

# **Finding the arbitrary parameter $L$ in Renormalization Group Theory**

VIA fitting Monte Carlo simulations to Statistical  
Associating Fluid Theory

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# **Exploring Phase Equilibrium with Statistical non-Associating Fluid Theory:**

A Generalized Renormalization Group Theory Approach.

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## **Abstract**

Abstract goes hereeee!

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# Chapter 1

## Introduction

### 1.1 Introduction

Outline: Introduction to liquid vapor coexistence Demonstrate the problem Fix the problem what I did

The liquid-vapor phase coexistence can be found by just placing some liquid into a sealed container. Some of the liquid will evaporate into the jar creating a vapor pressure. Provided we placed enough liquid into the jar, the system will now contain both a liquid and a vapor at the same time. By sealing the liquid into a jar, we have forced the pressure of the liquid to be the as the pressure of the gas. By allowing the atoms to swap between the liquid and gas phase, we have also allowed the chemical potential of the liquid to be the same as that of the gas.

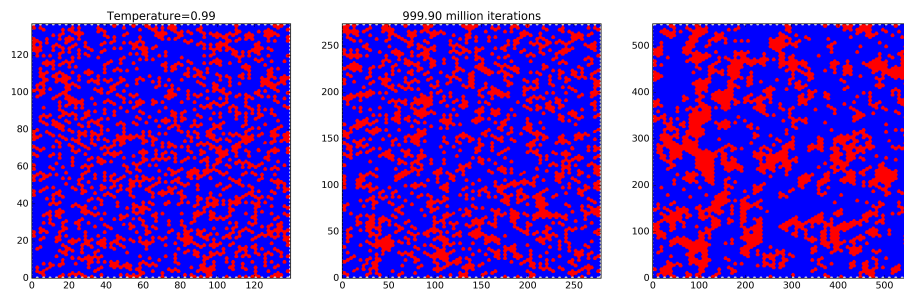
Although we can find the phase coexistence by physically sealing a liquid in a jar, an equivalent computational method is to use an empirically determined fluid model which we can use to run simulations that also equalize the pressure and chemical potential. The problem with the computational method is the empirical model requires fitting a few parameters to data, data which probably already includes points on the phase coexistence curve. The main benefit to the computational approach is that once the empirical parameters are found, we can then create the phase coexistence of a mixture of fluids using the previously determined parameters.

One of the difficulties with the computer simulations is computation time. A simulation with a handful of atoms can be finished within 20 minutes, yet a simulation with a 100 atoms can take as long as 4 days. To recreate the phase coexistence graph requires setting the pressure and chemical potential of both phases equal to each other, but this is equivalent to plotting the free energy as a function of density and searching for a common cotangent. For even a simulation that uses a small box, the problem is plotting free energy as a function of density requires many simulations at various densities; some simulations containing only a handful of atoms while other simulations containing as much as a couple hundred atoms. Total computation time for 10 computer cores to create the free energy as a function of density graph can take as long as three weeks.

Naturally there is a tradeoff between a realistic computation time for a project and how realistic the results are going to be. The simulations use periodic boundary conditions which is just the thermodynamic way of saying the boundary should not affect the bulk properties. The key part being whatever is in the simulation is considered the bulk, which is a problem since a small simulation can hardly be

considered the bulk. To get around this problem, the simulation size is usually increased until the simulation does represent the bulk.

Normally increasing the simulation size is just fine, but there is a regime where the bulk properties depend on length scales of the order of a millimeter. This regime occurs near the critical point where the liquid density approaches that of the vapor. Normally the liquid and vapor are entirely separated due to the surface tension. However; as the system approaches the critical point, the surface tension approaches zero which means the liquid and vapor will start to mix. Although figure 1 shows an extreme example of a liquid completely mixing with vapor, even under normal circumstances there exist natural fluctuations in the density of either phase. It just so happens that these fluctuations are significant as the density of the liquid approaches the density of the gas at the critical point. Basically the fluctuations within each phase would normally be rather small, but near the critical point the fluctuations are relatively big since the gas and liquid phases are morphing into each other. This is a problem since it requires the simulations to be about the same size as that of the largest fluctuation. For example, a 1mm length box would contain roughly  $10^{19}$  atoms, which would require an unfeasible computation time.



Renormalization group theory(RGT) can be applied to get around this large fluctuation problem. Simply put, RGT is a method in which fine details are omitted from calculations while still maintaining accuracy. This is done by transforming the original partition function into a smaller partition function, but the smaller system is renormalized to the original partition function. [add details...]

In particular, RGT is applied through an interaction wave length. The zeroth order is just the ideal gas term in which all atoms only interact with the walls of the enclosure. The next order is applied via SAFT-VR in which a mean interaction and an approximate wavelength interaction is applied. Longer wavelength interactions can then be applied using RGT via a iterative method that steadily increases the size of the box.

