Physics 217: The Renormalization Group
Fall 2018

Lecturer: McGreevy
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0.1 Introductory comments

The ‘renormalization group’ (RG) is a poor name for the central concept in many-body physics. It is a framework for addressing the question: what is the relationship between microscopic laws and macroscopic observations?

Or, closer to home, it allows us to answer questions such as: Why don’t you need to understand nuclear physics to make your tea in the morning?¹

Briefly, the RG is the realization that systems of many degrees of freedom (especially when they have local interactions) should be understood hierarchically, i.e. scale by scale.

There is a lot more to say to contextualize the RG, which, as you can see from the previous question, is really a piece of metaphysics, that is, it is a framework for how to do physics. But since it is such a broad and far-reaching concept, in order to avoid being vague and useless, it will be better to start with some concrete and simple ideas, before discussing of some of its many consequences.

---

A word about prerequisites: The official prerequisite for this course is graduate statistical mechanics. I think you would be able to get by with a good undergrad class.

The historical origins of the RG (at least its name) are tied up with high-energy particle physics and quantum field theory. That stuff involves quantum mechanics in a serious way. Much of the content of this course can be understood without quantum mechanics; the fluctuations could all be thermal. At various points along the way I will point out the connections with quantum field theory.

So this is mostly a course in statistical field theory (≡ statistical mechanics of many degrees of freedom). But there are many other applications of the RG which don’t quite fit in this category which I also hope to discuss.

Also, I think our discussion will all be non-relativistic, \( v \ll c \).

---

Initial Tentative Plan:

1. Scaling and self-similarity
2. RG treatment of random walks
3. Ising models
4. Critical phenomena (a great victory of the RG). \( 4 - \epsilon \) expansions

¹This framing of the question I heard from Savas Dimopoulos.
5. RG treatment of iterative maps and the period-doubling approach to chaos

6. RG treatment of percolation and lattice animals

7. RG understanding of the method of matched asymptotic expansions

8. RG treatment of stochastic PDEs

As the title indicates, this is a very rough guess for what we’ll do. An early target will be a renormalization-group understanding of the central limit theorem.

Sources for these notes (anticipated):


Lectures on Phase Transitions and the Renormalization Group, by Nigel Goldenfeld.


Introduction to Statistical Field Theory, by Eduard Brézin.

Renormalization Group Methods, a guide for beginners, by W. D. McComb.

Scaling and Renormalization in Statistical Physics, by John Cardy.


Statistical Field Theory, by David Tong.
0.2 Conventions

The convention that repeated indices are summed is always in effect unless otherwise indicated.

A useful generalization of the shorthand $\hbar \equiv \frac{h}{2\pi}$ is

$$d\bar{k} \equiv \frac{dk}{2\pi}.$$  

I will also write $\delta(q) \equiv (2\pi)^d \delta^d(q)$.

I will try to be consistent about writing fourier transforms as

$$\int \frac{d^d k}{(2\pi)^d} e^{ikx}\tilde{f}(k) \equiv \int d^d k \ e^{ikx}\tilde{f}(k) \equiv f(x).$$

RHS $\equiv$ right-hand side.
LHS $\equiv$ left-hand side.
BHS $\equiv$ both-hand side.
IBP $\equiv$ integration by parts.
$+\mathcal{O}(x^n) \equiv$ plus terms which go like $x^n$ (and higher powers) when $x$ is small.
I write log for base two and ln for base $e$.

I reserve the right to add to this page as the notes evolve.

Please send me email if you find typos or errors or violations of the rules above.
1 Scaling and self-similarity

[This discussion largely follows the early chapters of the book by Creswick et al.] First some somewhat-vague definitions to get us started. An object is self-similar if its parts, when magnified by a suitable scale factor $\lambda$, look like the whole. (Here is an example.) Something is scale-invariant if this is true for every $\lambda$. (Self-similarity is sometimes called ‘discrete scale invariance’. ) An important generalization is the notion of statistical self-similarity – something which is sampled from a distribution which is self-similar.

The point in life of the renormalization group is to provide a way of thinking about (and ideally relating quantitatively) what’s going on at different scales of magnification. So something which is self-similar or scale-invariant is a simple special case for the RG.

As we’ll see, a symptom of scale invariance is a power law.

1.1 Fractal dimension

The word ‘dimension’ is used in many ways in this business. Let’s consider a set of points in $d$-dimensional Euclidean space, $\mathbb{R}^d$. In the previous sentence ‘dimension’ is the minimum number of coordinates needed to specify the location of a point (this is usually called ‘Euclidean dimension’). It’s an integer.

A subset of $\mathbb{R}^d$ specified by some algebraic equations on the coordinates (we can call this an algebraic set) generically has a Euclidean dimension which is an integer (though it may not be the same integer for every point). That is, locally around almost every solution of the equations, the object will look like a piece of $\mathbb{R}^{d_T}$ for some $d_T \leq d$ (sometimes this notion is called ‘topological dimension’).

Here is a different, RG-inflected definition of the dimension of an object $O \subset \mathbb{R}^d$, called fractal dimension or Hausdorff dimension: cover the object $O$ with $d$-balls of diameter $a$,

$$B_{r_0}(a) \equiv \{ \vec{r} \in \mathbb{R}^d \text{ such that } |\vec{r} - \vec{r}_0| \leq a/2 \}.$$  

(1.1)

Let

$$N(a) \equiv \text{the minimum number of such balls required to cover } O,$$

minimizing over the locations of their centers. Do this for various values of $a$. Then, if this function is a power law,

$$N(a) \sim a^{-D}$$  

(1.2)
then $D$ is the fractal dimension of $O$. Even if $N(a)$ is not a power law, we can define $D \equiv -\log_a N(a)$.

A few observations:

- Notice that $D$ may itself depend on the range of ball-sizes $a$ we consider, that is, the same scaling relation may not hold for all $a$. Often (always) there is a short-distance ("UV") cutoff on the regime where the scaling relation (1.2) holds – if our object is the coastline of France, it is maybe not so useful to consider femtometer-sized balls. Also, there is often a long-distance ("IR") cutoff – in the same example, Earth-sized balls will not give an interesting power law (it just gives $N(r_\oplus) = 1$).

For objects defined by algebraic equations, $D = d_T$. For example, in the example at right, the required number of balls of size $a$ goes like $1/a$.

- $O$ is a set of points in $\mathbb{R}^d$, the dimension of the objects composing $O$ (maybe points themselves, maybe line segments...) have some topological dimension $d_T$, and

$$d_T \leq D \leq d.$$  

Where does the right bound come from? By placing $d$-balls centered at the sites of a cubic lattice (with a diameter $a$ proportional to the lattice spacing) we can cover a whole region of $\mathbb{R}^d$ with a number that goes like $a^{-d}$.

It behooves us to give some examples with $D \notin \mathbb{Z}$. Such things are called fractals and are often defined by a recursive process.

1. A Cantor set in $d = 1$ can be defined beginning with a line segment of length $a_0$. Divide it in thirds and remove the middle segment. Repeat for each subsegment. At the end of this process, we get a bunch of points ($d_T = 0$) in $d = 1$. According to our definition (1.1), 1-ball of diameter $a$ is an interval of length $a$. After $n$ steps of the above procedure, we end up with $2^n \equiv N$ line segments of length $a_n = a_0 3^{-n}, n = 1, 2, 3...$ (that’s what I’m drawing). Since we only remove stuff, we can cover the whole thing with these, so we have a lower bound of $N(a_n) = 2^n$, and you can’t do better. Eliminate $n : n = -\log a_n/a_0 \log 3$ (think of this as $n(a) = -\log a/a_0 \log 3$), so

$$N(a) = 2^{n(a)} = 2^{-\log a_n/a_0 \log 3} = \left(\frac{a}{a_0}\right)^{-\log 2/\log 3}$$
which gives fractal dimension

\[ D = \frac{\log 2}{\log 3} \simeq .63 \in (0, 1) \]  \hspace{1cm} (1.3)

Notice that this object is self-similar with scale factor \( \lambda = 3 \): the two remaining thirds are identical to the original up to a rescaling of the length by a factor of three. This fact can be used to infer the power-law, since it means \( N(a) = 2N(3a) \). So if \( N(a) \sim a^{-D} \), we must have \( a^{-D} = 2(3a)^{-D} \rightarrow 1 = 2 \cdot 3^{-D} \) which is (1.3).

2. Here’s an example in \( d = 2 \). Take a square with side length \( a_0 \). Now divide it into nine squares by dividing each side by three. Remove every other sub-square, leaving the corners. Repeat. This procedure gives the accompanying figures. The resulting figure is again self-similar with \( \lambda = 3 \) and has \( N(a) = 5N(3a) \) – we need only five times as many balls of diameter \( a \) to cover the region as balls of diameter \( 3a \). Therefore, if there is a scaling relation \( N(a) \sim a^{-D} \), we need \( D = \frac{\log 5}{\log 3} \simeq 1.46 \). Note that this is sensibly between 1 and 2.

The figure at left is defined by a similar procedure. I don’t know how I’m ever going to get any physics done if I don’t stop making these pictures. Lots of interesting fractals come from other procedures where the fractal dimension is not so easy to find.
1.2 Fractal dimension of a random walk

So far we’ve been discussing fractals defined by an artificial procedure. Consider a random walk in Euclidean space of dimension $d \geq 2$. Starting from some origin, we take discrete steps, where the displacement $\vec{r}$ of each step is chosen (e.g.) independently from some distribution $p(\vec{r})$. For example, we could take our steps to have fixed length $a_0$, and uniformly distributed direction. For now, we assume this distribution and that the walk is otherwise unrestricted.

Of interest is the net displacement after $M$ steps

$$\vec{R}_M \equiv \sum_{i=1}^{M} \vec{r}_i.$$ 

This is a random variable with average

$$\langle \vec{R}_M \rangle_M \equiv \int d^d r_1 \cdots d^d r_M p(\vec{r}_1) \cdots p(\vec{r}_M) \sum_{i=1}^{M} \vec{r}_i$$

which vanishes by our assumption of rotation invariance of the individual distributions. On the other hand, $\langle \vec{r}_i \cdot \vec{r}_j \rangle \propto \delta_{ij}$, so the square-length of the net displacement has

$$\langle |\vec{R}_M|^2 \rangle_M = \sum_{i}^{M} \sum_{j}^{M} \langle \vec{r}_i \cdot \vec{r}_j \rangle_M = \sum_{j=1}^{M} \langle |r_j|^2 \rangle = Ma_0^2.$$ 

The RMS displacement $R(M) \equiv \sqrt{\langle |\vec{R}_M|^2 \rangle_M} = \sqrt{Ma_0}$ goes like the square root of the number of steps, a probably-familiar result on which we are going to get some new perspective now.

What is the fractal dimension of a random walk?

A walk of $M$ steps can be regarded as $M/n$ subwalks of $n$ steps (choose $M$ so that these are integers). By the above result, the RMS displacement of the subwalks is $r(n) = \sqrt{n}a_0$; choose $M$ big enough so that this is a good approximation. This suggests that we may think of a random walk (RW) of $M$ steps of length $a_0$ as a RW of $M/n$ steps each of length (approximately) $a_1 \equiv \sqrt{n}a_0$. Notice that this ‘coarse-grained’ step size is not actually the same for each subwalk. (We are relying on the central limit theorem here to say that the distribution of subwalk sizes is well-peaked around the central value. We’ll give an RG proof of that result next.)
This perspective allows us to estimate the fractal dimension of an unrestricted RW. Let $N(a)$ be as above the number of balls of diameter $a$ needed to cover a walk (probably) of $M$ microscopic steps of size $a_0$. When the ball-size is about the same as the stepsize, we need one ball for each step (this is overcounting but should give the right scaling), we’ll have

$$N(a) \sim M, \quad \text{for } a \sim a_0.$$ 

For the sub-steps, the same relation says we should cover each subwalk step (length $\sqrt{n}a_0$, of which there are $M/n$) with a ball, so

$$N(\sqrt{n}a_0) \sim \frac{M}{n}.$$ 

Combining the previous two displayed equations (eliminate $M$) gives

$$M = N(a_0) = nN(\sqrt{n}a_0) \implies N(a) \sim a^{-2}$$

which says that the fractal dimension of the (unrestricted, in $d \geq 2$) random walk is $D = 2$.

---

**A few points regarding the notion of fractal dimension.**

The Hausdorff dimension we’ve defined is not the only candidate for such a scale-dependent and possibly-fractional notion of dimension. If fact there are many others, and they are not all equivalent. Two that are notable are the box-counting dimension, where one covers the whole $\mathbb{R}^d$ with a grid of boxes of side length $a$ and counts the number $N(a)$ of boxes containing an element of the set as a function of $a$; if $N(a) \sim a^{-D_{bc}}$ then this defines the box-counting dimension $D_{bc}$. This one is easier to implement numerically since it doesn’t involve a minimization procedure.

Another one is the correlation dimension, which is related to a problem on the homework.

1. As a practical physicist, why should you care about this result? Here’s one kind of answer: suppose you have in your hands some object which is locally one-dimensional, but squiggles around in a seemingly random way. It is governed by some microscopic dynamics which are mysterious to you, and you would like

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to know if you can model it as an unrestricted random walk. One diagnostic you might do is to measure its fractal dimension; if it’s not $D = 2$ then for sure something else is going on in there. (If it is $D = 2$ something else still might be going on.)

[End of Lecture 1]

3. For some statistically self-similar sets, a single fractal dimension does not capture the full glory of their fractaliciousness, and it is useful to introduce a whole spectrum of fractal dimensions. Such a thing is called multifractal.

I hope to say more about both of the previous points later on in the course.

### 1.3 RG treatment of random walk

Now we’ll study the random walk a bit more precisely, and use it to introduce the RG machinery. To be specific, suppose that each microscopic step is sampled from the (Gaussian) distribution

$$p(\vec{r}) = \mathcal{N} e^{-\frac{|\vec{r}|^2}{2\sigma_0^2}}, \quad \mathcal{N} = (2\pi\sigma_0^2)^{-d/2}.$$  

As before, the detailed form of the single-step distribution will be unimportant for the questions of interest to us – the technical term is ‘irrelevant’; this will be an outcome of the RG analysis. In this case, we have $\langle \vec{r} \rangle = 0$, $\langle \vec{r} \cdot \vec{r} \rangle = \sigma_0^2$.

Let $\vec{r'} \equiv \sum_{i=1}^n \vec{r}_i$. Think of this as a ‘coarse-grained step’ – imagine that the single steps (of RMS size $\sigma_0$) are too small to see, but for $n$ big enough, $n$ of them can get somewhere. The distribution for the coarse-grained step is:

$$P(\vec{r'}) = \int d^d r_1 \cdots d^d r_n p(\vec{r}_1) \cdots p(\vec{r}_n) \delta \left( \vec{r'} - \sum_{i=1}^n \vec{r}_i \right) = \int d^d k \ e^{i\vec{k} \cdot (\vec{r'} - \sum_{i=1}^n \vec{r}_i)}$$

(Do $n \cdot d$ Gaussian integrals.

Note that $d^d k = \frac{(2\pi)^d}{(2\pi)^d}$)

$$= \int d^d k \ \exp \left( -n|\vec{k}|^2 \sigma_0^2 - i\vec{k} \cdot \vec{r}' \right)$$

(One more Gaussian integral)

$$= \mathcal{N'} \exp \left( -\frac{|\vec{r}'|^2}{2n\sigma_0^2} \right), \quad \mathcal{N'} \equiv (2\pi n\sigma_0^2)^{-d/2}.$$  

(1.4)
This is the same form of the distribution, with the replacement $\sigma_0 \rightarrow \sigma' \equiv \sqrt{n}\sigma_0$. We can make it actually the same distribution if we rescale our units (the second half of the RG transformation): rescale $r' \equiv \sqrt{n}r''$, where the zoom factor is chosen to keep the width of the distribution the same after the coarse-graining step. Remembering that distributions transform under change of variables by

$$P(\vec{r'})d^dr' = P(\vec{r}'')d^dr''$$

we have

$$P(\vec{r}'') = \frac{1}{(2\pi\sigma_0)^{d/2}} e^{-|\vec{r}'|^2/2\sigma_0^2}$$

– the same distribution as we had for single step. Therefore, a random walk is (probably) a fractal – it is self-similar on average.

The two steps above – (1) coarse graining and (2) rescaling – constitute a renormalization group transformation (more on the general notion next). The ‘coupling constant’ $\sigma_0$ transforms under this transformation, in this case as

$$\sigma_0 \mapsto \sigma_{\text{renormalized}} = \sigma_0,$$

*i.e.* it maps to itself; such a parameter is called *marginal* and is a special case.

