asserted that

$$\Delta G_{solv} = -\frac{1}{2} \left(\frac{\epsilon - 1}{\epsilon} \right) \sum_{k,k'}^{atoms} q_k q_{k'} \gamma_{kk'}$$

where $\gamma_{kk'}$ has dimensions of 1/distance and is given in detail by

$$\gamma_{kk'} = \left[r_{kk'}^2 + \alpha_k \alpha_{k'} e^{-r_{kk'}/4\alpha_k\alpha_{k'}} \right]^{-1/2}$$

Here α_k is the effective Born radius of atom k . Note that for diagonal elements ($k = k'$, whence $r_{kk'} = 0$) this becomes $\gamma_{kk'} = 1/\alpha_k$ which is just the Born result. The GBA thus generalizes the Born model for atoms interacting with their own reaction fields to also include atoms interacting with the reaction fields of all other atoms as well.

The main advantage of the GBA is that the result is analytic and so can be evaluated very rapidly. It is therefore very popular in the biochemical community, where the solutes are big molecules like proteins and the solvation evaluation represents a large portion of the overall computation time.

The main disadvantage is that the GBA is rather approximate and so may not give a very accurate answer. In particular, the influence of atoms buried deep inside the solute seems to be overemphasized.

In their series of SMx models, Cramer and Truhlar have made additional refinements to the expression for $\gamma_{kk'}$, with some resulting improvement in accuracy.

IV.b. Poisson's equation

In principle, Poisson's equation is the governing law of electrostatics, and its accurate solution gives the exact answer for the electrostatic problem that is defined by the (very approximate) dielectric continuum model. For the record, it has the form of a second order differential equation involving the solute charge density $\rho(\vec{r})$,

$$\frac{d^2\Phi(\vec{r})}{dx^2} + \frac{d^2\Phi(\vec{r})}{dy^2} + \frac{d^2\Phi(\vec{r})}{dz^2} = -4\pi\rho(\vec{r}) \quad \text{inside the cavity}$$

and, assuming that all the solute charge is contained inside,

$$\frac{d^2\Phi(\vec{r})}{dx^2} + \frac{d^2\Phi(\vec{r})}{dy^2} + \frac{d^2\Phi(\vec{r})}{dz^2} = 0 \quad \text{outside the cavity.}$$

This equation has many solutions, and the one of interest is picked out by specifying two boundary conditions. One is that the potential remains continuous when crossing the cavity surface, $\Phi(\vec{s}^{in}) = \Phi(\vec{s}^{out})$ for any point s on the surface (\vec{s}^{in} and \vec{s}^{out} being the same point on the inner and outer faces of the surface). The other is that the electric field that is defined in general by

$$\vec{F}(\vec{r}) = -\vec{i} \frac{d\Phi(\vec{r})}{dx} - \vec{j} \frac{d\Phi(\vec{r})}{dy} - \vec{k} \frac{d\Phi(\vec{r})}{dz}$$

takes a discontinuous jump when passing across the outward directed normal to the cavity surface, as given by $F_{normal}(\vec{s}^{in}) = \epsilon F_{normal}(\vec{s}^{out})$. Those proficient in math might want to derive the Born result given above for $\Phi(\vec{r})$ from these specifications.

But no analytic solution is available for the Poisson equation, except for some very simple model problems, and in general it must be solved approximately on a computer. Very efficient programs have been developed for this, so that for small solute molecules the solution requires only a small additional time beyond that required for the gas phase electronic structure calculation.

Finally, the electrostatic potential is resolved into $\Phi(\vec{r}) = \Phi^{vac}(\vec{r}) + \Phi^{rxn}(\vec{r})$ and the free energy of solvation is obtained from

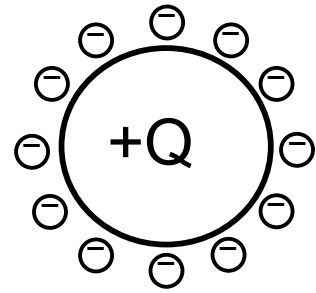
$$\Delta G^{solv} = \int_V \rho(\vec{r}) \Phi^{rxn}(\vec{r}) dV .$$

IV.c. Solution methods for Poisson's equation

One method of solution that is used mainly in the biochemical community (e. g., program DelPhi) is to solve the Poisson equation directly on a 3D grid of points, using finite differences between adjacent grid points to approximate the necessary derivatives.