The main problem this project addresses is the transition from SAFT-VR to the application of RGT. Within RGT there is an arbitrary base wavelength  $L$  which is usually fit to the data. However; this arbitrary wavelength shouldn't really be an arbitrary parameter as SAFT-VR already includes interactions at some unknown wavelength. This project attempts to find the base wavelength that SAFT-VR implements, and tests how the results of RGT change when using this base wavelength.

The base wavelength is found by using Monte Carlo Markov Chain (MCMC) simulations at various box sizes. The idea is that a MCMC simulation using a fixed box size of  $L_0$  will incorporate interactions at this box size. The box size is then varied until the results from the MCMC simulations fit the results from SAFT-VR.

Once the optimal box size is found, RGT is implemented using this optimal box size and the results are compared to previous results.

Test of fancyhdr page.



# Chapter 2

## Methods

Outline: SAFT

liquid-vapor+run-absolute

How comparisons were made

### 2.1 Partition function separation

The Monte Carlo simulations can be partitioned into high and low temperature regimes. At low temperature the interactions dominate, while at high temperatures the entropy dominates. Both regimes can be partitioned yet again by separating the kinetic energies into an ideal gas term. In terms of equations, we start with the partition function and separate the summation into the three partitions:

$$Z = \frac{1}{N!} \sum_i e^{-\beta \cdot E_i} Z = \frac{1}{N!} \int \dots \int e^{-\beta \cdot [\{P_1^2/2m + P_2^2/2m + \dots\} + V(\vec{R}_1, \vec{R}_2, \dots)]} d\vec{P}_1 \cdot d\vec{P}_2 \dots d\vec{P}_N \cdot d\vec{R}_1 \cdot d\vec{R}_2 \dots d\vec{R}_N$$

The momentum integrals are independent of the position integrals, so we separate the momentum integrals which we then incorporate into an ideal gas term by multiplying by  $V^N/V^N$ .

$$Z = Z_{ideal} \cdot \frac{1}{V^N} \cdot \int \dots \int e^{-\beta \cdot V(\vec{R}_1, \vec{R}_2, \dots)} d\vec{R}_1 \cdot d\vec{R}_2 \dots d\vec{R}_N$$

where

$$Z_{ideal} = V^N \cdot \frac{1}{N!} \int \dots \int e^{-\beta \cdot [P_1^2/2m + P_2^2/2m + \dots]} d\vec{P}_1 \cdot d\vec{P}_2 \dots d\vec{P}_N$$

The remaining potential energy term is separated into the low temperature and high temperature regime. At high temperatures, the atom energies are much higher than the potential well; this means the finite potential well can be considered zero. However; even at infinite temperature the atoms are assumed to be a hard sphere. This hard sphere behavior is incorporated into the partition function by multiplying by  $Z_{HS}/Z_{HS}$ .

$$Z = Z_{ideal} \cdot Z_{HS} \cdot \frac{1}{Z_{HS}} \cdot \frac{1}{V^N} \cdot \int \dots \int e^{-\beta \cdot V(\vec{R}_1, \vec{R}_2, \dots)} d\vec{R}_1 \cdot d\vec{R}_2 \dots d\vec{R}_N$$

where  $Z_{HS} = \frac{1}{V^N} \int \dots \int e^{-\beta \cdot V_{HS}(\vec{R}_1, \vec{R}_2, \dots)} d\vec{R}_1 \cdot d\vec{R}_2 \dots d\vec{R}_N$

The last part is just the ratio between the interaction and the hard sphere partition function; we call this the dispersive term.

$$Z = Z_{ideal} \cdot Z_{HS} \cdot \frac{Z_{interaction}}{Z_{HS}} = Z_{ideal} \cdot Z_{HS} \cdot Z_{disp}$$

where  $Z_{interaction} = \frac{1}{V^N} \cdot \int \dots \int e^{-\beta \cdot V(\vec{R}_1, \vec{R}_2, \dots)} d\vec{R}_1 \cdot d\vec{R}_2 \dots d\vec{R}_N$   
 and  $Z_{disp} = \frac{Z_{interaction}}{Z_{HS}}$

## 2.2 Free Energy via Monte Carlo Simulations

Given the separated partition function, the free energies are just the sum of the free energies due to the ideal term, the hard sphere term, and the dispersive term. The ideal term is ignored because it stays the same between theory and the Monte Carlo simulations. Due to the finite nature of the Monte Carlo simulations, the hard sphere term in the simulations aren't exactly the hard sphere terms in theory. Although we can make some corrections due to the finite nature, ultimately we have to enforce the boundary condition that at high temperature the atoms behave like hard spheres. Given this boundary condition, we are then able to define what the dispersion term should be based on estimation of the density of states.