Consider the RMS distance covered by a walk in $M$ steps,

$$R(M)^2 \equiv \left\langle \sum_{i=1}^{M} |\vec{r}_i|^2 \right\rangle_M .$$

It depends on $M$ and the typical step size, which is $\sigma$ (since $\sigma^2 = \int d^d r |\vec{r}|^2 p(\vec{r})$). Dimensional analysis tells us that we must have $R(M) \propto \sigma$ and the statistical self-similarity we’ve just found suggests a power law dependence on $M$:

$$R(M) \sim \sigma M^\nu$$

which scaling relation defines the exponent $\nu$. The coarse-grained walk (no rescaling) takes $M' = N/n$ steps. Demanding the same outcome for the RMS displacement in both the microscopic description and in the coarse-grained description says

$$\sigma M'' = \sqrt[n]{M'} \nu = \sqrt{n}\sigma \left( \frac{M}{n} \right) ^\nu = n^{\frac{1}{2} - \nu} \sigma M'' .$$

(1.5)
(In the context of quantum field theory, a relation with the same logical content is called a Callan-Symanzik equation.) In order for this to be true for all \( n \), we must have

\[
\nu = \frac{1}{2}.
\]

Recalling that the fractal dimension \( D = 2 \) also came from \( \sigma' = \sqrt{n} \sigma_0 = n^{1/D} \sigma_0 \), we’ve shown that an unrestricted random walk in \( d \geq 2 \) has a relationship between the fractal dimension and the RMS displacement exponent: \( \nu = 1/D \).

**Measurability of the fractal dimension.** I’ve spoken above about the fractal dimension of a random walk, for example of a random polymer configuration, as an ‘observable’. How could you measure it?

Suppose the monomers making up the polymer scatter light (elastically). The fractal dimension can be extracted from the structure factor \( S(k) \), as measured by the intensity of scattering of light off the object, as a function of the wavenumber \( k \) of the light. (This statement is related to the open-ended question on the first homework.)

1.4 **Anatomy of an RG scheme**

As we saw in (1.5), we are taking a passive point of view on the RG transformations: the observable physics (whatever it may be, \( R(M) \) in the example above) is the same, and we are only changing our description of that physics.

An RG transformation has two steps:

1. **Coarse-graining or decimation:** The idea of this step is familiar from the central idea of how thermodynamics emerges from statistical mechanics: we should
average over the stuff we can’t keep track of (microscopic configurations of the system), holding fixed the stuff we do keep track of (the thermodynamic variables like energy and volume). In the connection mentioned in the previous sentence, we do it all at once.

The key new idea of the RG is to do it a little bit at a time. That is: Integrate out or average over some set of short-distance/fast degrees of freedom, holding fixed a set of long-wavelength/slow degrees of freedom.

Notice that this step is not necessarily reversible: the value of a definite integral (or sum) does not uniquely determine the integrand (or summand). We lose information in this step. This means that a set of transformations defined this way is not in fact a group in the mathematical sense, since there is no inverse element (it is a semigroup). So much for that.

The idea is that we are squinting, so that the smallest distance $\Delta x$ we can resolve gets a little bigger, say before the coarse-graining, we had a resolution $\Delta x = \epsilon$, and afterwards we only keep track of stuff that varies on distances larger than $\Delta x = \lambda \epsilon$ for some scale factor $\lambda > 1$.

2. **Rescaling**: Now we change units to map the coarse-grained system back onto the original one, so that $\lambda \epsilon \mapsto \epsilon$. We do this so that we can compare them.

Now we’re going to think about the space on which this transformation is acting. Its coordinates are the parameters of the system, such as the parameters defining the probability distribution such as $\sigma_0$ for the random walk, or the couplings in the Hamiltonian if $p = e^{-\beta H}/Z$. Let’s call the set of such parameters $\{h_j\}$, where $j$ is an index which runs over as many parameters as we need to consider\(^2\). These parameters get transformed according to

\[
\{h_j\} \xrightarrow{\text{steps 1, 2}} \{h'_j \equiv R_j(\{h\})\}.
\]

This map is something we can do over and over, coarse-graining (zooming out) by a factor of $\lambda$ each time, until we get to macroscopic sizes. The repeated application of

\(^2\)For example, in the random walk case, other parameters we could include are $b, c, ...$ in

\[
p(\vec{r}) = \exp - \left( b \cdot \vec{r} + \frac{r^2}{2\sigma^2} + cr^4 + ... \right).
\]

\(^3\)One of the many crucial contributions of Ken Wilson to this subject was (I think) allowing for the possibility of including arbitrarily many parameters. The terror you are feeling at this possibility of an infinite-dimensional space of coupling parameters will be allayed when we discover the correct way to organize them two pages from now.
the map $h_j' \equiv R_j(h)$ describes a dynamical system on the space of parameters. If we are interested in macroscopic physics, we care about what happens when we do it lots of times:

\[ h \mapsto R(h) \mapsto R(R(h)) \equiv R^2(h) \mapsto R^3(h) \mapsto \ldots \]

(When studying such a possibly-nonlinear dynamical system more generally, it is a good idea to ask first about the possible late-time behavior.)

What can happen? There are three possibilities:

1. We can reach a fixed point, $h_* = R(h_*)$. (We’ll include $h \to \infty$ in some direction in this case. That just means we chose a bad parametrization.)

2. We can go around in circles forever. This is called a limit cycle.

3. We can jump around chaotically forever.

The first case, where there is a fixed point, is the one about which we have a lot to say, and fortunately is what seems to happen usually.

A crucial point: the distribution described by such a fixed point of the RG is self-similar, by the definition of the RG transformation. (If this is true when our zooming size $\lambda \to 1$, then it is actually scale-invariant.)

1.5 Scaling behavior near a fixed point

Now, suppose we have found a fixed point $h_*$ of our RG transformation, which is a candidate for describing the macroscopic behavior of our system. It is then a good idea to look at the behavior in the neighborhood of the fixed point (this is also a good piece of advice for general dynamical systems): linearize about the fixed point. We will see that this analysis immediately spits out the phenomenology of scaling behavior near a critical point. If that is not a familiar notion, don’t worry, we’ll come back to it.

First, define the set of points which flows to the fixed point to be the

\[
\text{critical surface of } h_* \equiv \{ h \mid \lim_{n \to \infty} R^n(h) = h_* \} \equiv S(h_*)
\]

– this is the basin of attraction of the fixed point in question.
Linearizing about the fixed point, let \( h_j \equiv h^*_j + \delta_j \), where \(|\delta| \ll 1\) will be our small parameter. This maps under the RG step according to

\[
h_j \equiv h^*_j + \delta_j \rightarrow h'_j = \mathcal{R}(h^* + \delta) = h^*_j + \delta_k \frac{\partial h'_j}{\partial h_k} + \mathcal{O}(\delta^2)
\]

where in the last step we assumed that the RG map \( \mathcal{R} \) is analytic in the neighborhood of the fixed point, \( i.e. \) that it has a Taylor expansion. How could it not be? We got it by doing some finite sums of analytic functions. By \(+\mathcal{O}(\delta^2)\) I mean plus terms that go like \(\delta^2\) and higher powers of delta which are small and we will ignore them. If we ignore them, then the map on the deviation from the fixed point \( \delta_j \) is a linear map:

\[
\delta_j \rightarrow \delta'_j = R_{jk} \delta_k.
\]

We know what to do with a linear map: find its eigenvalues and eigenvectors:

\[
R_{jk} \phi^{(n)}_k = \rho_n \phi^{(n)}_j.
\]

Notice that nothing we’ve said guarantees that \( R_{jk} \) is a symmetric matrix, so its right and left eigenvectors need not be the same (the eigenvalues are), so we’ll also need

\[
\tilde{\phi}^{(n)}_j R_{jk} = \rho_n \tilde{\phi}^{(n)}_k.
\]

Together, these are orthonormal

\[
\sum_j \tilde{\phi}^{(n)}_j \phi^{(n')}_j = \delta_{n,n'}
\]

and complete

\[
\sum_n \tilde{\phi}^{(n)}_j \phi^{(n)}_k = \delta_{jk}.
\]

About the eigenvalues, notice the following. We’ve defined the RG transformation \( \mathcal{R} \equiv \mathcal{R}_\lambda \) to accomplish a coarse-graining by a scale factor \( \lambda \). We can imagine defining such a transformation for any \( \lambda \), and these operations form a semigroup under composition

\[
\mathcal{R}_\lambda \mathcal{R}_\lambda' = \mathcal{R}_{\lambda \lambda'}.
\]

This is useful because it says that the eigenvalues of the linearized operators

\[
R_\lambda \phi^{(n)} = \rho_n(\lambda) \phi^{(n)}
\]
must satisfy the same multiplication law\(^4\)
\[
\rho_n(\lambda)\rho_n(\lambda') = \rho_n(\lambda\lambda').
\] (1.7)

But a function which satisfies this rule must have the form\(^5\)
\[
\rho_n(\lambda) = \lambda^{y_n}
\] (1.8)

for some \(y_n\) independent of \(\lambda\).

The eigenvectors of \(R\) give a preferred coordinate basis near the fixed point:
\[
\delta_j = \sum_n g_n \phi_j^{(n)} = \sum_k \tilde{\phi}_k^{(n)} \delta_k,
\]
which we will use from now on. \(y_n\) is called the *scaling dimension* of the coupling \(g_n\).

Now we can see the crucial RG dichotomy which tames the infinitely many couplings: If \(|\rho_n| < 1\) \((y_n < 0)\) then as we act with \(\mathcal{R}\) many times to get to long wavelengths, then \(g_n \to 0\). Such a coupling is called *irrelevant*: it goes away upon repeated RG transformations and its effects on macroscopic physics can be ignored. Notice that since the perturbation is getting smaller, the approximation \(|\delta| \ll 1\) becomes better and better in this case.

In contrast, if \(|\rho_n| > 1\) \((y_n > 0)\) then as we act with \(\mathcal{R}\) many times to get to long wavelengths, then \(g_n\) grows. Such

---

\(^4\) Why do \(R\lambda\) for different \(\lambda\) have the same eigenvectors?

It really follows from the semigroup property. The eigenvectors are physical things: an eigenvector determines some operator \(O\) with the following property: if I add \(O\) to the fixed-point hamiltonian, \(H + \alpha gO\), an RG transformation does not generate any other operators, i.e. it gives \(H = H + \alpha gO\) for some \(\alpha\).

On the other hand, the choice of by how much to zoom out \((\lambda)\) is an arbitrary one. Doing the RG step by \(\lambda\) twice should give the same result as doing it once by \(2\lambda\). So in particular either one should give the same set of special directions.

\(^5\) The function \(y(\lambda) \equiv \log \rho_n(\lambda)\) then satisfies \(y(\lambda) + y(\lambda') = y(\lambda\lambda')\). First this implies \(y(1) = 0\). If we consider \(\lambda' = 1 + \epsilon\), we have
\[
y(\lambda) + y(1 + \epsilon) = y(\lambda + \lambda\epsilon)
\]
\[
y(\lambda) + y(1) + \epsilon y'(1) = y(\lambda) + \lambda\epsilon y'(\lambda) + \mathcal{O}(\epsilon^2)
\]
which says that \(y\) satisfies the differential equation \(y'(\lambda) = \frac{y'(1)}{\lambda}\) which is solved by
\[
y(\lambda) = y'(1) \ln \lambda.
\]

I’m not sure if the statement (1.8) follows if we only know (1.7) for discrete values of \(\lambda\). Does it?
a parameter is called *relevant*, and represents an instability of the fixed point: our linearization breaks down after repeated applications of \( R \) and we leave the neighborhood of the fixed point.

The case of a coupling with \( y_n = 0 \) which doesn’t change is called *marginal*.

In these terms, the critical surface (actually its tangent space near the fixed point) is determined by

\[
S(h_*) = \{ g_n = 0 \text{ if } y_n > 0 \}.
\]

In particular, the *codimension* of the critical surface in the space of couplings is the number of relevant perturbations of the fixed point.

[End of Lecture 2]

## 2 Random walks

Next we generalize our ensemble of random walks to illustrate some features of the RG that were missing from our simple pure Gaussian example above.

### 2.1 Biased gaussian walk

First, we can see an example of a relevant operator if we study a *biased* walk, with

\[
p(\vec{r}) = (2\pi \sigma^2)^{-d/2} \exp \left( -\frac{|\vec{r} - \vec{r}_0|^2}{2\sigma^2} \right) .
\]

Again define the distribution for the coarse-grained step to be

\[
P(\vec{r}') = \int \prod_{i=1}^{n} (d^d \vec{r}_i p(\vec{r}_i)) \delta \left( \vec{r}' - \sum_{i}^{n} \vec{r}_i \right)
\]

\[
= (2\pi n\sigma^2)^{-d/2} \exp \left( -\frac{|\vec{r} - n\vec{r}_0|^2}{2n\sigma^2} \right) .
\]

So, after the coarse-graining step, we have

\[
\begin{align*}
\sigma' &= \sqrt{n}\sigma \\
\vec{r}_0' &= n\vec{r}_0
\end{align*}
\]

After the rescaling step, to keep the width of the distribution fixed, we have

\[
\begin{align*}
\sigma^{(R)} &= \sigma \\
\vec{r}_0^{(R)} &= \sqrt{n}\sigma_0
\end{align*}
\]
So \( R \) is diagonal already. This says that the bias of the walk is a relevant operator of dimension \( y_0 = \frac{1}{2} > 0 \).

We have here an explicit example of an RG map \( R \). Let’s study its fixed points. There’s one at \((\sigma, \vec{r}_0 = 0)\) (for any \( \sigma \), so actually it is a family of fixed points parametrized by the marginal coupling \( \sigma \)) which is the unbiased walk we studied earlier. This fixed point is unstable because if we turn on a little \( r_0 \) it will grow indefinitely.

And there’s another fixed point at \((\sigma, \vec{r}_0 = \infty)\). This is where we end up if we perturb the unbiased fixed point. The distribution \((2.1)\) says (by direct calculation) that

\[
R(M) = \sqrt{\left\langle |\vec{R}_M|^2 \right\rangle} = \sqrt{M^2|\vec{r}_0|^2 + M\sigma^2} \quad M \gg 1 \quad \rightarrow \quad M|\vec{r}_0|.
\]

This means that for large \( a \), we’ll need \( N(a) \sim 1/a \) spheres of diameter \( a \) to cover the walk – it will be one dimensional.

This means that a system defined by some microscopic distribution of the form \((2.1)\) with some value of \( \vec{r}_0 \) and \( \sigma \) will look like a Brownian walk of the type described above, with fractal dimension \( D = 2 \), if you look at it closely, with a resolution \( \delta x \ll \sigma \). But from a distance (resolution worse than \( \delta x \gg \sigma \)), it will look like a one-dimensional path \((D = 1)\) in the \( \vec{r}_0 \) direction. For example, the number of balls defining the fractal dimension behaves as

\[
N(a) \sim \begin{cases} 
a^{-2}, & a \ll \sigma \\
a^{-1}, & a \gg \sigma. 
\end{cases}
\]

### 2.2 Universality class of the (unrestricted) random walk

Now let the distribution from which a single step is sampled be any rotation-invariant distribution \( p(\vec{r}) = p(|\vec{r}|) \) with finite moments. For example, the fixed-step-length distribution \( p(\vec{r}) = \frac{1}{4\pi a^2} \delta (|\vec{r}| - a) \) is a good one to keep in mind. (This is still not the most general walk, since we’re still assuming the steps are independent. More on that next.) The distribution for the coarse-grained step is

\[
P(\vec{r}') = \int \prod_{i=1}^n d^d r_i p(\vec{r}_i) \delta \left( \vec{r}' - \sum_i \vec{r}_i \right) = \int d^d k \ e^{-i\vec{k} \cdot \vec{r}'} \left( \left\langle e^{i\vec{k} \cdot \vec{r}} \right\rangle \right)^n.
\]

The quantity

\[
\left\langle e^{i\vec{k} \cdot \vec{r}} \right\rangle = \int d^d r p(\vec{r}) e^{i\vec{k} \cdot \vec{r}} \equiv g(k)
\]
is called the characteristic function of the distribution \( p(\vec{r}) \), and is a generating function for its moments:

\[ \langle r^m \rangle = (-i\partial_k)^m g(k)|_{k=0}. \]

The Taylor expansion in \( k \) of its logarithm is the cumulant expansion:

\[ \log g(k) = \sum_m \frac{(ik)^m}{m!} C_m, \quad C_m = (-i\partial_k)^m \log g|_{k=0}. \]

The important point for us is the expansion:

\[
\langle e^{i\vec{k} \cdot \vec{r}} \rangle = \exp \left( i\vec{k} \cdot \langle \vec{r} \rangle - \frac{1}{2} \sum_{\mu, \nu} k_\mu k_\nu \left( \langle r_\mu r_\nu \rangle - \langle r_\mu \rangle \langle r_\nu \rangle \right) + \frac{(ik)^3}{3!} C_3 + O(k^4) \right).
\]

If we don’t truncate the sum in \( \sum_m \frac{(ik)^m}{m!} C_m \), then the \( \{C_m\} \) are just another set of coordinates on the space of couplings for the walk. Why should we treat the integration variable \( k \) in (2.3) as small? Because the integrand is suppressed by the Gaussian factor. If the Gaussian bit dominates, then the integrand has support at \( k \lesssim \frac{1}{\sqrt{n\sigma_0^2}} \), at which the \( m \)th term in the cumulant expansion contributes to the exponent in (2.3) as

\[ nk^m C_m \sim n^{1-\frac{m}{2}} \xrightarrow{n \to \infty} 0 \quad \text{if } m > 2, \]

where the important thing for getting zero is just that \( C_m \) is finite and independent of \( n \) and \( k \). This is the statement that the couplings \( C_m \) for \( m > 2 \) are irrelevant. Then we can do the remaining Gaussian integral (ignoring the small corrections which are suppressed by \( e^{-n^{1-\frac{m}{2}} C_m} \))

\[
P(\vec{r}') \xrightarrow{n \gg 1} (2\pi n\sigma_0^2)^{d/2} e^{-\frac{1}{2} \frac{\|\vec{r}' - n\langle \vec{r} \rangle\|^2}{n\sigma_0^2}}.
\]

What’s this? This is the Gaussian we used at the beginning, with \( r_0 = n \langle \vec{r} \rangle \).