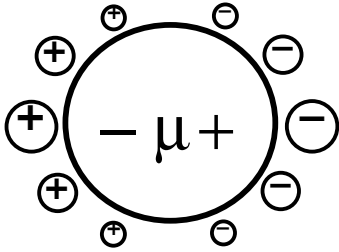
Another method of solution that is popular in the electronic structure community is to use a boundary element method (BEM), introduced by Tomasi et al (1981) and used since by many others. Here one does not solve directly for $\Phi^{rxn}(\vec{r})$ itself, but rather for a set of apparent surface charges (ASC) that produce the same electrostatic potential as does $\Phi^{rxn}(\vec{r})$.

For the example of a point charge in a spherical cavity, the ASCs would look like the panel at the right. Actually they would be a continuous infinitesimally thin distribution of charge spread over the cavity surface, but in practice we approximate that by a set of finite charges q_k located at grid points on the surface as in the picture (don't confuse these with the GBA atomic charges that were used above with the same notation). A continuous surface charge distribution given by



$$\sigma(\vec{R}) = -\left(\frac{\epsilon - 1}{\epsilon}\right) \frac{Q}{4\pi R^2}$$

would produce the previously given Born solvation energy.



For the example of a point dipole in a spherical cavity, the ASCs would look like the panel at the left. A continuous surface charge distribution given by

$$\sigma(\vec{R}) = -\left(\frac{\epsilon - 1}{\epsilon + 1/2}\right) \frac{3\mu \cos \theta}{4\pi R^3}$$

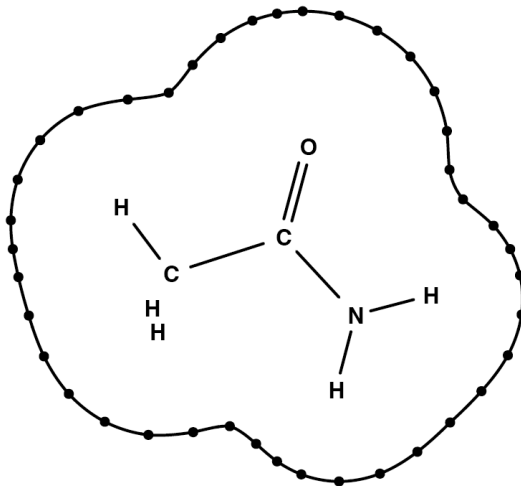
would produce the previously given Kirkwood dipole solvation energy. Note that the magnitudes of the charges here vary as $\cos \theta$ across the surface, with θ being the angle from the dipole axis.

For a general multipolar solute in a spherical cavity the surface charge distribution that produces the relevant $\Phi^{rxn}(\vec{r})$ is

$$\sigma(\vec{R}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \left(\frac{\epsilon_{st} - 1}{\epsilon_{st} + \ell / (\ell + 1)} \right) \frac{(2\ell + 1) M_{\ell m} P_{\ell}(\cos \theta) \sin(m\phi)}{4\pi R^{\ell+2}} .$$

IV.d. Surface polarization for a general cavity

For a general solute with its charge density contained in an appropriate molecular shaped cavity one defines a grid of points on the cavity surface, as for example in this picture.