### 2.2.1 ideal gas free energy

To find the ideal gas free energy we can use previous results based on knowing the entropy of the system which we can then use to find  $F_{ideal} = U_{ideal} - T \cdot S_{ideal}$ .

$$U_{ideal} = 3/2 \cdot N \cdot k \cdot T$$

$$S_{ideal*} \approx k \cdot N \left( \ln \left[ \frac{V}{N} \left( \frac{4 \cdot \pi \cdot m}{3 \cdot h^2} \cdot \frac{U}{N} \right)^{3/2} \right] + \frac{5}{2} \right)$$

The Sackur-Tetrode equation with the Stirling approximation actually does not make physical sense as the entropy per particle at constant temperature only depends on density. A simple example can show why this doesn't make sense. Consider two atoms in boxes separated by a partition, and compare the entropy per particle to when the partition in the box has been removed. Once the partition has been removed, the two atoms can explore many more configurations than previously, which means the entropy should have increased once the two atoms were allowed to mix. Unfortunately the Sackur-Tetrode equation with Stirlings approximation would predict the entropy per particle with or without the partition should be the same. This is a bit of a problem since every box in a Monte Carlo simulation will contain exactly N particles, which means the entropy is actually lower than a real ideal gas.

The entropy problem can be fixed by using the Sackur-Tetrode equation without Stirling's approximation. Essentially use a constant density and compare the entropy per particle of a small box to the entropy per particle of a large box. The difference in entropy shows how the ideal gas entropy within a box will deviate from the expected ideal gas entropy.

$$S_{ideal} = k \cdot N \left( \ln \left[ V \cdot N!^{-1/N} \left( \frac{4 \cdot \pi \cdot m}{3 \cdot h^2} \cdot \frac{U}{N} \right)^{3/2} \right] + \frac{3}{2} \right)$$

It would be natural to think we can just incorporate this deviation in entropy for the Monte Carlo simulations, unfortunately the simulations contain an intractable problem involving the periodic nature of the simulations. The atoms in the box are repeated in a periodic way to represent the atoms in the entire fluid, however by forcing a periodic boundary condition the entire state of a fluid is now defined by only the atoms within the small box. It is very unlikely that 100 atoms can fully define a system containing an Advogadro's number of atoms, so the entropy should be much less than a realistic system. Rather than incorporate such a change in entropy, we instead must recognize that these Monte Carlo simulations are defining the boundary conditions relative to the smaller sub system; this is basically the equivalent of mean field theory where the boundary is defined by the smaller sub system.

Recognizing that Monte Carlo simulations are a variation of mean field theory, the loss in entropy due to reduced configurations is ignored. Instead the boundary conditions are enforced. At any temperature we expect the kinetic energies to behave like an ideal gas. At high temperatures we expect the system to behave like a hard sphere system.

### 2.2.2 hard sphere free energy

The hard sphere partition function can be found by calculating the excess entropy at  $T \rightarrow \infty$ . This can be seen as follows:

$$\begin{aligned}
 Z_{exc} &= Z_{HS} \cdot Z_{disp} \Rightarrow \\
 F_{exc} &= -k \cdot T \cdot \ln(Z_{exc}) = -k \cdot T \cdot \ln(Z_{HS}) - k \cdot T \cdot \ln(Z_{disp}) \Rightarrow \\
 S_{exc.\infty} &= \lim_{T \rightarrow \infty} - \left( \frac{\partial F_{exc}}{\partial T} \right)_{V,N} \quad \text{but} \quad \lim_{T \rightarrow \infty} Z_{exc} = \text{constant} \Rightarrow \\
 S_{exc.\infty} &= -k \cdot \ln(Z_{HS.\infty}) - k \cdot \ln(Z_{disp.\infty}) \\
 \text{but } Z_{HS} &\text{ is constant and } Z_{disp.\infty} = Z_{interaction.\infty} / Z_{HS} = Z_{HS} / Z_{HS} = 1 \Rightarrow \\
 S_{exc.\infty} &= -k \cdot \ln(Z_{HS}) - k \cdot \ln(1) = -k \cdot \ln(Z_{HS}) \Rightarrow \\
 Z_{HS} &= e^{-S_{exc.\infty}/k}
 \end{aligned}$$

To find the hard sphere partition function, we need to find the maximum excess entropy as  $T \rightarrow \infty$ . The method used to find the maximum excess entropy starts by considering N atoms in an extremely large box. The hard sphere component in

### 2.2.3 dispersive free energy

The dispersive term is found by estimating the density of states using a \* method. The main problem is the density of states is found by sampling the energy levels, but the relative distribution of energy levels is not unique to a single density of states. In other words, the partition function can be changed by an arbitrary factor without actually changing the total energy. This can be seen as follows:

Suppose

$$Z = \sum_i D(E_i) \cdot e^{-\beta \cdot E_i}$$

then

$$U = \sum_i E_i \cdot D(E_i) \cdot e^{-\beta \cdot E_i} / Z$$

Now suppose we let

$$D_2(E_i) = \alpha \cdot D(E_i)$$

then

$$Z_2 = \sum_i \alpha \cdot D(E_i) \cdot e^{-\beta \cdot E_i} = \alpha \cdot Z \Rightarrow$$

$$U_2 = \sum_i E_i \cdot D_2(E_i) \cdot e^{-\beta \cdot E_i} / Z_2$$

$$U_2 = \sum_i E_i \cdot \alpha \cdot D(E_i) \cdot e^{-\beta \cdot E_i} / (\alpha \cdot Z)$$

$$U_2 = \sum_i E_i \cdot D(E_i) \cdot e^{-\beta \cdot E_i} / Z$$

$$U_2 = U$$

Basically the partition function will define the total energy at all temperatures, but knowing the total energy at all temperatures will not define a unique partition function. Specifically, the partition function up to some arbitrary factor will give the same total energy. This is a bit problematic considering the method to find the density of states makes observations of the total energy to estimate the density of states, which then results in a density of states that is only defined up to some unknown factor.

To get around this problem of an unknown factor in the density of states, note that the dispersive partition function will go towards one as T approaches infinity. This happens because  $Z_{disp}$  is the ratio of the interaction term to the hard sphere term, and the interaction term approaches the hard sphere term as the temperature increases. Essentially we can leave the unknown  $\alpha$  term alone, and it will show up in both the interaction and hard sphere partition function.

That is:

$$Z_{disp} = \frac{Z_{interaction}}{Z_{HS}} = \frac{\sum_i \alpha \cdot D(E_i) \cdot e^{-\beta \cdot E_i}}{\lim_{T \rightarrow \infty} \sum_i \alpha \cdot D(E_i) \cdot e^{-\beta \cdot E_i}} = \frac{\sum_i D(E_i) \cdot e^{-\beta \cdot E_i}}{\sum_i D(E_i)}$$

## 2.3 SAFT

SW.fid+SW.fdisp+SW.fhs Explain.

### 2.3.1 $S_{exc.\infty}$

# Chapter 3

## GRG Theory

### 3.1 GRG Theory

Some more splaining.

And also a citation example [1].

And this one too [2]

# Chapter 4

## Data

### 4.1 Computation

Provide computation methods and data of what I have done so far.  
This is how you can refer to fig 4.1.

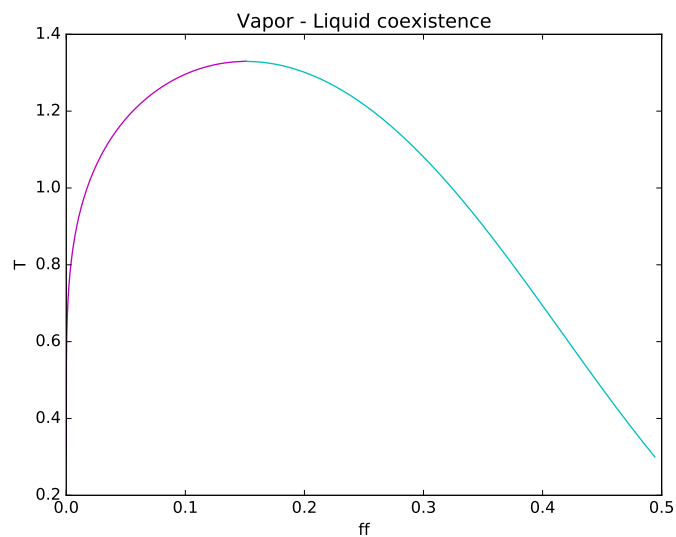
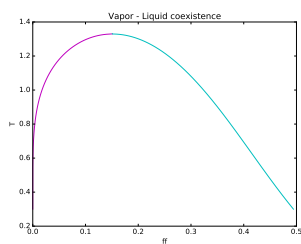
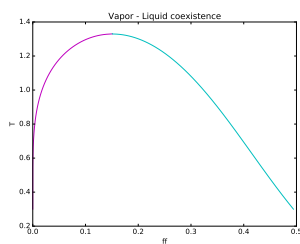


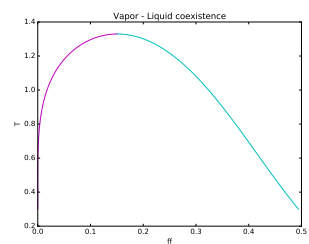
Figure 4.1: Caption for this image.



(a) Caption 01



(b) Caption 02



(c) Caption 03

Figure 4.2: Caption for all three.

# Chapter 5

## Conclusion

### 5.1 Conclusion

ta-da!