This result, that the distribution for a sum of many random variables independently distributed according to some distribution with finite moments, is usually called the Central Limit Theorem or the Law of Large Numbers. (For more on the derivation I recommend the discussion in Kardar volume 1.)

In the framework of the RG it is an example of universality: all such probability distributions are in the basin of attraction of the gaussian random walk – they are said to be in the same universality class meaning that they have the same long-wavelength
physics. In particular, their RMS displacement goes like $R_M \sim M^{1/2}$ for large number of steps $M$, and (for $d \geq 2$) their fractal dimension is $D = 2$.

Notice that we did not prove that the Gaussian fixed point is the only one: we had to assume that we were in its neighborhood in order to use the $k \sim n^{-1/2}$ scaling – this scaling is a property of the neighborhood of the fixed point, just like the exponents $y$ we got by linearizing about the general fixed point in §1.5.

In fact there are other fixed points in the space of $d$-dimensional walk distributions. For example, we could have chosen the scaling to fix the coefficient $C_m$ for any $m$. In that case we would find that the $m - 1$ perturbations $C_{l<m}$ are relevant and all the $C_{l>m}$ are irrelevant. The special case where we fix $C_1$ (i.e. choose $k \sim 1/n$) gives the same fixed-point we reached for the biased walk. The fixed points with $C_{m>2}$ fixed have more than one relevant operator (we will learn to call this ‘multicritical’), which means reaching them requires tuning several parameters.

Also, the assumption in the statement of the CLT also has an RG analog: if the initial distribution does not have finite moments, then our expansion in terms of cumulants is no good. An example is a Lorentzian distribution, $p(r) = \frac{\sigma/\pi}{r^2 + \sigma^2}$. In fact in a certain sense the Lorentzian is a fixed point (if we set $n = 2$ where $n$ is the parameter in the coarse-graining transformation as above).

(We will see another fixed point next when we include interactions between the steps of the walk.)

One lesson which does generalize, however, is that most of the possible perturbations of the fixed point are irrelevant, and there is only a small number of relevant or marginal perturbations.

### 2.3 Self-avoiding walks have their own universality class

[Still from Creswick! I like this book. According to Amazon, Dover has put out a second edition.] Suppose that the random 1d objects we are studying are actually polymers – long chain molecules made of ‘monomers’ which cannot be in the same place, i.e. they have some short-ranged repulsion from each other. We can model this as lattice paths without self-intersection, or self-avoiding walks (SAWs). Does this microscopic modification of our ensemble change the long-wavelength physics?

It certainly changes our ability to do all the sums. If our polymer has $n$ monomers, we’d like to know about the numbers

$$M_n(\vec{R}) \equiv \# \text{ of SAWs with } n \text{ steps connecting } \vec{0} \text{ to } \vec{R}. \quad (2.4)$$

Then we could figure out the RMS displacement from head-to-tail of the $n$ step polymer
(actually we are not distinguishing between head and tail):

\[ R(n)^2 \equiv \langle |\vec{R}|^2 \rangle = \frac{\sum \vec{R} M_n(\vec{R}) |\vec{R}|^2}{M_n}. \]

The denominator here is \( M_n \equiv \sum \vec{R} M_n(\vec{R}) \). As with the unrestricted random walk, we might expect to have (we will) a scaling relation

\[ R(n) \sim n^{\nu} \tag{2.5} \]

with some characteristic exponent \( \nu \).

Enumerating \( M_n \) is not so easy. For the square lattice, \( M_1 = 4, M_2 = 4 \cdot 3 \) since there are three choices for the second step, \( M_3 = 4 \cdot 3 \cdot 3 \), but after that we can make loops (for some of the previous choices) and it gets ugly and grows rapidly. A generating function which packages this information is the grand-canonical-type object

\[ G(K, \vec{R}) \equiv \sum n K^n M_n(\vec{R}) \tag{2.6} \]

where \( K \) is a fugacity whose size determines the relative contributions of walks of different lengths to \( G(K) \).

Let

\[ \xi^2(K) \equiv \sum R \sum_n |\vec{R}|^2 K^n M_n(\vec{R}) \frac{G(K, \vec{R})}{G(K, \vec{R})} \tag{2.7} \]

be the square of the RMS displacement at fixed \( K \), the typical size of a SAW.

In this ensemble, for \( K < 1 \), the falloff of \( K^n \) with \( n \) fights against the growth of \( M_n \) to produce a sharp peak at some \( n_0(K) \).

There is a value of \( K \) where this peak step-length diverges, since it is finite for \( K \to 0 \) and infinite for \( K \geq 1 \).
Preview: if $M_n$ grows exponentially, with some power-law prefactor,

$$M_n \sim K_c^{-n} n^{\gamma-1}$$

then $n_0(K)$ occurs at the maximum of

$$K^n M_n = e^{n \ln(K/K_c) + (\gamma-1) \ln n}$$

$$\implies n_0(K) = -\frac{\gamma - 1}{\ln (K/K_c)} K \to K_c \sim (\gamma - 1) \left( \frac{K_c - K}{K_c} \right)^{-1}$$

which diverges at (the aptly named) $K_c$, and the typical walk size goes like

$$\xi(K) \sim R(n_0(K)) \sim n_0(K)^\nu \sim \left( \frac{K_c - K}{K_c} \right)^{-\nu}.$$ 

So from this grand-canonical point of view, the reason there are scaling relations and power laws is the existence of this critical point where the length of the typical walk diverges. End of preview.

Let’s implement an RG for a 2d SAW on the square lattice. What is the space of couplings we should consider? Previously, our only coupling was the bond-fugacity $K$, that is, a walk was weighted by $K^n$ with $n$ the number of bonds covered by the walk. We could also consider multiplying this weight by $K_{n'}$ where $n'$ is the number of next-nearest neighbor bonds covered, or $K_a^3$ where $a$ is the area of the region between the SAW and some reference curve. Any property of the SAW you can quantify can appear in the weight, if you want. Call the weight $W(K)$, where $K$ now represents some collection of such parameters. When pressed, I’ll just consider the one fugacity $K$ for the number of steps.

Here’s the coarse-graining we’ll do: take SAWs $\Gamma$ on the fine-grained lattice $\Lambda$ with weight $W_{\Gamma}(K)$. We will use these to build SAWs $\Gamma'$ on a coarser lattice $\Lambda'$, with some relative zoom factor $\lambda$. For example, if $\lambda$ is an integer, we could take $\Lambda'$ to be a square lattice with lattice spacing $\lambda a$ where $a$ is the lattice spacing of $\Lambda$. ($\lambda = 2$ in the figure at right.)

The weights are related by

$$W_{\Gamma'}(K') = \sum_{\Gamma \in \Gamma'} W_{\Gamma}(K)$$

where we regard $\Gamma'$ as defining an equivalence class of walks on the finer lattice.
Here is an example of a possible rule for determining the inclusion $\Gamma \in \Gamma'$, for $\lambda = 2$. It is very non-unique. Depicted is a unit cell of $\Gamma'$ (blue) and the overlapping unit cells of $\Gamma$ (black). A SAW which enters the cell at the lower left must leave through the right or the top. The model has a $\pi/2$ rotation symmetry so we can consider just the latter.

Since on the coarser lattice, each of these represents, just a single step, $W_{\Gamma'}(K') = K'$. The result is

$$K' = 2(K^4 + 2K^3 + K^2).$$  \hfill (2.8)

Let me emphasize that the details of this real-space RG procedure are not to be taken too seriously, and other similarly-legitimate schemes produce somewhat different polynomials on the RHS here.

At right is a visualization of the map (2.8). Fixed points are (by definition) intersections between the curve (2.8) and the line $K' = K$. The map (2.8) has three fixed points:

1. $K = 0$, which is an ensemble dominated by very short walks, and in particular finite-length ones.
2. $K = \infty$, which is dominated by crazy lattice-filling walks. Maybe interesting.
3. $K = K_c \simeq 0.297$. This third one is where we go from finite walks at $K$ slightly below $K_c$ to infinite walks at $K > K_c$.

The jagged line between $K' = K$ and the curve defined by (2.8) depicts the repeated action of the map with an initial condition near (but slightly below) the fixed point at $K = K_c$. As you can see from the jagged line, the fixed point $K_c$ is unstable – the perturbation parametrized by $K - K_c$ is relevant. Its dimension determines the exponent $\nu$ defined in (2.5) as follows.

Because we are zooming out by a factor of $\lambda$, the typical size will rescale as

$$\xi(K) = \lambda \xi'(K').$$

Near the critical point,

$$\xi(K) \xrightarrow{K \to K_c} |K - K_c|^{-\nu} = \lambda \left[ \frac{\partial K'}{\partial K} |K_c| \right]^{-\nu} \xi(K') = 2|K' - (K - K_c)|^{-\nu}$$

Therefore

$$|K - K_c|^{-\nu} = \lambda \left( \left| \frac{\partial K'}{\partial K} |K_c| \right| \right)^{-\nu} |K - K_c|^{-\nu}$$
from which we conclude

\[ \nu = \frac{\ln \lambda}{\ln \left| \frac{\partial K}{\partial K} \right| K_c} = 0.771. \]

Numerical simulations give \( K_c = 0.379 \) and \( \nu = 0.74 \).

Where are we making an approximation in the above? For example, some configurations on the fine lattice have no counterpart on the coarse lattice (an example is a walk which enters the cell and leaves again the same way). We are hoping that these don’t make an important contribution to the sum. The real-space RG can be systematically improved by increasing the zoom factor \( \lambda \) (clearly if we coarse-grain the whole lattice at once, we’ll get the exact answer).

The important conclusion, however, is pretty robust: the \( d = 2 \) SAW has a different exponent than the unrestricted walk:

\[ \nu_{\text{SAW}} > \nu_{\text{RW}} = 1/2. \]

This makes sense, since it means that \( R_{\text{RMS}}(\text{SAW}) > R_{\text{RMS}}(\text{unrestricted}) \) for many steps – the SAW takes up more space (for a fixed number of steps) since it can’t backtrack. The fractal dimension is therefore smaller \( D_{\text{SAW}} = \frac{1}{\nu} \simeq 1.3 < 2 \).

Different exponents for the same observable near the critical point means different universality class.

**Teaser:** This ensemble of self-avoiding walks is the \( n \to 0 \) limit of the \( O(n) \) model! More specifically, the critical point in temperature of the latter model maps to the large-walk limit: \( T - T_c \sim M^{-1} \). This realization will allow us to apply the same technology we will use for the Ising model (which we could call the \( O(1) \) model) and its \( O(n) \) generalizations to this class of models.
3 Ising models

Words about the role of models, solvable and otherwise, and universality:

Fixed points of the RG are valuable. Each one describes a possible long-wavelength behavior, and each one has its own basin of attraction. That basin of attraction includes lots of models which are in some sense ‘different’: they differ in microscopic details of values of couplings, and sometimes even more dramatically. Two important examples:

(1) a lattice model and a continuum model can both flow to the same fixed point. The idea is that if the correlation length is much longer than the lattice spacing, the lattice variable looks like a continuous field, and we can interpolate between the lattice points. And at a fixed point scale invariance requires that the correlation length be infinity (or zero).

(2) a model with two states per site (like an Ising magnet, the subject of this section) and a model with infinitely many states at each site can flow to the same fixed point. Here’s a picture of how that might come about. Suppose we have at each site a variable called $S$ which lives on the real line, and it is governed by the potential energy function $V(S) = g(S^2 - 1)^2$. (So for example the Boltzmann distribution is $e^{-\beta V(S)}$.)

The parameter $g$ might be relevant, in the sense that $g \to \infty$ at long wavelengths. This process of making $g$ larger is depicted in the following figures (left to right $g = 1, 11, 21$):

As you can see, it becomes more and more energetically favorable to restrict $S$ to just the two values $S = \pm 1$ as $g$ grows.

I’ve just made a big deal about universality and the worship of fixed points of the RG. Part of the reason for the big deal is that universality greatly increases the power of simple models: if you can understand the physics of some simple (even ridiculously over-idealized) model and show that it’s in the same universality class as a system of interest, then you win.

[Goldenfeld §2.5, Creswick §5, lots of other places] The Ising model is an important common ground of many fields of science. At each site $i \in \Lambda$ ($\Lambda$ may be a chain, or the square lattice, or an arbitrary graph, and $i = 1...|\Lambda| \equiv N(\Lambda) = N$ is the number of sites), we have a binary variable $s_i = \pm 1$ called a spin, whose two states are sometimes called up and down. There are $2^N$ configurations altogether. (Although I
will sometimes call these ‘states’ I emphasize that we are doing classical physics.)

The name ‘Ising model’ connotes the following family of energy functionals (also known as Hamiltonians):

$$-H(s) = \sum_{i} h_{i} s_{i} + \sum_{ij} J_{ij} s_{i} s_{j} + \sum_{ijk} K_{ijk} s_{i} s_{j} s_{k} + \cdots$$

where this sum could go on forever with terms involving more and more spins at once. (The RG will generically generate all such terms, with coefficients that we can hope do not cause too much trouble.) With this definition, the model may describe magnetic dipoles in a solid, a lattice gas (where \( s_{i} = \pm 1 \) correspond to presence or absence of a particle at \( i \)), constrained satisfaction problems, neural networks, ... anything with bits distributed over space. This list also could go on forever.

**Equilibrium statistical mechanics.** Why might we care about \( H(s) \)? We can use it to study the equilibrium thermodynamics of the system, at some temperature \( T \equiv 1/\beta \). Let’s spend a few moments reminding ourselves about the machinery of equilibrium statistical mechanics. The key ‘bridge’ equation between the microscopic world (stat mech) and the macroscopic world (thermo) in thermal equilibrium is

$$e^{-\beta F} = \sum_{s} e^{-\beta H(s)} \equiv Z.$$

Here in our theorists’ paradise, we measure temperature in units of energy, \( k_B = 1 \). Notice that in classical equilibrium stat mech, the temperature is redundant with the overall scaling of the Hamiltonian, only the combinations \( \beta h, \beta J \ldots \) appear in the partition function, so a system with twice the temperature and twice the couplings will have the same physics. The sum here is over the \( 2^{N} \) configurations of the spins:

$$\sum_{s} \equiv \sum_{s_1=\pm 1} \sum_{s_2=\pm 1} \cdots \sum_{s_N=\pm 1} \equiv \prod_{i=1}^{N} \sum_{s_i=\pm 1} \equiv \text{tr}$$

and we will sometimes write tr for ‘trace’. I emphasize that we are doing classical physics here.

Why do we care about the free energy \( F \)? For one thing, it encodes the thermodynamics of the system: the average energy is

$$E \equiv \langle H \rangle \equiv \frac{1}{Z} \text{tr} He^{-\beta H} = -\partial_{\beta} \log Z,$$

\(6\) Here is an example I learned of recently of how an Ising model is used for data clustering.
\(7\) Sometimes the word ‘Ising’ is used to indicate the presence of the \( \mathbb{Z}_2 \) symmetry under \( s \rightarrow -s \) which is present when only even terms appear in \( H \) \((h = 0, K = 0)\).
the entropy is
\[ S = -\partial_T F, \]
the heat capacity is
\[ C_V = \partial_T E = \frac{1}{T^2} \left( \langle H^2 \rangle - \langle H \rangle^2 \right), \]
a dimensionless measure of the number of degrees of freedom. Notice the familiar thermodynamic identity \( F = E - TS \) follows by calculus.

More ambitiously, if we knew how \( F \) depended on all the coupling parameters \( \{ h_i, J_{ij}, K_{ijk}, \ldots \} \) in (3.1), we would know all of the correlation functions of the spins, for example
\[ \partial_h F = -T \partial_h \log Z = -T \frac{1}{Z} \text{tr} \frac{s_i}{T} e^{-\beta H} = -\langle s_i \rangle. \]
And similarly,
\[ \partial_h \partial_h F = (\langle s_i s_j \rangle - \langle s_i \rangle \langle s_j \rangle) T^{-1} \equiv G_{ij} T^{-1}. \]
It is a generating function for these (connected) correlation functions.