Poisson's equation then implies that the surface charge distribution that generates a potential equivalent to that of $\Phi^{ext}(\vec{r})$ is given by

$$\sigma(\vec{s}) - \frac{(\epsilon - 1)}{(\epsilon + 1)} \frac{1}{2\pi} F_n^\sigma(\vec{s}) = \frac{(\epsilon - 1)}{(\epsilon + 1)} \frac{1}{2\pi} F_n^p(\vec{s})$$

where $F_n^p(\vec{s})$ is the normal electric field at the surface that would be produced by the solute in vacuum and $F_n^\sigma(\vec{s})$ is that produced by entire surface charge distribution. The presence of the latter implies that the value of $\sigma(\vec{s})$ at one surface point is coupled to its values at all other surface points. The consequence is that when this equation is projected onto a set of N grid points one must solve a matrix equation of the form $\underline{\underline{A}}\underline{\underline{q}} = \underline{\underline{b}}$ for the ASCs q_k . The dimension of the matrix $\underline{\underline{A}}$ is N by N , and this step is usually the most time consuming on the computer.

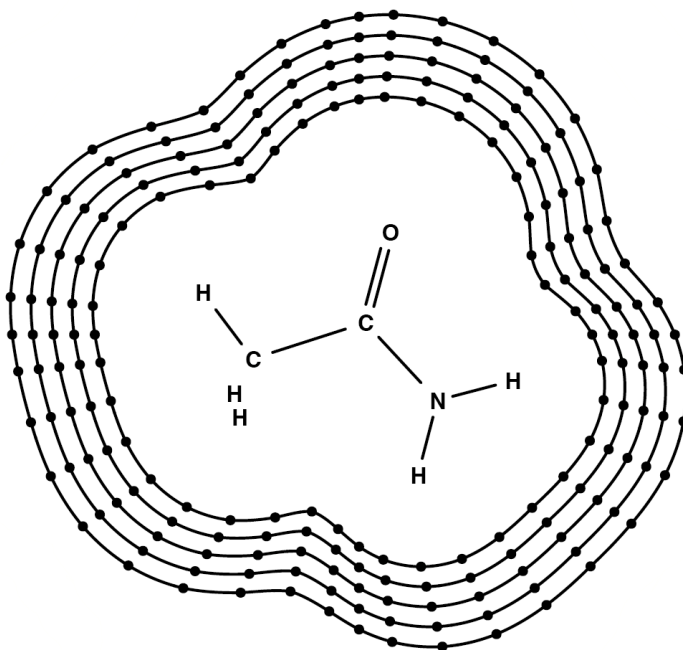
One can show from Gauss's Law that the total ASC, $\bar{\sigma} \equiv \int_{\Gamma} \sigma(\vec{s}) d^2\vec{s} \approx \sum_{k=1}^N q_k$, should be related to the net solute charge Q (e.g., 0 for a neutral, +1 for a cation, etc.) by $\bar{\sigma} = -(\epsilon - 1)Q / \epsilon$. But in practice, calculations have indicated that this relation is rarely satisfied very well. This led to considerable confusion in the older literature. A number of different proposals were made of various ways to "renormalize" $\sigma(\vec{s})$ after the fact in order to force satisfaction of this equation. The infamous IComp option in previous versions of Gaussian allowed for several of these to be used. But sometimes these made things worse instead of better. Next we discuss the proper resolution of this matter.

IV.e. Volume polarization for a general cavity (Chipman et al, 1997)

The reason for the discrepancy found from Gauss's Law can be seen from the original formulation. Any unconstrained QM calculation of the solute charge density inevitably produces a tail that extends beyond the cavity surface. For the sizes of cavities normally used in practice this typically amounts to a few tenths of an electron or more living outside the cavity. The proper formulation of Poisson's equation in that situation is as before for points inside the cavity, but should be replaced by

$$\frac{d^2\Phi(\vec{r})}{dx^2} + \frac{d^2\Phi(\vec{r})}{dy^2} + \frac{d^2\Phi(\vec{r})}{dz^2} = -\frac{4\pi\rho(\vec{r})}{\epsilon} \quad \text{outside the cavity.}$$

(Before the RHS was set to zero). This means that the reaction potential must include not only a surface polarization, as discussed above, but also a volume polarization outside the cavity. For this we need to introduce apparent volume charges at points outside the cavity, as in this picture. The volume charges b_k are most conveniently located



at grid points on concentric layers outside the surface charges q_k . The layers must extend over the region where the solute charge density remains nonnegligible, typically about 0.5–1 Å beyond the cavity surface. The total polarization charge, surface and volume both, satisfies $\bar{\sigma} + \bar{\beta} = -(\epsilon - 1)Q / \epsilon$, thus resolving the Gauss's Law paradox.