**Clean and local Ising models.** Two important specializations of (3.1) are quite important in physics (not always in the other applications of the Ising model). We will (usually) restrict to the important special case with the following two assumptions.

1. the couplings \( (J_{ij} \text{ and friends}) \) are *local* in the sense that the coupling between two sites goes away \( (J_{ij} \to 0) \) if the sites are far apart \( (|r_i - r_j| \to \infty) \).

   A reason to care about the two point function in the case where there is a notion of locality, then, is that it allows to define a *correlation length* \( \xi \):

   \[ G_{ij} \sim e^{-r_{ij}/\xi} \]

   – here \( a \) is the range of the interactions, or the lattice spacing, and \( r_{ij} \equiv |r_i - r_j| \) is the distance between the locations of spins \( i \) and \( j \). The correlation length will depend on the parameters in \( H \) and on the temperature, and it measures the distance beyond which the spin orientations are uncorrelated. More formally, \( \xi^{-1} = -\lim_{r \to \infty} \partial_r \ln G_{i,i+r} \) (but of course the \( \infty \) here has to stay within the box containing the system in question).

2. the couplings are translation invariant: \( J_{ij} = J f(|r_i - r_j|) \) for some function of the distance \( f(r) \). (If one thinks of variations of \( J_{ij} \) with \( i,j \) as coming from some kind of microscopic disorder, one refers to this case as *clean*.) We will often consider the case where \( f(r) \) only has support when \( r = a \) is one lattice spacing. (Notice that \( s^2 = 1 \) means that we can ignore the case when \( r = 0 \).)
These two assumptions are independent, but we will usually make both. So: on any graph (of \(N\) sites), the nearest-neighbor ‘clean’ Ising model has energy functional

\[-H = h \sum_i s_i + J \sum_{\langle ij \rangle} s_i s_j\]

where \(\langle ij \rangle\) means the set of nearest neighbors \(i, j\).

An important observable (especially in this case) is the magnetization

\[M \equiv \frac{1}{N} \sum_{i=1}^{N} \langle s_i \rangle = -\frac{1}{N} \partial_h F.\]

Also of interest is the spin susceptibility:

\[\chi \equiv \frac{1}{N} \partial_h M = \frac{1}{T N^2} \sum_{ij} (\langle s_i s_j \rangle - \langle s_i \rangle \langle s_j \rangle) = \frac{1}{N^2 T} \sum_{ij} G_{ij}.\]

When \(J > 0\), the energy of a configuration is lower if neighboring spins point the same way; in this ‘ferromagnetic’ case everybody can be happy (and \(M \neq 0\)). In the antiferromagnetic case \(J < 0\), neighbors want to disagree. All spins can agree to disagree if the graph has no loops. Any loop with an odd number of sites, like a triangle, leads to a frustration of the antiferromagnetic interaction, which requires compromise and leads to drama.

---

**Lack of drama for bipartite lattices.** A bipartite lattice is one which can be divided into two distinct sublattices \(A, B\) each of which only neighbors sites of the other lattice. That is \(\langle ij \rangle\) contains only pairs, one from \(A\) and one from \(B\). For example, hypercubic lattices are all bipartite: let the \(A\) lattice be those sites \((x, y, ...)\) whose (integer) coordinates add up to an even number \(x + y + ... \in 2\mathbb{Z}\). The honeycomb lattice is also bipartite. The triangular lattice is not. \(^8\)

[End of Lecture 4]

A consequence of bipartiteness is that any loop traverses an even number of sites, since it must alternate between the two sublattices. Hence there is no frustration for a (nearest-neighbor!) Ising antiferromagnet on a bipartite lattice. In fact, a stronger statement is true. Since

\[H_{h=0, J}(s^A, s^B) = -J \sum_{\langle ij \rangle} s_i^A s_j^B\]

\(^8\)Notice, by the way, that bipartite does not require that \(A\) and \(B\) be isomorphic or even that they have the same number of sites. For example, if we simply removed a (periodic) subset of sites (and all the associated links) from the \(A\) sublattice of a lattice, we would still have a bipartite lattice. You can find an example by googling ‘Lieb lattice’. Beware confusion in the literature on this point.
if we flip the spins of one sublattice, we also reverse $J$:

$$H_{h=0,J}(s^A, -s^B) = +J \sum_{\langle ij \rangle} s^A_i s^B_j = H_{h=0,-J}(s^A, s^B).$$

But for any function $\phi$

$$\sum_{\{s\}} \phi(\{s\}) = \sum_{\{s\}} \phi(\{-s\}) \quad (3.2)$$

by renaming summation variables. Therefore on a bipartite lattice

$$Z(h = 0, J) = \sum_{\{s\}} e^{-\beta H_{h=0,J}(s^A, s^B)} = \sum_{\{s\}} e^{-\beta H_{h=0,-J}(s^A, s^B)} = Z(h = 0, -J).$$

So on a bipartite lattice, a ferromagnet and an antiferromagnet have the same thermodynamics.

The nearest-neighbor restriction is essential here. Even for a one-dimensional chain, we can make frustration by adding antiferromagnetic interactions for $s_i s_{i+1}$ and for $s_i s_{i+2}$.

**Symmetry and spontaneous symmetry breaking.** Notice that the general Ising Hamiltonian (3.1) enjoys the following property

$$H_{h,J,K...}(s) = H_{-h,J,-K...}(-s)$$

-- flipping all the spins and flipping the coefficients of odd powers of the spins preserves the energy. In particular, if $h = 0, K = 0$, all odd powers do not appear, and flipping the spins is a symmetry of the Hamiltonian. What consequence does this have for thermodynamics?

$$Z(-h, J, -K, T) = \sum_{\{s\}} e^{-\beta H_{-h,J,-K}(s)} = \sum_{\{s\}} e^{-\beta H_{h,J,K}(-s)} \quad (3.2) \equiv Z(h, J, K, T).$$

And therefore the free energy in particular satisfies $F(-h, J, -K, T) = F(h, J, K, T)$. Let’s set $K = 0$ from now on. This operation $s_i \rightarrow -s_i$ is a $\mathbb{Z}_2$ transformation in the sense that doing it twice is the same as doing nothing. It is a symmetry when $h = 0$. (Only when $h = 0$ does the transformation map the ensemble to itself.)

**Question:** does this mean that when $h = 0$ we must have zero magnetization,

$$M = \frac{1}{N} \sum_i \langle s_i \rangle \propto \partial_h F \equiv 0 \ ?$$

A nonzero value of $M$ (without an applied field $h$) is called **long-range order**, because it means that distant spins must conspire to point in the same direction.
Answer: It would if $F(h)$ had to be a smooth, differentiable function. In order for $\langle s \rangle_{h=0}$ to be nonzero, $F(h)$ must have a different derivative coming from positive and negative $h$, as in the figure at right. This phenomenon is called spontaneous symmetry breaking because the symmetry reverses the sign of the magnetization $M \to -M$.

But this phenomenon, of $\partial_h F|_{h=0^+} \neq \partial_h F|_{h=0^-}$ requires the function $F(h)$ to be non-analytic in $h$ at $h = 0$. This is to be contrasted with the behavior for a finite system ($N < \infty$) where

$$Z(h) = \sum_{\{s\}} e^{-\beta H(s)} = e^{-\beta h N m_1 c_1} + e^{-\beta h N m_2 c_2} + \ldots + e^{-\beta h N m_n c_n}$$

where $n = 2^N$ is the number of configurations, $c_a$ are positive coefficients (functions of $\beta J$) independent of $h$, and $m_a$ is the magnetization in configuration $a$ ($m_a = \sum_i s_i(a)/N$). The important point is just that there is a finite number of terms in this sum, and $Z$ is therefore a polynomial in $e^{-\beta h}$, so $F(h) = -T \log Z(h)$ is only singular when $Z = 0$ or $Z = \infty$, which doesn’t happen for finite values of $\beta, h$.

In conclusion: spontaneous symmetry breaking requires the thermodynamic limit $N \to \infty$.

### 3.1 Decimation RG for 1d nearest-neighbor Ising model

Let’s step back from these grand vistas and apply the RG for the Ising model in one dimension. Consider a chain of sites $i = 1 \ldots N$, arranged in a line with spacing $a$, and with an even number of sites, $N \in 2\mathbb{Z}$. And for definiteness, if you must, take periodic boundary conditions $s_{N+1} = s_1$. Turn off the magnetic field, so

$$H = -J \sum_{i=1}^N s_i s_{i+1}.$$

We’ll speak about the ferromagnetic case, $J > 0$ (though the same results apply to $J < 0$ since the chain is bipartite). The partition function

$$Z = \text{tr} e^{-\beta H} = Z(\beta J)$$

is calculable exactly in many ways, each of which instructive. Since the partition function only depends on the combination $\beta J$, let us set $\beta = 1$.

In the spirit of the RG, let us proceed by a hierarchical route, by decimating the even sites:

$$\sum_{\{s\}_{i, \text{even}}} e^{-H(s)} = e^{-H_{\text{eff}}(s_{\text{odd}})}$$
On the right hand side, we have defined the effective Hamiltonian for the spins at the odd sites. The odd sites are separated by distance $a' = 2a$ and there are half as many of them. We can use this as the first half of an RG implementation (the second half is rescaling). We’ve zoomed by a factor of $\lambda = a'/a = 2$.

In this 1d case we can actually do these sums:

$$\sum_{s_2 = \pm 1} e^{J s_2 (s_1 + s_3)} = 2 \cosh (J (s_1 + s_3)) \equiv \Delta e^{J s_1 s_3}$$

where in the last step we defined $\Delta, J'$, constants independent of the configuration of the remaining, not-yet-decimated spins. Then the result for the whole trace over even spins is

$$e^{-H_{\text{eff}}(s')} = \Delta^{N/2} e^{J' \sum_{i} (s_{2i+1} + s_{(i+1)+1})} \implies H_{\text{eff}}(s') = \sum_{i, \text{ odd}} J' s_i s_{i+2} + \frac{N}{2} \log \Delta.$$ 

The $\Delta$ business just adds a constant to the (free) energy, which divides out of the partition function and we don’t care about it here.

We can figure out what the new parameters are by checking cases, of which only two classes are distinct:

if $s_1 = s_3$: $2 \cosh 2J = \Delta e^{J'} \implies \Delta^2 = 4 \cosh 2J$
if $s_1 = -s_3$: $2 = \Delta e^{-J'} \implies e^{2J'} = \cosh 2J.$ \hfill (3.3)

The solution can be usefully written as

$$v' = v^2, \quad \Delta = 2\sqrt{\cosh 2J} \hfill (3.4)$$

where $v \equiv \tanh J \in [0, 1]$ (using hyperbolic trig identities). The map (3.4) is another explicit example of an RG map on the parameters. In this case, unlike the previous SAW example, it happens to be exact.

**The RG preserves symmetries.** Why is the effective Hamiltonian of the same form as the original one? The couplings like the magnetic field multiplying odd numbers of spins vanish by the Ising spin-flip symmetry of the original model. (More precisely: because of the locality of $H$, we can determine $H_{\text{eff}}$ by decimating only a finite number of spins. This rules out generation of nonzero $h'$ by some version of spontaneous symmetry breaking. This requires locality of the interactions.) This line of thinking leads us to expect that the effective Hamiltonian should generally have the same symmetries as the original one.

The 4-spin interaction vanishes because in 1d, each site has only two neighbors with whom it interacts, each of which has only one other neighbor. So that was a bit of an accident.
This map has two fixed points: One is \( v^* = 0 \), which is \( \beta J = 0 \), meaning infinite temperature, or no interactions; this one is ‘boring’ from the point of view of the study of many-body physics and collective phenomena, since the spins don’t care about each other at all. The other fixed point is \( v_* = 1 \), which is \( \beta J = \infty \), meaning zero temperature or infinite interaction strength. This is a ferromagnetic fixed point where it is very urgent for the spins to agree with each other. The fact that there is no fixed point at a finite temperature means that there is no critical behavior in the 1d nearest-neighbor Ising model; only at \( T = 0 \) do the spins align with each other.

More explicitly, how does the correlation length behave? In zooming out by a factor of \( \lambda \), it changes by

\[
\xi(v) = \lambda \xi(v') = 2 \xi(v^2) \quad \Rightarrow \quad \xi = -\frac{K}{\log v} \left( T \to 0 \right) 2e^{2J/T} \tag{3.5}
\]

(where \( K \) is a constant not determined by this argument) which is finite for \( T > 0 \).

Why did it happen that there is no critical point at \( T > 0 \)? A point of view which illuminates the distinction between 1d and \( d > 1 \) (and is due to Peierls and now permeates theoretical condensed matter physics) is to think about the statistical mechanics of defects in the ordered configuration.

Consider a favored configuration at low-temperature, where all spins point the same way. Small deviations from this configuration require reversing some of the spins and will cost energy \( 2J \) above the aligned configuration for each dissatisfied bond. In 1d, a single dissatisfied bond separates two happy regions, and is called a kink or domain wall. Notice that the energy is independent of the size of each happy region (which is called a domain). \( n \) domains of reversed spins cost energy \( 4Jn \), since each domain has two boundary links.

In 1d, each region of spins that we reverse has two boundaries, a kink and an antikink.

At \( T = 0 \), the state minimizes the energy and there is no reason to have any kinks. But at \( T > 0 \), we care about (i.e. the macroscopic equilibrium configuration minimizes) the free energy \( F = E - TS \), and the fact that there are many kink configurations matters.

\[9\] A log is a special case of a power law: Taylor expand \( v^\nu \) in \( v \) about 0.

\[10\] Preview: near less weird fixed points, the correlation length will diverge like a power law \( \xi(T) \sim (T - T_c)^{-\nu} \) instead of this weird function.
How many are there? If there are \( n \) segments of \( s = -1 \) in a sea of \( s = +1 \) then we must decide where to place \( 2n \) endpoints. The number of ways to do this is:

\[
\Omega(n) \simeq \binom{N}{2n} = \frac{N!}{(2n)! (N-2n)!} \sim e^{N \log N - 2n \log 2n - (N-2n) \log(N-2n)}
\]

where in the last step we used Stirling’s formula. So the free energy for \( 2n \) kinks is

\[
F_n = n \cdot 4J - T \log \Omega(n) \simeq 4Jn - T (N \log N - 2n \log 2n - (N-2n) \log(N-2n))
\]

In equilibrium, the free energy is minimized with respect to any variational parameters\(^{11}\) such as \( n \), which happens when

\[
\frac{4J}{T} = 2 \log 2n - 2 \log(N-2n) \quad \Rightarrow \quad \frac{n}{N} = \frac{1}{2} \frac{e^{-2J/T}}{1 + e^{-2J/T}} \sim 2 J \frac{1}{2} e^{-2J/T}.
\]

As a check, the correlation length is approximately the size of the domains, which is approximately the inverse kink density:

\[
\xi \sim \left( \frac{n}{N} \right)^{-1} \sim 2e^{2J/T}
\]

which again agrees with our RG result (3.5).

The codewords for this phenomenon are: the destruction of long-range order by the proliferation of topological defects. (They are topological, for example, in the sense that a kink must follow an antikink, and the number of kinks on circle must equal the number of antikinks.)

In the special case of 1d, we can be completely explicit and verify the result for the correlation length by calculating the correlation function.

First of all,

\[
G(r) = \langle s_{i+r} s_i \rangle \quad (3.6)
\]

(let’s keep the disconnected bits in there for now) is independent of \( i \) because of translation invariance. The Boltzmann factor can be written as

\[
e^{\beta J \sum_{(ij) s_i s_j}} = \prod_{(ij)} e^{\beta J s_i s_j}
\]

Since \( s = \pm 1 \), we are multiplying

\[
e^{\beta J s_i s_j} = \cosh \beta J + s_i s_j \sinh \beta J = \cosh \beta J (1 + vs_i s_j)
\]

\(^{11}\)Actually, we’ll prove this statement in section 4.
where \( v \equiv \tanh \beta J \) (as above). Think about expanding this product over links into a sum. Each term in the sum gets either a 1 or a \( vs_is_j \) from each link. Any term in the sum can be visualized by coloring the links which contribute a \( vs_is_j \).

When we multiply this out, the dependence on any one of the spins \( s_i \) can be only two things: 1 if the term has an even number of factors of \( s_i \), or \( s_i \) if it has an odd number. Here’s the Ising model integration table:

\[
\sum_{s_i} 1 = 1 + 1 = 2, \quad \sum_{s_i} s_i = 1 - 1 = 0.
\]

(3.7)

In the last two paragraphs, we haven’t used the restriction to 1d at all. (This will be useful in §3.2.) Consider a single spin \( s_2 \) of an infinite 1d chain; if it is not one of the two sites \( i \) or \( i + r \) in (3.6) the factors which matter to it are\(^{12}\):

\[
\sum_{s_2} (1 + vs_1s_2)(1 + vs_2s_3) \equiv \sum_{s_2} (1 + vs_2(s_1 + s_3) + v^2s_1s_3) = 2 \left(1 + v^2s_1s_3\right).
\]

This is just of the same form as if we had a direct link between 1 and 3 with weight \( v^2 \) (up to the overall prefactor). Therefore, doing this repeatedly \( (r \) times) for the sites in between \( i \) and \( i + r \),

\[
G(r) = \frac{\text{tr} s_i 2^r (1 + v^r s_i s_{i+r}) s_r}{\text{tr} 2^r (1 + v^r s_i s_{i+r})} = v^r
\]

(The red factors are the ones that survive the trace.) Therefore

\[
\xi^{-1} = -\partial_r \log G(r) = -\log v
\]

which agrees with (3.5) with \( K = 1 \).

The thing that’s special about 1d here is that only a single term in the expansion of the product survives the sum. This is because there is only one path between the two sites \( i \) and \( i + r \). If we had taken \( N \) finite and periodic boundary conditions, there would be another path (around the back of the circle) and hence another term in the answer

\[
G(r) = v^r + v^{N-r} \sim v^r.
\]

In \( d > 1 \) there are many paths and the answer is more interesting, as we’ll see below.

---

\(^{12}\)Note that this expression gives a very simple derivation of (3.4).
3.2 High-temperature expansion

Return now to the moment at (3.7), right before we restricted our discussion to one dimension. We had written the partition function of the nearest-neighbor Ising model (on any graph) as a product over links

\[ Z = \cosh^{N_{\Lambda}} (\beta J) \prod_s \left( 1 + v s_i s_j \right) \]  

(3.8)

and argued that expanding this binomial gives a sum over paths in the graph. More explicitly, we think of the two terms in each link factor in (3.8) as a sum over another dynamical variable, \( n_{(ij)} = 0, 1 \):

\[ 1 + v s_i s_j = \sum_{n_{ij} = 0, 1} (v s_i s_j)^{n_{ij}}. \]

So we can write the Ising partition function as

\[ Z = \cosh^{N_{\Lambda}} (\beta J) \prod_{\ell} \sum_{\{n_{\ell}=0,1\}} \sum_{\{s\}} \prod_{(ij)} (v s_i s_j)^{n_{ij}}. \]

Now we can do the sums over the spins using our ‘integration table’ above (3.7). For each spin, the sum is

\[ \sum_{s_i = \pm 1} s_i \sum_{(ij)} n_{ij} = \delta \left( \sum_{(ij)} n_{ij} \equiv 0 \mod 2 \right) \]

Here we’ve defined the notation ‘\( \langle i | j \rangle \)’ to mean ‘neighbors \( j \) of a fixed site \( i \)’. That is: the sum is only only nonzero if an even number of the links ending at site \( i \) have \( n_{ij} = 1 \). If we represent \( n_{\ell} = 1 \) by coloring the link \( \ell \), the configurations which survive this constraint are made of closed loops.

\[ Z = \cosh^{N_{\Lambda}} (\beta J) \prod_{(ij)} (1 + v s_i s_j) = \cosh^{N_{\Lambda}} (\beta J) \sum_C v^{\sum_{i} n_{i}(C)} \]  

(3.9)

where we are summing over configurations of binary numbers \( n_{\ell} = 0, 1 \) on the links that are closed in the sense that

\[ \sum_{(ij)} n_{(ij)} \equiv 0 \quad \forall i. \]
That is: we sum over lattice curves which have an even number of links going into each site. The contribution of a curve $C$ (which is not necessarily connected) is weighted by $v^{\text{length}(C)}$.

This rewriting of the Ising partition sum will be useful below.

### 3.3 RG evaluation of physical quantities

#### Behavior of the correlation length under RG

We’ve defined the correlation length using the spin-spin correlator $G(r)$, in terms of its rate of falloff for large $r$. Let us use this to examine its behavior under the RG more directly. To do this, denote more explicitly

$$G_H(r) \equiv \frac{\text{tr}s_i s_{i+r} e^{-H}}{\text{tre}^{-H}}.$$

Now suppose that $i$ and $i + r$ are both odd sites (so that they survive our decimation); in that case we can still do all the decimation as in the partition function:

$$G_H(r) \equiv \frac{\text{tr}_{o}s_i s_{i+r}e^{-H(s_e,s_o)}}{\text{tre}^{-H(s_e,s_o)}} = \frac{\text{tr}_{o}s_i s_{i+r} e^{-H(s_e,s_o)}}{\text{tre}^{-H(s_e,s_o)}}.$$

I emphasize that the argument of $G_H$ is measured in units of the lattice spacing, i.e. the number of lattice sites between the spins. But recall that $e^{-H'(s_o)} \propto \text{tr}_e e^{-H(s_e,s_o)}$ defines the effective Hamiltonian for the remaining odd sites, so this is precisely

$$G_{H'}(r/2) \equiv \frac{\text{tr}_{o}s_i s_{i+r/2}e^{-H'(s_o)}}{\text{tre}^{-H'(s_o)}}.$$

where now there are only half as many sites in between the spins in the new coarser lattice. Under this RG, we are zooming out by a factor of 2. Altogether, $G_{H'}(r/2) = G_H(r)$. Combining this with the definition of $\xi$, we have

$$\xi_{H'} = \frac{1}{2} \xi_H \quad (3.10)$$

(as we said earlier).

The notation $\xi_H$ is to emphasize that the correlation length is completely determined by the Hamiltonian (I am assuming thermal equilibrium here). At a fixed point, the Hamiltonian does not change under the RG, so the correlation length can’t either. This can be consistent with (3.10) in one of two ways

$$\xi_* = 0 \quad \text{or} \quad \xi_* = \infty.$$

The first case means that spins at different sites do not care about each other, as at $T = \infty$. I’ve already disparaged this case as boring. The second case of a divergent correlation length characterizes critical behavior and we define it to be interesting.
[Domany, RG notes, chapter 1] **Free energy density.** Next I want to show how to calculate the free energy from an ‘RG trajectory sum’. It is a reason to care about the constants in the effective hamiltonian, as in

$$H'(s') = \sum J's's' + a'N'.$$

In the example above, we found $a' = \frac{1}{N} \log \Delta$, where $\Delta$ was some function of the microscopic $J$.

Let the free energy density (free energy per site) be

$$f \equiv -\frac{T}{N} \log Z_N(K).$$

Here I am denoting by $K$ the collection of all couplings, and labelling the partition function $Z_N$ by the number of sites. More explicitly,

$$Z_N \equiv \sum_{\{s\}} e^{-\beta H(s)} \equiv \sum_{\{s\}} e^{-\beta(NC+H(s))} \equiv e^{-N\beta C} \tilde{Z}_N.$$

Here $\tilde{H}$ is a Hamiltonian modified by subtracting a constant so that

$$\sum_{\{s\}} \tilde{H}(s) = 0$$

so that it has no constant piece (for quantum mechanical folks: it is like a ‘normal-ordered’ Hamiltonian). And $\tilde{Z}_N \equiv \sum s e^{-\beta \tilde{H}(s)}$, and naturally we’ll denote

$$\tilde{f} \equiv -\frac{T}{N} \log \tilde{Z}_N.$$

This last expression is a little less innocent than it seems: I am anticipating here that the free energy is extensive – has a leading piece at large $N$ that grows like $N$, $F \sim N f + O(N^0)$ – so that $\tilde{f}$ is independent of $N$ in the thermodynamic limit. (We’ll give an RG-based proof of this statement in §5.) Then $f(K) = C + \tilde{f}(K)$.

Now some RG content: the partition function is invariant under the RG:

$$Z_N = e^{-\frac{NC}{b}} \tilde{Z}_N = e^{-\frac{NC}{b}} e^{-\frac{N' a'}{b'}} \tilde{Z}_{N/b'}(K') = e^{-\beta(NC+N' a'+N^{(2)}(2) a^{(2)})} \tilde{Z}_{N/b^2}(K^{(2)}) = e^{-\beta(NC+N' a'+\cdots+N^{(n)}(n) a^{(n)})} \tilde{Z}_{N/b^n}(K^{(n)}) \quad (3.11)$$

Here we’ve defined $N^{(n)}$ to be the number of sites decimated at step $n$, and $N/b^n$ is the number of sites remaining. For the example above, these are the same, and $b = 2$: $N^{(n)} = N/2^n$. As above $K^{(n)} = R^n(K)$ is the image of the couplings under $n$-times repeated RG transformation. (Notice that if we were in $d$ dimensions, we would have $b = \lambda^d$, where $\lambda$ is the linear zoom factor, and the number of sites decimated would not
equal the number remaining even for $\lambda = 2$.) Taking logs of the BHS of the previous equation

$$f(K) = C + \sum_{k=1}^{n} \frac{N^{(k)}}{N} a^{(k)} + \frac{N}{b^n} \tilde{f}(K^{(n)}).$$

If we iterate the RG transformation enough times, and $\tilde{f}^{(n)}$ is finite, its contribution is suppressed by $b^{-n} \to 0$.

**Magnetization.** The magnetization can be calculated by taking derivatives of the previous result:

$$M \propto \partial_h f = \langle s_i \rangle$$

but here is some cleverness. By translation invariance the BHS is independent of $i$. Therefore, we can choose $i$ to be a site that survives all the decimation. Then

$$\langle s_i \rangle_H = \frac{\sum s_i e^{-H}}{\sum s e^{-H}} = \frac{\sum s_0 s_i \sum s_c e^{-H(s_0,s_c)}}{\sum s_0 \sum s e^{-H(s_0,s)}} = \frac{\sum s_0 s_i e^{-H'(s_0)}}{\sum s_0 e^{-H'(s_0)}} = \langle s_i \rangle_{H'}.$$

We have just shown that the magnetization is an RG invariant. This result required that we are using a *decimation* scheme, where the spins surviving the RG are a subset of the initial spins. I will come back to alternatives soon, and we will see why we need them. This means we can compute the magnetization for a macroscopic system just by following the flow to the end:

$$\langle s_i \rangle = \frac{\sum s_i = \pm 1 s_i e^{-H^\infty(s_i)}}{\sum s_i e^{-H^\infty(s_i)}}$$

but $H^\infty(s_i) = a^\infty + h^\infty s_i$ (these are the only two possible terms) and $h^\infty$ is the fixed-point value of the Zeeman field. So

$$\langle s_i \rangle = \frac{\sum s_i = \pm 1 s_i e^{-h^\infty s_i}}{\sum s_i e^{-h^\infty s_i}} = \frac{-e^{+h^\infty} + e^{-h^\infty}}{e^{+h^\infty} + e^{-h^\infty}} = -\tanh h^\infty.$$

I emphasize again that this works only for decimation schemes.

### 3.4 Need for other schemes

Let’s think about decimation of the Ising model on the square lattice. Again it is bipartite, and we can do the sum of each spin on one of the sublattices fixing the spins on the other, one at a time:

$$\sum_{s_z} e^{J s_z(s_1 + s_2 + s_3 + s_4)} \equiv \psi(s_1 + s_2 + s_3 + s_4).$$
The argument of the function $\psi$ defined by this equation only takes the values 0, $\pm 2$, $\pm 4$. We’ve set the Zeeman field $h = 0$, so it is even $\psi(-x) = \psi(x)$, and there are only three values of the argument we care about. For these values, it can be written as

$$
\psi(s_1 + s_2 + s_3 + s_4) = e^{a' + J'(s_1s_2 + s_2s_3 + s_3s_4 + s_4s_1 + s_1s_3 + s_2s_4) + M's_1s_2s_3s_4}
$$

with values of $a'$, $J'$, $M'$ determined by $J$ which you can figure out. The first term $a'$ is just a constant. The first four terms multiplied by $J'$ are nearest-neighbor interactions on the new (square) lattice with lattice spacing $\sqrt{2}a$ (rotated by $\pi/4$). This means $\lambda = \sqrt{2}$; the number of remaining spins is $N/2$, so $b = \lambda^{d-2} = 2$ as expected in two dimensions. The next two terms are next-nearest-neighbor exchange couplings ($s_1$ and $s_3$ are separated by $2a$) of the same size. Finally, $M'$ multiplies a qualitatively-new 4-spin interaction, proportional to $J^4$. Ick!

This isn’t so bad if we think of the initial Hamiltonian as sitting in a special corner of the large and high-dimensional space of possible couplings, and the RG just moves us to a more generic point:

$$(J, 0, 0, \ldots) \xrightarrow{\mathcal{R}} (J', K', M', \ldots).$$

That’s just a little ugly. But there’s a reason why it’s objectively bad: we can’t repeat this RG step. After the first iteration, we generate couplings between spins of the same sublattice of the remaining square lattice. This means we can’t just sum them independently anymore. We could do some uncontrolled truncation, or we can find a better scheme. There are 2d lattices for which a decimation scheme can work (i.e. can be iterated).
We can nevertheless persevere by truncating the generation of couplings. For example, if we keep terms only to order $J^2$ and order $K$, we do not generate any further couplings beyond $J, K$, and we find a closed set of RG recursion equations:

$$J' = K + 2J^2, \quad K' = J^2.$$  

These equations have three fixed points: $(J, K) = (0, 0), (\infty, \infty)$ and $(1/3, 1/9)$. The nearby flow diagram is indicated at right. Fixing the couplings and varying $T$ amounts to the replacement $(J, K)$ to $(J/T, K/T)$. Increasing the temperature corresponds to scaling $J, K$ down towards $K_0 = (0, 0)$, the infinite-temperature fixed point, where everyone is decoupled. This point and the zero-temperature fixed point $(K_\infty$, where all couplings are infinite) are separated by a new fixed point with a single relevant perturbation. Let’s focus on just the relevant dimension (which is not orthogonal to the temperature direction), so we can draw a one-dimensional plot (after all, we are already ignoring infinitely many other irrelevant directions). We see that there is a critical value $T_c$ below which we flow to $K_\infty$, and above which we flow to $K_0$. A fixed point with a single relevant operator describes a critical point, a continuous phase transition between two phases.
3.5 Low-temperature expansion, and existence of phase transition in \(d > 1\)

Maybe you still don’t believe me that there has to be a phase transition in the nearest-neighbor Ising model, even in \(d = 2\). At arbitrarily high temperatures, there is definitely no spontaneous symmetry breaking, since each spin is just looking out for itself and there can be no collective behavior, and \(\langle s \rangle = m = 0\). At \(T = 0\), the spins all align (as they do in \(d = 1\), too). Here is an argument (due to Peierls, still) that the ordered state survives to some finite temperature for \(d \geq 2\).

A configuration of lowest energy, say all \(s_i = +\), has energy \(E_0 = -J N_l\), where \(N_l\) is the number of links of the graph (this is \(2N\) for the square lattice since there are two links in each unit cell, one up and one right). The minimal excitation above the ordered configuration flips one spin and has energy \(E_0 + 2zJ\) where \(z\) is the number of neighbors of the flipped spin. We can estimate the entropy of a dilute gas of \(n\) such flipped spins, with energy \(E(n) \sim E_0 + 2Jzn\); the number of configurations is again approximately \(\Omega(n) = \binom{N}{n}\), and so their free energy is

\[
F \sim n z 2J - T (N \log N - (N - n) \log(N - n) - n \log n).
\]

(Actually, the flipped spins have a short-ranged attraction because if they are adjacent they share a happy bond. We ignore this; think about why we can get away with it.) This is minimized by an equilibrium density of flipped spins

\[
\frac{n_{\text{eq}}}{N} \approx e^{-2zJ/T}.
\]

All this so far is just like in the \(1d\) argument, except we replaced 2 neighbors with \(z\) neighbors, and counted spin flips rather than domain walls.\(^{13}\)

Here’s the catch: The magnetization is not so strongly affected by a flipped spin as it is by a domain wall. It is only decreased from the maximum \((m = 1)\) to

\[
m = 1 - 2 \frac{n_{\text{eq}}}{N} \approx 1 - 2e^{-2zJ/T} \approx 1 \text{ if } T \ll zJ.
\]

So this means that at low (but nonzero) temperature, the magnetization survives. And therefore something interesting has to happen at some intermediate temperature.

\[\text{[End of Lecture 6]}\]

\(^{13}\text{Why did we count domain walls in } d = 1? \text{ Because in } d = 1, \text{ the energy of a row of } k \text{ flipped spins in a row is the same for any } k. \text{ The elementary dynamical object is really the kink itself in } d = 1. \text{ This is the tip of an iceberg called ‘fractionalization’}.\]
3.6 A word from our sponsor

We’ve been spending a lot of time talking about Ising models. Let’s take a break and talk about another role it plays in physics.