In practice, inclusion of volume polarization doesn't change the solvation energies of neutral solutes very much, but it can have a considerable effect on spectroscopic properties of neutrals and on the solvation energies of ions. It also makes results somewhat less sensitive to the choice of basis set.

Several models have been developed that explicitly include only surface polarization, but with the surface charges modified to approximate the influence of volume polarization.

IV.f. Guide to the available methods

SMx (Solvation Model x, with x being a version number; currently x=8)

Cramer, Truhlar et al

uses GBA

module added on to many programs

COSMO (conductor screening model; has an approximation to vol pol)

Klamt et al

uses BEM

ADF; MolPro; NWChem; DMol; etc.

D-PCM (dielectric polarized continuum model, originally just PCM; neglects vol pol)

IEF-PCM (integral equation formalism PCM; has an approximation to vol pol)

C-PCM (conductor PCM; has an approximation to vol pol)

Tomasi et al

uses BEM

Gaussian; Gamess

SVPE (surface and volume polarization for electrostatics; exact treatment of vol pol)

SS(V)PE (surface and simulation of volume polarization for electrostatics)

Chipman et al

uses BEM

Gamess (both SVPE and SS(V)PE); QChem (SS(V)PE only)

In high dielectric solvents with not too much charge penetration, COSMO, IEF-PCM, C-PCM, SS(V)PE, and SVPE all give nearly the same results, provided that the cavity is constructed the same way in each. In low dielectric solvents COSMO and C-PCM perform less well than the others. In some cases of high charge penetration (e. g. for the final state in a vertical electronic excitation) the more exact SVPE is necessary. If there is any significant charge penetration, and there usually is, then D-PCM performs less well than the others.

With the PCM implementations in Gaussian and Gamess, the default cavity is the GePol construction. This is based on a union of atomic spheres and requires that the radii of all solute atoms be specified. The default radii are parameterized to reproduce experimental results for a few small neutrals, and may lead to poor results for other things, especially ions. In Gaussian there is also an isodensity surface implementation available with the IPCM (isodensity PCM) and SCIPCM (self-consistent IPCM) keywords, but these use the obsolete D-PCM method for electrostatics that entirely neglects volume polarization effects and so are not recommended for general use.

The SVPE and SS(V)PE implementations in Gamess and QChem use an isodensity surface and treat volume polarization, but do not (yet) have any terms representing nonelectrostatic contributions. We are currently working on that.

IV.g. SCRF considerations

All of the above methods can, and in most implementations do, include the apparent charges in the solute Hamiltonian, which just requires additional one-electron integrals to be evaluated. The solute wave function then becomes perturbed by its own reaction field, causing a change in the solute internal energy from its gas phase value. This extra contribution to the solvation energy is given by

$$\Delta G_{\text{int}} = \langle \Psi^{\text{solv}} | H_{\text{int}} | \Psi^{\text{solv}} \rangle - \langle \Psi^{\text{gas}} | H_{\text{int}} | \Psi^{\text{gas}} \rangle .$$

Also, it should be noted that the effective energy obtained as the eigenvalue from solving a Schrodinger equation that includes the apparent charges is not directly related to the solvation free energy, because of the factor of 1/2 in the latter that accounts for the work of polarizing the solvent.

IV.h. Poisson-Boltzmann equation

Ionic strength effects due to having dissolved salt in the solvent can also be treated with dielectric continuum theory. The distribution of ionic charge becomes polarized by its interaction with the solute according to a Boltzmann distribution. The Poisson equation of the salt-free situation is then replaced by the more complicated Poisson-Boltzmann equation, or more frequently by an approximation known as the linearized Poisson-Boltzmann equation. These equations can also be solved by means of either finite element or boundary element methods. It is not uncommon to see a calculation described as done with the Poisson-Boltzmann equation even in the special case of no salt, which strictly speaking corresponds to the Poisson equation.