**Lattice gas.** Suppose our dynamical variables are the locations $r_1..r_N$ of a collection of point particles. The grand canonical partition function is

$$\Xi(\zeta) = \sum_N \frac{\zeta^N}{N!} \int d^d r_1 \cdots d^d r_N \ e^{-\beta \sum_{i<j} V(r_i-r_j)}$$

(3.12)

where $\zeta$ is a fugacity for particle number, and $V(r)$ is an interparticle potential, which usually has a short-range repulsion and long-range attraction (most kinds of particles find each other vaguely attractive from far away...). The kinetic energy was $\sum_i \frac{\vec{p}_i^2}{2m}$, but we did the $p$ integrals already: $\int d^d p \ e^{-\beta \frac{\vec{p}^2}{2m}} = (\pi mT)^{d/2}$.

These integrals in (3.12) are hard. If our interest is in critical behavior, we can zoom out, and take the particles to live at the sites of a lattice $r \in \Lambda$, so our dynamical variables are instead the number of particles at site $r$, $n(r)$. To implement the short-range repulsion, we take $n(r) = 0, 1$. Then we study

$$\Xi_\Lambda(\zeta) = \sum_{\{n(r)=0,1\}} \zeta^{\sum_r n(r)} e^{-\frac{1}{2} \beta \sum_{r,r'} J_{r,r'} n(r)n(r')}$$

where $J(r-r')$ implements the long-ranged part of the potential. If we change variables to $s(r) \equiv 2n(r) - 1 = \pm 1$, we have

$$H(s) = - 0.5 \beta \sum_{r,r'} J_{r,r'} s_r s_{r'} - \beta \sum_r h_r s_r + \text{const}$$

with $\beta h_r = \frac{1}{2} \log \zeta + \beta \sum_r J_{r,r'}$. This is an Ising model. The ferromagnetic ordering transition is the liquid-gas transition! Recalling that this occurs at $h = 0$, we see that the $s \to -s$ symmetry of the Ising model (with $h = 0$) is a symmetry of the lattice gas only near the critical point – it is an ‘emergent symmetry’.

Another useful interpretation of the same model is as a ‘binary fluid’, where $n = 0, 1$ represent occupation by two kinds of fluid elements.
3.7 Duality

[Feynman, *Statistical Mechanics* §5.4, Parisi, §4.6]

Let’s set $J = 1$ for a bit, since only the combination $\beta J$ appears in this discussion.

Now consider again the low-temperature expansion: previously we thought about flipping some dilute collection of isolated spins, each of which costs a (Boltzmann) factor of $e^{-2\beta J z}$ in the partition function. More accurate is to think of this as a sum over *islands* of reversed spins. If we were speaking about a 3d lattice, they would be regions, with two-dimensional boundaries. Let’s focus on the case of a 2d lattice, so that the boundaries of the islands are one-dimensional curves.

If we keep track of the boundaries between these regions, we have complete information about the spin configuration, up to an overall reversal. The weight for a given configuration $C$ is $e^{-2\beta \ell(C)}$ where $\ell(C)$ is the total length of boundary in that configuration. We could include a field $h$ in this description, that multiplies the weight by

$$e^{-\beta h(A_{\text{in}}(C) - A_{\text{out}}(C))}$$

where $A_{\text{in/out}}(C)$ is the number of sites inside/outside the chosen configuration of boundaries.

Can we represent the entire partition sum as a sum over these boundaries (which are called *domain walls*?) It is not just a sum over curves. Notice that the boundaries are always closed curves – it is a deep topological fact that a boundary has no boundary. Furthermore, the boundary curve is always *contractible* in the sense that by flipping back some of the spins in the region to agree with the rest, we can gradually shrink it away to nothing. Here’s an example of some curves that are not contractible, on the surface of a complicated pastry:

The curves $A$ and $B$ are not the boundary of any 2d region on the surface of the pastry. Let us restrict ourselves for now to lattices which do not contain such curves (they are called *simply-connected*).

It is useful to introduce at this point the *dual lattice*: for a 2d lattice $\Lambda$, this is a lattice $\hat{\Lambda}$ whose sites correspond to the plaquettes of $\Lambda$. A link of $\Lambda$ separates two plaquettes of $\Lambda$; it corresponds to a link of $\hat{\Lambda}$ connecting the two corresponding sites of $\hat{\Lambda}$:

The domain walls of a spin configuration on the sites of $\Lambda$ cover a set of links of $\hat{\Lambda}$:
But our description of the low-temperature expansion on Λ as

\[ Z_\Lambda(T) = 2 \sum_C e^{-2\beta(C)} \tag{3.13} \]

has exactly the same form as our high-temperature expansion (3.9) if we identify

\[ e^{-2\beta} = \tilde{\nu} \equiv \tanh \tilde{\beta}. \]

This equation relates high temperature (small \( J \)) on Λ to low temperature (large \( J \)) on \( \tilde{\Lambda} \). It is due to Kramers and Wannier.

For the square lattice, the dual lattice is the square lattice again! This means that if there is only one critical point (remember: fixed points of the RG are rare and valuable), it must be a fixed point (not only of the RG but also) of the duality transformation on the couplings:

\[ e^{-2\beta J} = \tilde{\nu} \equiv \tanh \beta J. \]

The dual of the honeycomb lattice is the triangular lattice (and vice versa). To learn their critical temperature, we add one more maneuver, called star-triangle transformation: The honeycomb lattice is bipartite, and the two sublattices are triangular lattices. By decimating one of the two sublattices, we can relate

\[ Z^N_\Lambda(J) = \Delta^{N/2} Z^N_{\Delta}(K) \]

where \( \Delta \) and \( K \) are determined from \( J \) by:

\[ \sum_{s_2=\pm 1} e^{J s_2 (s_1 + s_2 + s_3)} = \cosh^3 J \left[ 1 + \tanh^2 J \cdot (s_1 s_2 + s_2 s_3 + s_3 s_1) \right] \equiv \Delta e^{K (s_1 s_2 + s_2 s_3 + s_3 s_1)}. \]

Combining this with the duality relation we can relate the critical temperature of the Ising model on the triangular lattice to itself.

Here is a table of the critical values of \( \frac{1}{\beta J} \) for various lattices. \( z \) is the coordination number, the number of neighbors of each site.

<table>
<thead>
<tr>
<th>Λ</th>
<th>( z )</th>
<th>( T_c/J )</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>○</td>
<td>3</td>
<td>1.52</td>
</tr>
<tr>
<td>□</td>
<td>4</td>
<td>2.27</td>
</tr>
<tr>
<td>△</td>
<td>6</td>
<td>3.64</td>
</tr>
</tbody>
</table>
The first entry is the 1d chain. You can see that the critical temperature rises with coordination number.

Notice that the disordered (high-temperature) phase is dual to the ordered (low-temperature) phase. That this is not a contradiction is related to the factor of 2 in front of the partition sum in (3.13): the description in terms of domain walls doesn’t really know about the magnetization.

If you can’t wait to learn more about the many generalizations of Kramers-Wannier duality, here are some references: Kogut, Savit.

There is more to be said about this sum over curves. They can be used to solve the 2d Ising model exactly. They are the worldlines of free fermions.

### 3.8 Block spins

Here we introduce a more general class of coarse-graining transformations, called *blocking*. The essential rule is that the partition function is an RG invariant:

\[
Z = \sum_s e^{-H(s)} = \sum_{s'} e^{-H'(s')}. \tag{3.14}
\]

Previously, in the decimation schemes, the coarse-grained variables \(\{s'\} \subset \{s\}\) were a subset of the microscopic variables. This is a special case of the more general blocking rule

\[
e^{-H'(s')} \equiv \sum_s \prod_{\text{blocks}, b} T(s'; s_{i \in b}) e^{-H(s)}
\]

where \(T\) is a function which decides how the *block spin* \(s'\) depends on the spins \(s_i\) in the block. Decimation is the special case where we weight the opinion of one of the spins over all the others:

\[
T_{\text{decimate}}(s'_b; s_{i \in b}) = \delta_{s'_b, s_2}.
\]

Another option is majority rule:

\[
T(s'_b; s_{i \in b}) = \begin{cases} 
1, & \text{if } s'_b \sum_{i \in b} s_i > 0 \\
0, & \text{otherwise}
\end{cases}
\]

Notice that for each block, \(\sum_{s' = \pm 1} T(s'; s) = 1\) guarantees (3.14). Furthermore, it is useful if \(T(s'; s) \geq 0\), so that everything is a probability. Also, it is best if \(T\) preserves the symmetries of the system.
4 Mean Field Theory

Mean field theory (MFT) is always simple and sometimes right, and it is all around us in physics departments, so we must understand well when to believe it. We will see that it goes bad near critical points, and the RG will come to our rescue. It is great for getting a big picture of the phase diagram.

We’ll give three roads toward MFT, in order of decreasing squiggliness. For definiteness, consider the Ising model, on any graph Λ:

\[ Z = \sum_s e^{-H(s)}, \quad H(s) = -\frac{1}{2} \sum_{i,j \in \Lambda} J_{ij}s_i s_j - h \sum_i s_i. \]

(I’ve put the ½ to agree with our previous definition of \( J \), because here the sum is over all \( i, j \).) Mean field theory is an attempt to fulfill the urge everyone has to be able to do the sums over the spins one at a time. If only \( J \) were zero, we could do this, for example to compute the magnetization:

\[ m = \langle s \rangle = \frac{\sum_{s=\pm 1} s e^{\beta hs}}{\sum_{s=\pm 1} e^{\beta hs}} = \tanh \beta h. \]  

But \( J \neq 0 \) is much more interesting. So what to do?

Our first approach to MFT is via political science. Mean field theory is the physics realization of libertarian political philosophy\(^\text{14}\). This has two ingredients.

(1) **No one cares about anyone else.** What I mean by this is: put yourself in the position of one of the spins in the Ising model. How does it even know about its neighbors? Its role in the hamiltonian is

\[ H(s_i) = s_i \left( -\frac{1}{2} \sum_{j \neq i} J_{ij} s_j - h \right). \]

From its point of view, this is just like some external magnetic field depending on what its neighbors are doing. What’s \( s_j \)? Well, it’s probably equal to its average value, \( \langle s_j \rangle = m \). So let’s just forget everyone else, and assume they are average and incorporate them into an effective magnetic field:

\[ h_{\text{eff}} \equiv \frac{1}{2} \sum_j J_{ij} m + h. \]

The second tenet is

(2) **Everyone’s the same (and I am just like everyone).** That is: if there is only

\(^{14}\text{Disclaimer: I actually don’t know anything at all about political philosophy and made all this up during lecture.}\)
one spin in the world, and this is the field it sees, then we can compute \( m \) using (4.1):

\[
m \stackrel{(4.1)}{=} \tanh \beta h_{\text{eff}} = \tanh (z J m + h). \]

Here I defined \( J \equiv \frac{1}{2} \sum_j J_{ij} \). This is an equation for \( m \)! We can solve it!

At least graphically or numerically we can solve it. Here is \( m \) (yellow) and tanh\((z J m + h)\) (blue) plotted versus \( m \) for two values of \( J \) (large and small compared to \( T \), with some small \( h \))

Here’s our second approach to MFT. Basically, here we will be more explicit about what we’re leaving out (but it is the same as the previous discussion). We rewrite the interaction term in the Ising hamiltonian as

\[
s_i s_j = (m + (s_i - m))(m + (s_j - m)) \equiv (m + \delta s_i)(m + \delta s_j) = m^2 + m(\delta s_i + \delta s_j) + \mathcal{O}(\delta s)^2 = -m^2 + m(s_i + s_j) + \mathcal{O}(\delta s)^2. \tag{4.2}
\]

We are going to treat the fluctuation about the mean \( \delta s \) as small. Then

\[
-H = \frac{1}{2} \sum_{ij} J_{ij} (m(s_i + s_j) - m^2) + h \sum_i s_i + \mathcal{O}(\delta s)^2
= -\frac{1}{2} N J m^2 + (z J m + h) \sum_i s_i + \mathcal{O}(\delta s)^2. \tag{4.3}
\]

\( N \) is the number of sites, and \( J \equiv \sum_j J_{ij} \). The contribution \( J m \) to the external field from the neighbors is sometimes called the ‘molecular field’. What we are neglecting here (when we drop the \( \mathcal{O}(\delta s)^2 \) in a moment) is the correlations between the spins at different sites \( i, j \). This is not small if \(|r_i - r_j| < \xi \), by definition of the correlation length \( \xi \). Brutally ignoring the correlations, then, we can do all the sums have

\[
Z \simeq e^{-\frac{1}{2} N \beta J m^2} (2 \cosh(\beta(z J m + h)))^N \equiv Z_{\text{MFT}}
\]

So in this approximation, the free energy density is

\[
f_{\text{MFT}}(m) \equiv -\frac{T}{N} \log Z_{\text{MFT}} = \frac{1}{2} J m^2 - T \log \cosh(\beta(z J m + h)) + \text{const}.
\]

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I claim, and will prove next, that \( f_{\text{MFT}}(m) \geq f \) is an upper bound on the correct free energy. This is true for every \( m \), and so the best bound comes from minimizing over \( m \). That condition gives back the equation for \( m \) (namely \( m = \tanh(\beta \{ zJm + h \}) \)) that we got from self-consistency above. (And it will tell us what to do in the case of \( J \gg T \) where there are three solutions.)

Our third approach is the variational method. [There is a good discussion of this in Parisi’s book.] It will give our proof that \( f_{\text{MFT}}(m) \) upper bounds \( f \). The idea can be found from a Bayesian viewpoint on statistical mechanics. Let’s put this in a box:

**Bayesian viewpoint on statistical mechanics.** Suppose we are given a (classical) physical system, defined by a configuration space (e.g. the values of a bunch of spins \( \{ s \} \)) and a Hamiltonian \( (H(s)) \). Further suppose that the only thing we know about the state of the system is the average energy \( E \). What probability distribution \( P(s) \) should we use to make predictions? We don’t want to add unjustified information. One way is to find the distribution \( P^\star \) which maximizes the (Shannon) entropy

\[
S[P] \equiv - \langle \log P \rangle_P = - \sum_s P(s) \log P(s),
\]

subject to the constraint that \( E = \langle H \rangle_{P^\star} \equiv E[P^\star] \). The distribution should also be normalized \( \sum_s P(s) = 1 \). We can impose these conditions with lagrange multipliers:

\[
\Phi[P] \equiv S[P] + b(E[P] - E) + a\left( \sum_s P(s) - 1 \right) = - \sum_s P(s) \log(P(s)) + \sum_s (bH(s) + a)P(s) - bE - a
\]

\[
\frac{\delta \Phi[P]}{\delta P(s)} = - \log P(s) - 1 + bH(s) + a
\]

\[
\Rightarrow P^\star(s) = e^{bH(s) + a - 1}
\]

where \( a, b \) must be determined to satisfy the two constraints.

If instead of fixing the average energy, we want to fix the temperature \( 1/\beta \), what do we do? We should instead find the distribution \( P^\star(s) \) which minimizes the free energy

\[
\]

\(^{15}\text{A useful way to think about this quantity is the following. Given a distribution } P(s), \text{ the quantity } - \log P(s) \text{ is called the surprise of the configuration } s \text{ – the bigger it is, the more surprised you should be if } s \text{ actually obtains. So the Shannon entropy is simply the average surprise (or maybe the expected surprise). Clearly, all else being equal, we will make the best predictions using the distribution that minimizes the expected surprise. If you like this perspective on the world, the place to get more is E. T. Jaynes, Probability Theory: The Logic of Science.}\)
as a functional of $P$. It is still normalized, so we need to use a lagrange multiplier again, and minimize

$$F_\lambda [P] \equiv F[P] + \lambda \left( \sum_s P(s) - 1 \right)$$

which is extremized when

$$0 = H(s) + T + \lambda + T \log P(s)$$

from which we again recover the Boltzmann distribution, $P(s) = e^{-\beta H(s)/Z}$ (the multiplier $\lambda$ is eliminated in favor of $Z$ by normalizing).

This derivation is useful philosophically (for example, it evades all the vexing questions about ergodicity), and it also implies a variational bound on the free energy $F$. That is, if we pick some arbitrary other distribution $P_{\text{off-the-street}}(s)$, then we know that its free energy is bigger than the correct equilibrium free energy:

$$F[P_{\text{off-the-street}}] \geq F[e^{-\beta H}/Z].$$

So: to recover mean field theory, we choose a distribution which we like because we know how to calculate its averages, that is, one which factorizes:

$$P_{\text{MFT}}(s) = \prod_i p_i (s_i) \quad (4.4)$$

where we can parametrize the individual factors as $p_i(s) = e^{-\beta h_i}/z_i$ or as

$$p_i(s) = \frac{1 + m_i}{2} \delta_{s,1} + \frac{1 - m_i}{2} \delta_{s,-1}.$$ 

It is normalized since each factor is. For any distribution of the form (4.4) all the moments factorize:

$$\langle g_1(s_1)g_2(s_2) \rangle_P = \langle g_1(s_1) \rangle_{p_1} \langle g_2(s_2) \rangle_{p_2}$$

and each factor is

$$\langle g(s) \rangle_{p_1} = \frac{1 + m_i}{2} g(1) + \frac{1 - m_i}{2} g(-1).$$

And in particular,

$$\langle s \rangle = m_i, \quad \langle H \rangle = -\frac{1}{2} \sum_{ij} J_{ij} m_i m_j - \sum_i h m_i$$

and its entropy is

$$S[P] = -\langle \log P \rangle_P = \sum_i s(m_i), \quad s(x) \equiv -\frac{1 + x}{2} \log \frac{1 + x}{2} - \frac{1 - x}{2} \log \frac{1 - x}{2}.$$
Now we apply the variational bound. The free energy $F(m_i) = F[P_{\text{MFT}}^{(m_i)}] \geq F$ upper bounds the true free energy for any $m$, so we do best by minimizing it:

$$0 = \partial_{m_i} F = -\sum_j J_{ij} m_j - h_i + T \tanh m_i$$

which gives back

$$m_i = \tanh \beta \left( \sum_j J_{ij} m_j + h_i \right)$$

the mean field equation.

This perspective on mean field theory has the further advantage that it is systematically improvable. For example, rather than writing a completely factorized distribution $p(s) = \prod_i p_i(s_i)$, we could instead consider, for example, a trial state of the form

$$p(s) = \prod_b p_b(s_{i\in b})$$

where $b$ represent some blocks of sites. Such a state is more general than the MFT ansatz, and will have more variational parameters, and necessarily gives a better estimate of the correct free energy. Further thinking in this direction leads to cluster mean field theory and belief propagation algorithms.

On the form of the mean-field free energy. The most important conclusion from the mean field theory is that (for $h = 0$) there are two phases distinguished by whether or not the $\mathbb{Z}_2$ symmetry is spontaneously broken – at high $T$, we have $m = 0$, and at low $T$ $m \neq 0$. In between there is a phase transition\footnote{In case I forgot to say so, a phase transition occurs when physical quantities are non-analytic in the parameters at some point in the parameter space – it means that Taylor expanding physics on one side of the phase transition gives the wrong answer (for something) on the other side.}, where $m$ suddenly grows from zero. If we set $h = 0$ and study small $m$, we can expand $f_{\text{MFT}}$ in $m$ and find

$$f_{\text{MFT}}(m) \simeq a + \frac{1}{2} B m^2 + cm^4 + \ldots$$

where $a, c$ are constants. The coefficient $B$ is

$$B = (1 - \beta J) \equiv bt,$$

where $t \equiv \frac{T - T_c}{T_c}$ is the “reduced” temperature. If $c > 0$, this function looks like one of the figures at right, where the top left figure is for $T > T_c^{\text{MF}} = J$ and the bottom left
figure $T < T_c$ (disordered phase) and $m \neq 0$ for $T < T_c$ (ordered phase). This figure makes it clear that the third solution of the MF equations (at $m = 0$) that exists for $T < T_c$ is a maximum of the free energy – it is unstable.

4.1 Landau-Ginzburg theory

[Parisi §4.3, 5.2] Before drawing any further physical conclusions from the MFT free energy we just derived, let me say some words in defense of this form of the free energy (4.5). These are the words (the idea is due to Landau; this is a paraphrase):

What else could it be?

If the free energy is analytic near $m = 0$, it looks like this. So all that song and dance about justifying mean field theory is really irrelevant to the conclusions we draw about the phase transition from $m = 0$ (at $T > T_c$) to $m \neq 0$ (at $T < T_c$). The dependence of $B$ on $T - T_c$ follows from (4.5) itself! With this assumption, $f_{\text{MFT}}(m)$ is the most general answer, consistent with the symmetry under $\begin{cases} m &\mapsto -m \\ h &\mapsto -h \end{cases}$ (at the same time).

So: the only real assumption leading to (4.5) is the analyticity of $f(m)$. Some points:

1. we will see immediately below that analytic $f(m)$ does not mean that the physics is analytic in external parameters – we can get critical behavior from this framework.
2. When we find out that MFT gives wrong predictions for critical exponents, we will have to find out how and why we get an $f(m)$ which is not analytic. (3) The fact that the coefficient of $m^2$ is proportional to the deviation from the critical temperature follows from our analysis of (4.5). The only input from the microscopic calculation (with all the approximations above) is how do the coefficients $a, b, c, d$ depend on the microscopic couplings. Notice that the actual magnetization $m = N^{-1} \sum_{i=1}^{N} \langle s_i \rangle$ is an average of numbers each $\pm 1$, and therefore lies between these two numbers. The minimum of $f(m)$ will not satisfy this constraint for all values of $a, b, c, d...$ consistent with the input above: this is a “UV constraint on IR physics” of the kind that the string theorists dream about.

Types of phase transitions. A first order phase transition is one where the minimum of the free energy jumps from one value to another, distant value, like if the potential evolves as in this comic strip as a function of the parameter in question:
The two configurations need have nothing to do with each other, and there is no notion of universal properties of such a transition. The correlation length need not grow. This is what happens when we vary $h$ from positive to negative, at nonzero $t < 0$. The correlation length stays fixed, but the minimum jumps from $-m_0$ to $+m_0$ as $h$ goes through zero (as in the comic strip above).

The alternative is a continuous phase transition which is more interesting, because then, as we will see, there is a field theory which encodes a collection of universal phenomena at and near the critical point.

(Sometimes, one hears about ‘$n$th-order’ phase transitions, where the $n$th derivative of the free energy is discontinuous for various $n \geq 2$, but I haven’t found the need to distinguish between these. Moreover, it is only in mean field theory that the free energy goes like integer powers of $t$ (as in (4.6) below); more generally, taking enough derivatives of the free energy will give a divergent (not just discontinuous) behavior at the transition. So this more detailed ‘classification’ (due to Ehrenfest) is both incomplete and not useful.)

Notice that when we say that ‘a transition is continuous’ it can depend on what parameter we are varying: at $T < T_c$, as a function of the magnetic field, the transition from one minimum to the other of the Ising model is first order. (This is what’s illustrated in the comic above). But at $h = 0$, there is a continuous transition as $T$ is varied through $T_c$.

Here are some simple examples of the power of the LG point of view: If we break the Ising symmetry the transition should generically be first order. This allows a cubic term in the potential, and it means that as we cool from high temperatures, one of the two minima at $m \neq 0$ will have $f(m) < f(0)$ before (at a higher temperature than the one where) $f''(0)$ becomes negative.

A continuous transition is, however, not an inevitable consequence of Ising symmetry: if $c < 0$, then we must consider the $m^6$ term. Depending on the signs, there is a regime where the minima at $m \neq 0$ descend before $f''(0)$ goes negative.

Usually (but not always) $T_\text{c}^{\text{MF}} > T_c$, since the fluctuations we are ignoring disfavor the ordered state. (Sometimes in fact $T_c \leq 0.$)
Mean field critical exponents. The very fact that there is a notion of $T_c$ in MFT is worth remarking on. Lots of stuff is non-analytic at $T_c$!

Near $T_c$, we can expand

$$f_{MF}(m) = a + btm^2 + cm^4 + \mu hm + \ldots$$

where $T \equiv \frac{T - T_c}{T_c}$ is the non-dimensionalized deviation from the critical temperature. Notice that $a, b, c, \mu$ really do depend on $T$, but only weakly (i.e. $a = a_0 + a_1 t + \cdots$).

When $h = 0$, the free energy is minimized when:

$$m = \begin{cases} 0, & t > 0 \\ \pm \sqrt{\frac{b}{2c}} \sqrt{-t}, & t < 0 \end{cases}$$

The magnetization critical exponent is called $\beta$ and $\beta_{MFT} = \frac{1}{2}$.

When $h \neq 0$ (and small) and $t > 0$, we can ignore everything but $f \sim a + btm^2 + \mu hm$ (beware typos in Cardy’s book here) to find

$$m \sim \frac{\mu h}{bt}.$$ 
This exponent in $t$ (which determines $\chi = \partial_h m \sim t^{-\gamma}$) is called $\gamma$, and $\gamma_{MFT} = 1$.

Right at the transition, $t = 0$, we must keep the quartic term and we find

$$m \sim \left( \frac{\mu h}{c} \right)^{1/3}.$$ 
This exponent is called $\delta$ and $\delta_{MFT} = \frac{1}{3}$. (I’m mentioning this botany of greek letters because there are people for whom these letters are close friends.)

Finally, the free energy density evaluated at the minimum, at $h = 0$, is

$$f(t) = \begin{cases} a, & t > 0 \\ a - \frac{(bt)^2}{2c}, & t < 0 \end{cases}$$

which means that $\partial_t^2 f$ jumps at the transition; this jump is actually an artifact of MFT.

Otherwise, the behavior in general predicted by MFT is good, but we’ll see that the values of these exponents aren’t always right (and why and when, and then we’ll understand how to fix them). In particular, mean-field critical exponents are always rational numbers. In contrast, for the 3d Ising model, $\beta = 0.326419(3)$, which isn’t looking very rational. This value comes from the conformal bootstrap program to solve and classify fixed points.
Notice that the critical exponents do not depend on the particular values of the parameters $a, b, c, \mu \ldots$. This is one reason to hope that they can be understood, and that they are universal in the sense defined earlier.

It is worth thinking about what the extrema of this potential do as we vary the parameters. At right is a plot of the free energy evaluated at all of the critical points of $f(m)$ as $h$ varies (the other couplings are fixed to $T < T_c$). (This picture is sometimes called a ‘swallowtail’.) Inset in red is the shape of the potential at the corresponding value of $h$. Plotted below is the corresponding magnetization. Notice that the number of (real) critical points goes from 1 to 3 as $|h|$ is decreased below some value; the two new extrema are pair-produced from the complex plane, that is, the new extrema come in pairs and have a larger free energy. Notice further that $\partial_h^2 f > 0$ along the top trajectory – this is the maximum near the origin. The other one is actually a local minimum – a metastable state, responsible for hysteresis phenomena at the first-order transition. More on the physics of this in §5.5.
LG Theory for other symmetries. Here is another illustration of the Power of Landau. We’ve been studying models with a $\mathbb{Z}_2$ symmetry acting by $\{m \mapsto -m, h \mapsto -h\}$. 

Suppose instead of this, we made the replacement $\mathbb{Z}_2 \sim O(n)$ rotation symmetry acting on a generalization of the magnetization with $n$ components, $m \sim m_a$, in that case the external field would be $h \sim h^a$, and the transformation rule would be

$$\begin{align*}
m_a &\mapsto R^b_a m_b \\
h^a &\mapsto h^a R^b_a
\end{align*}$$

(where $R$ is an orthogonal matrix ($R^t R = 1$) so that $m_a h^a$ is invariant and can be added to the hamiltonian). Incidentally, the field $m_a$ playing the role of the magnetization, the thing that orders at low temperatures, is called the order parameter.

What's the free energy in this case? If it’s analytic in $m$, for small $m$ it must be of the form\textsuperscript{17}

$$f_{\text{LG}}(m_a) = a + b t \sum_a m_a^2 + c \left( \sum_a m_a^2 \right)^2 + \ldots + \mu h^a m_a .$$

For $t < 0$, a minimum occurs at $m_a = (m_0, 0, 0\ldots)_a$ with $m_0 = \sqrt{-\frac{bt}{2c}}$, as well as at all its images under an arbitrary $O(n)$ rotation. The $O(n)$ symmetry is broken in the sense that the free energy minima form a nontrivial orbit of the symmetry (and furthermore, the free energy at the minimum will be non-analytic in $h$ near $h = 0$). This degeneracy has the following consequence. If we expand $m_a = (m_0, 0, 0\ldots)_a + \delta m_a$ about the minimum, we find

$$f_{\text{LG}} = c + 2b|t|\delta m_1^2 + \mathcal{O}(\delta m^4)$$

- the quadratic terms are completely independent of the other $N$ components of the fluctuations $\delta m_2\ldots\delta m_N$! We’ll see in a moment that this absence of a restoring force means that those degrees of freedom have infinite correlation length, even in the ordered phase. They are called Goldstone modes.

[End of Lecture 8]

\textsuperscript{17}Dachuan Lu reminds me that for some values of $n$, there can sometimes be extra invariants, such as $\epsilon_{i_1\ldots i_n} m_{i_1} \cdots m_{i_n}$.
‘Microscopic’ Landau-Ginzburg Theory. In our variational derivation of mean field theory, we actually derived a stronger bound, since we allowed for spatially-varying magnetization. Let’s combine the Landau point of view with the knowledge that the free energy is extensive\textsuperscript{18} to learn the answer without doing any work. Because $F$ is extensive, we can write the free energy as a sum over a contribution associated to each lattice site, or patch of the lattice $F = \sum_i f_i$, where $f_i$ depends on the magnetization $m_i$ at site $i$ and nearby sites. (Think about assembling the system from big enough chunks.) If the correlation length is not so small, $f_i$ will vary smoothly and we can approximate this as an integral: $\sum_i f_i(x_i) \simeq a^{-d} \int d^d x f(x)$. The integrand, in turn, depends locally on the field and its derivatives. Translation invariance forbids any explicit dependence on $x$:

$$F[m] = \int d^d x f(m(x), \nabla m(x), \nabla^2 m(x) ...).$$

Symmetries further constrain the form of $f$: $\mathbb{Z}_2$ symmetry forbids terms odd in $m$ and $h$, parity symmetry forbids terms with an odd number of derivatives, rotation invariance requires us to dot all the vector indices together. So, under the crucial analyticity assumption, we have

$$f_{\text{LG}} = V(m) + \kappa \nabla m \cdot \nabla m + \kappa' (\nabla^2 m)^2 + ... \quad (4.7)$$

where $V(m) = a + Bm^2 + cm^4 + dm^6 + ...$ is the value when $m$ is constant in space – it contains all the information about the mean field treatment of phase transitions, some of which we discussed above.

We will have a lot more to say about how to organize this expansion. So far it is an expansion in powers of $m$ (since know that in the neighborhood of the critical point $m$ is small). It is also an expansion in the number of derivatives, something like the dimensionless quantity $a \nabla m$, where $a$ is the lattice spacing. If this quantity is not small then we are asking the wrong question, because the ‘field’ we are treating as continuous is varying rapidly on the scale of the lattice spacing $a$. The RG will give us a better understanding of this expansion: we’ll see that operators with more derivatives are more irrelevant (near any of the fixed points under discussion here).

The equation (4.7) contains an enormous amount of information. To better appreciate it, let’s first discuss the mean-field treatment of the correlation function.

\textsuperscript{18}I owe you some discussion of why this is the case. This happens in §5.1.
The answer to this is that it is the free energy with the constraint that the (coarse-grained) magnetization is fixed to be \( m(r) \):

\[
e^{-\beta F_{LG}[m]} \equiv \sum_{s} e^{-\beta H(s)} \prod_{\text{blocks}, r} \delta \left( \sum_{i \in r} s_i - m(r) N_\Lambda(r) \right).
\]

(4.8)

Here \( r \) denotes a block, and \( N_\Lambda(r) \) is the number of sites in the block \( r \). This is just like the construction of the block-spin effective Hamiltonian. It is only more ambitious in that we are hoping that \( m(r) \) is smoothly varying in \( r \), which will be true if \( \xi > a \). So the LG free energy \( S \) can be regarded as (a parametrization of) the coarse-grained free energy.

It is indeed analytic in \( m \), since we need to do only a finite number of sums in (4.8). And, also because there is only a finite number of sums, it need not be convex.

How do we get the actual, thermodynamic free energy from \( F_{LG} \) (which is convex and need not be analytic in its arguments)? We have to do the rest of the sums, the ones over \( m \):

\[
e^{-\beta F} = \sum_{\{s\}} e^{-\beta H(s)} = \sum_{m} e^{-\beta F_{LG}[m]}.
\]

Because \( m(r) \) is a continuous variable, \( \sum_{m} \) is actually an integral, one for every block, \( r \):

\[
\sum_{m} = \int \prod_{r} dm(r) \equiv \int [Dm]
\]

where the right equation defines what we mean by such a ‘functional integral.’

Altogether, we have

\[
Z = \int [Dm] e^{-\beta F_{LG}[m]}
\]

– we have rewritten the partition function (in a regime of moderately large correlation length) in terms of a field theory functional integral. The quantity appearing in the exponent of such an integral

\[
Z = \int [Dm] e^{-S[m]}
\]

is usually called the (euclidean) action, \( S[m] = \beta F_{LG}[m] \).

Doing this integral over \( m \) (which is our job for the next few weeks) is what restores convexity of \( F \), and what can allow \( F \) to be non-analytic, and what can produce non-mean-field critical behavior.
4.2 Correlations; Ginzburg criterion for MFT breakdown

[Goldenfeld §5.7] You might think that the spirit of mean field theory is antithetical to obtaining information about correlations between the spins, since after all that was precisely what we ignored to do the sums. Not so!