V. Nonelectrostatic contributions to the solvation energy

The simplest idea here is to assume that cavitation, exchange repulsion, dispersion attraction and any other nonelectrostatic interactions that might be imagined can all be treated together by assuming that their net contribution is about the same as that of a nonpolar solute (e. g., a hydrocarbon) having about the same size and shape as the solute of interest. Experimental data on hydrocarbons indicate that their solvation energies are approximately proportional to their surface areas, $\Delta G^{\text{nonel}} = \sigma A$, where A is the cavity surface area and σ , called a surface tension because of its dimensions, is an empirical constant, typically about 7 cal/mol Å².

As a refinement, many workers use $\Delta G^{\text{nonel}} = \sum_i \sigma_i A_i$, where A_i is the exposed surface area of atom i (or sometimes of functional group i) and σ_i is an empirical parameter adjusted for each atom type. In the SMx models, the σ_i are related to various measurable properties of the solvent, e. g. macroscopic surface tension, index of refraction, H-bonding acidity and basicity, etc., leading to a huge number of parameters to be adjusted. Hundreds of solutes are included in their fitting, some being ions, and as result the SMx

models are generally able to reproduce solvation energies of most ground state solutes at their equilibrium geometries quite well.

The PCM models use more detailed physical models having some theoretical justification behind them to separately estimate the various contributions from cavitation, exchange repulsion, and dispersion attraction. However, the parameters are fitted to only a small set of neutral solutes, so poor results can be expected for ions, excited states, etc.

All of the approaches to nonelectrostatic contributions that are discussed here are limited in that they only correct the free energy, and do not perturb the solute wavefunction and hence do not alter any other properties of the solute.

VI. Nonequilibrium solvation

All the above discussion pertains just to equilibrium solvation. For time-dependent processes like electron transfer and vertical electronic excitation a generalization is necessary. Typically the problem is split into two parts. First the initial state is fully equilibrated to its own reaction field using the static dielectric constant ϵ_{st} . This is taken to be the situation just prior to the event. Then a sudden change happens to produce a final state, which is equilibrated to two reaction fields. One is its own reaction field obtained by calculation using the optical dielectric constant ϵ_{op} , often taken as the square of the solvent refractive index, which describes that part of the dielectric response due to electronic motions in the solvent that are fast enough to follow the sudden change. The other is that part of the initial reaction field that is too slow to follow the sudden change, which corresponds mostly to orientational motions of the solvent.

VII. Exercise

Do a calculation with Gaussian on your favorite molecule, turning on the keyword SCRF=IEFPCM. By default, this will do an IEF-PCM calculation in a GePol cavity with certain specified atomic radii and with a static dielectric constant of 78.3553, corresponding to that of bulk water. This result gives the contribution from the entire dielectric response of water.

Then do the same calculation again but with a dielectric constant set to that for the nonpolar solvent xenon. This may be done by using the keyword SCRF=(IEFPCM,Read) and also including after your geometry input a blank line, followed by a line with eps=1.706, and another blank line. The xenon dielectric constant is close to that of the fast electronic response of water, as measured by its optical dielectric constant (1.776).

The difference between these results is then a reasonable measure of the contribution from the slow orientational response of water.

VIII. Suggested further reading

- J. Tomasi and M. Persico, *"Molecular Interactions in Solution: An Overview of Methods Based on Continuous Distributions of the Solvent,"* Chem. Rev. **94**, 2027 (1994).
- C. J. Cramer and D. G. Truhlar, *"Implicit Solvation Models: Equilibria, Structure, Spectra, and Dynamics,"* Chem. Rev. **99**, 2161 (1999).
- C. J. Cramer, *Essentials of Computational Chemistry – Theories and Models*, 2nd Ed., (Wiley, New York, 2004), Chapter 11.
- J. Tomasi, B. Mennucci, and R. Cammi, *"Quantum Mechanical Continuum Solvation Models,"* Chem. Rev. **105**, 2999 (2005).