Here’s a first pass. The connected correlator (assume translation invariance) is

\[ G(r_i - r_j) \equiv \langle s_i s_j \rangle - \langle s_i \rangle \langle s_j \rangle. \]

The magnetization is related to \( \langle s_i \rangle \) by

\[ m = \frac{1}{N} \sum_i \langle s_i \rangle = \frac{1}{\beta N} \partial_h \log Z \]

and the (isothermal magnetic) susceptibility is

\[ \chi_T = \partial_h m = \frac{1}{N \beta} \partial^2_h \log Z = \frac{1}{NT} \sum_{ij} G(r_i - r_j) = \frac{1}{T} \sum_i G(r_i). \quad (4.9) \]

This is called the static susceptibility sum rule. It relates a thermodynamic quantity \( \chi_T \) to a (integrated) correlation function. If the correlation length is big enough, \( \xi > a \), then we can approximate the sum by an integral

\[ \chi_T = \frac{1}{Ta^d} \int d^d r G(r). \]

Is the integral well-defined? The lower limit of integration, the UV, is fine because we are talking about a lattice model. When \( \xi \) is finite, the fact that the correlations fall off rapidly \( G(r) \sim e^{-r/\xi} \) means that the integral converges in the IR (the upper limit of integration) as well.

But: \( \chi_T \to \infty \) at the critical point, in fact we saw above that \( \chi_T \overset{\text{MFT}}{\sim} \frac{1}{T-T_c} + \text{regular terms} \) as \( T \to T_c \). The only way this can happen consistently with the susceptibility sum rule is if \( \xi \to \infty \) as well at the transition. We’ll see in a moment with what power it diverges.

**MFT for \( G(r) \).** We can actually do better and find the form of \( G(r) \) **within** the mean field approximation. This is because \( G(r) \) is a **response function**. Here’s what this means.

When \( h = 0 \), the correlation function is

\[ \langle s_r s_0 \rangle = \sum_s s_r s_0 e^{-H(s)} \cdot \frac{1}{\sum_s e^{-H(s)} \cdot 1}. \]

\[ 19 \text{If I keep chanting ‘γ = 1’ maybe I will remember these letters someday.} \]
where we can write 1 cleverly as

\[ 1 = \delta_{s_0, 1} + \delta_{s_0, -1}. \]

Using the fact that \( H(-s) = H(s) \) (for \( h = 0 \)), we have

\[ \langle s_r s_0 \rangle = \sum' s_r e^{-H(s)} \sum' e^{-H(s)} \equiv \langle s_r \rangle' \]

where \( \sum' \) means we sum over all the spins but the one at 0, and we fix \( s_0 = +1 \), and \( \langle ... \rangle' \) denotes expectation in this ensemble. So the correlation function \( \langle s_r s_0 \rangle \) is just the magnetization at \( r \), \( m(r) \) in response to an (infinite) applied field (completely) localized to \( r = 0 \). In the presence of this localized source, \( m(r) \) will certainly depend on its distance from the source. But the mean field equation (for \( r \neq 0 \)) still takes the form

\[
m(r) = \tanh \beta \left( \sum_{r'} J_{rr'} m(r') \right) \\
m \ll 1 \approx \beta \sum_{r'} J_{rr'} m(r') \quad (r \neq 0)
\]

In the second line, we retreated to small \( m \), which is useful for \( T > J \). (Otherwise maybe we need some numerics.) We can do better and include the corrections at the origin, by including a source:

\[
m(r) = \beta \sum_{r'} J_{rr'} m(r') + A \delta(r).
\]

This (linear!) equation

\[
\sum_{r'} (\delta_{rr'} - \beta J_{rr'}) m(r') = A \delta(r)
\]

can be solved by Fourier transform (assuming translation invariant couplings \( J_{rr'} = J(r - r') \)). That is, the matrix we need to invert is diagonal in momentum space. That is, take \( \sum_r e^{i \vec{k} \cdot \vec{r}} \) (BHS) to get:

\[
(1 - \beta \tilde{J}(k)) \tilde{m}_k = +A,
\]

where

\[
\tilde{m}_k \equiv \sum_{r \in \Lambda} e^{i \vec{k} \cdot \vec{r}} m(r), \quad m(r) = \int_{BZ} \! d^d k \ e^{-i \vec{k} \cdot \vec{r}} \tilde{m}_k.
\]
In the inversion formula, the integral is over the Brillouin zone of the lattice $\Lambda$; for a cubic lattice, this just means $k \in (-\pi/a, \pi/a]$. The Fourier transform of the coupling is

$$\tilde{J}(k) \equiv \sum_{r} e^{i \vec{k} \cdot \vec{r}} J_{r,0}.$$ 

For example, for a cubic lattice, this is $\tilde{J}_{\text{cubic}}(k) = \sum_{\mu=x,y,z} 2 \cos k_{\mu} a$, where $a$ is the lattice spacing. For small $k$, the general case is

$$\tilde{J}(k) = z J (1 - R^2 k^2) + O(k^4)$$

where $R^2 \equiv \frac{\sum_{r} r^2 J_{r,0}}{\sum_{r} J_{r,0}}$ is the range-squared of the coupling. In the last expression we assumed the lattice had an inversion symmetry so that there are no terms with odd powers of $k$. We’ll be interested in small $k$ because it determines the long-distance behavior of $G(r)$.

Therefore,

$$\tilde{m}_k \simeq \frac{A}{1 - \beta z J (1 - R^2 k^2)}$$

and (using the mean-field relation $bt = 1 - \beta z J$)

$$\tilde{G}_k = \frac{A/(R^2 \beta z J)}{k^2 + \xi_{\text{MF}}^{-2}}, \quad \xi_{\text{MF}} = \frac{R}{\sqrt{bt}} \sim t^{-1/2}.$$ 

You can check that $\int d^d r G(r) = \tilde{G}_{k=0} = \chi_T = \frac{\mu}{bt}$, independent of $R$ as we found above, consistent with the susceptibility sum rule.

Why is $\xi$ in this formula the correlation length? Fourier transform back:

$$G(r) \sim e^{-r/\xi_{\text{MF}}^d} \frac{1}{r^{d-1}}$$

which is a formula named after Ornstein-Zernicke, I don’t know why. So we’ve found the rate at which the correlation length diverges as we approach the critical temperature from above (in the mean field approximation) $\xi_{\text{MF}} \sim \frac{1}{\sqrt{t}}$; This scaling relation $\xi \sim t^{-\nu}$, defines another critical exponent $\nu$ whose mean-field value is $\nu_{\text{MF}} = \frac{1}{2}$.

Right at $t = 0$, we have

$$G(r) = \int d^d k \frac{e^{i \vec{k} \cdot \vec{r}}}{k^2} \sim r^{-d+2}$$

which says $\eta_{\text{MF}} = 0$.

**Ginzburg criterion for breakdown of MFT.** [Goldenfeld §6] So, is mean field theory right? To get it, we had to ignore the following term in the hamiltonian

$$\Delta H = \sum_{r,r'} J_{rr'} \delta s_r \delta s_{r'}.$$ 

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A necessary condition for its self-consistency is that the expected value of this term, calculated within MFT, is small compared to the MFT energy:

$$\langle \Delta H \rangle_{\text{MFT}} \lesssim E_{\text{MF}}.$$  

The right hand side divided by $N$ is

$$\frac{1}{N} E_{\text{MF}} = -\partial_\beta (\beta f_{\text{MF}}) \sim J t,$$

where we used $f_{\text{MF}} \lesssim 1$. The LHS/N is

$$\frac{1}{N} \langle \Delta H \rangle_{\text{MFT}} = \frac{1}{N} \sum_{r,r'} J_{rr'} \langle \delta s_r \delta s_{r'} \rangle_{\text{MF}} = \sum_{r,r'} J_{rr'} G_{rr'},$$

where $J_{rr'}$ has a smaller range than $G_{rr'}$ (i.e. $R < \xi$), so that we may approximate the RHS as

$$z J G(0) = A \int_{\text{BZ}} \frac{d^d k}{1 - \beta \tilde{J}(k)} \simeq \frac{A}{R^2 \beta} \int_{|k| < a^{-1}} \frac{d^d k}{k^2 + \xi^{-2}}. \quad (4.10)$$

In a lattice model, the integral is over the Brillouin zone. The dangerous bit, where the RHS can become big, though, comes from $k \to 0$, which doesn’t care about your lattice details. We used this in replacing $\tilde{G}_k$ with its long-wavelength approximation in the last step of (4.10). In making this approximation, we may as well replace the BZ integral with a simple cutoff $|k| < a^{-1}$ since the form of the integrand is wrong for $|k| \sim a^{-1}$ anyway.

To separate out the UV physics ($k \sim \frac{2\pi}{a}$) from the IR physics ($k \sim \frac{2\pi}{L}$), let’s use the partial-fractions trick familiar from calculus:

$$\frac{1}{k^2 + \xi^{-2}} = \frac{1}{k^2} - \frac{\xi^{-2}}{k^2 (k^2 + \xi^{-2})},$$

so that

$$I \equiv \int_{|k| < a^{-1}} \frac{d^d k}{k^2 + \xi^{-2}} = \int_{|k| < a^{-1}} \frac{d^d k}{k^2} \underbrace{- \xi^{-2}}_{\text{ind. of } T} \int_{|k| < a^{-1}} \frac{d^d k}{k^2 (k^2 + \xi^{-2})}.$$ 

The first term is a (possibly big, honking) constant, which doesn’t care about the temperature or the correlation length. The second term is finite as $a \to 0$ if $d < 4$ (finding that this integral is infinite as $a \to 0$ just means that the short-distance stuff
at the lattice matters). (Note that the integral is finite as $L \to \infty$ if $d > 2$.) When the integral is finite, we can scale out the dependence on $\xi$:

$$I \xi^{2-d} \cong \text{const} + \xi^{2-d} K_d \int_0^\infty \frac{x^{d-3}dx}{x^2 + 1}$$

where

$$K_d \equiv \frac{\Omega_d}{(2\pi)^d}$$

is a ubiquitous combination of angular factors; $\Omega_d$ is the volume of the unit $d$-sphere.

So: the demand that the things we ignored be small corrections to the MFT energy computed within MFT requires

$$\frac{AT_c \xi^{2-d}}{R^2} \ll Jt$$

Remembering that we derived $\xi_{MF} = R t^{-1/2}$, we can write this condition purely in terms of the mean field correlation length. If the condition

$$\xi^{4-d} \ll R^d$$

is violated then mean field theory is wrong. (The $R^d$ on the RHS stands in for some quantities with the right dimensions which do not vary with $t$ near the transition)

So for sure this condition is violated if ever $\xi \to \infty$ in $d < 4$. (Remember that $d$ is the number of space dimensions.)

Note that the condition depends on the range $R$ of the interactions: MFT works better for longer-range interactions, and in more dimensions.

**Why does mean field theory get better in more dimensions?**

Mean field theory is valid if in the energy depending on a spin $s_i$

$$H_i \equiv Js_i \left( \sum_{\langle ij \rangle} s_j + h_i \right)$$

we can approximate the values of the neighboring spins by their average $s_j \overset{?}{=} \langle s_j \rangle$, and treat the coefficient of $s_i$ as an effective ‘molecular’ field $h_i^{\text{eff}} = \sum_{\langle ij \rangle} \langle s_j \rangle + h_i$.

More dimensions or longer range means more neighbors (for example, for the hyper-cubic lattice in $d$ dimensions, each site has $2d$ neighbors); more neighbors means that there are more terms in the sum $\sum_{\langle ij \rangle} s_j + h_i$. If the correlations between the terms in the sum are small enough, the central limit theorem tells us that the fractional error
decays with the number of terms in the sum. And this assumption is self-consistent, since in MFT the spins $s_j$ are statistically independent (the probability distribution factorizes).

The preceding argument says that at asymptotically large $d$, MFT becomes more and more correct. You saw on the homework that when the number of neighbors grows with $N$ (namely with all-to-all interactions), then MFT is exact. When $d = 1$ MFT is completely wrong, since there is no ordering at all at finite $T$. So something must happen somewhere in between. We’ve just learned that that somewhere is $d = 4$.

$d = 4$ is maybe not so exciting for statistical mechanics applications. However, the same machinery can be used with one of the dimensions interpreted as time. For more on this, I refer you to references on QFT (such as my 215C notes).

$d = 4 = d_c$ is called the upper critical dimension (in the sense that mean field theory is correct for larger dimensions) for the Ising critical behavior (since we’ve been talking about the case with Ising symmetry). More generally, the upper critical dimension can be efficiently determined from the zoo of critical exponents as follows. The fractional error in mean field theory can be rewritten as

$$\text{error} \sim \frac{\int_V d^d r G(r)}{\int_V d^d r m(r)^2}$$

(4.11)

where $V$ is a ‘correlation volume’, a region of space whose linear size is $\xi$. The numerator is $\int_V d^d r G(r) = T\chi_T \sim t^{-\gamma}$. The denominator is $\xi^d |t|^{2\beta} \sim t^{2\beta - \nu d}$, so the condition that (4.11) is small is

$$1 \gg t^{-\gamma - 2\beta + \nu d} \quad \implies \quad d_c = \frac{2\beta + \gamma}{\nu}.$$

Continuum field theory

Along the way in the preceding discussion of correlation functions in mean field theory, we showed the following, which is a useful summary of the whole discussion, and makes contact with the microscopic Landau-Ginzburg theory. Consider the simple case where

$$J_{ij} = \begin{cases} J, & r_{ij} \leq R \\ 0, & r_{ij} > R \end{cases}.$$

Then we showed that the contribution to the mean-field free energy from the interaction term is

$$-\Delta f_{MF}[m] = \sum_{ij} J_{ij} m_i m_j$$
\[
\begin{align*}
\sum_{i} \sum_{|\delta| \leq R} \left( \frac{m_{i+\delta} - m_i}{a} \right)^2 - \left( \frac{m_{i+\delta} + m_i}{a} \right)^2 \\
\sum_{i} \sum_{|\delta| \leq R} \left( \frac{m(r_i + \delta) - m(r_i)}{a} \right)^2 + O(m^2) \\
\sum_{i} \sum_{|\delta| \leq R} \left( \frac{\vec{\delta} \cdot \vec{\nabla} m(r_i)}{a} \right)^2 + O(m^2) \\
\sum_{i} \int \frac{d^dr}{a^d} \left( \vec{\nabla} m \right)^2 + O(m^2)
\end{align*}
\]

where \( z \) is the coordination number of the lattice. Comparing this to our ‘local’ Landau-Ginzburg expression (4.7), we’ve learned that the constant in front is

\[
\kappa \simeq R^2 \left( \frac{Jz}{4a^d} \right) = \frac{R^2 T_c^{MF}}{a^d}.
\]

The equations of motion for \( m \) coming from extremizing

\[
f_{LG} = \int d^d r \left( \kappa \vec{\nabla} m \cdot \vec{\nabla} m + V(m(x)) + h(x)m(x) \right)
\]

in this continuum approximation, are\(^{20}\)

\[
0 = \frac{\delta F_{LG}}{\delta m(x)} = -2\kappa \nabla^2 m + \frac{\partial V}{\partial m} \bigg|_{m=m(x)} + \ldots \quad (4.12)
\]

If \( V \) contains a source term \( \int dx h(x)m(x) \), then this is

\[
0 = -2\kappa \nabla^2 m(x) + h(x) + 2btm(x) + O(m^2).
\]

For the case of a localized source, \( h(x) = \delta(x) \), (and ignoring the interaction terms \( m^{n>1} \)) the solution in Fourier space

\[
\tilde{m}_k = \frac{(2\kappa)^{-1}}{k^2 + bt/\kappa}
\]

gives back \( \xi^{-1} = \sqrt{bt/\kappa} \). You might think that ignoring the higher powers of \( m \) is OK near the critical point, since \( m \) is small; this assumption gives back mean field theory (which we’ve already seen is not always correct).

In case you’re not comfortable with this derivation of the continuum field theory description of Ising models with large correlation length, another approach is outlined on the problem set.

\(^{20}\)For those of you who are not at home with variational calculus, please see the sidebar on the subject at §4.2.1.
Return for a moment to our discussion of the LG theory of a system with an $O(n)$ symmetry. Recall that in the ordered phase, we found that $n - 1$ of the modes did not appear in the quadratic term of the LG free energy. Now you can see why I said that the existence of these Goldstone modes implied that the correlation length was infinite everywhere in the ordered phase.
4.2.1 Sidebar on Calculus of Variations

Let us spend a moment thinking about functionals – a functional is a monster that eats a function and returns a number – and how they vary as we vary their arguments. I’ll describe this in the context where the function in question is \( x(t) \), the trajectory of a particle in time, but you can substitute \( m(x) \).

The basic equation of the calculus of variations is:

\[
\frac{\delta x(t)}{\delta x(s)} = \delta(t - s).
\]

This the statement that \( x(t) \) and \( x(s) \) for \( t \neq s \) are independent. From this rule and integration by parts we can get everything we need. For example, let’s ask how does the potential term in the action \( S_V[x] = \int dt V(x(t)) \) vary if we vary the path of the particle. Using the chain rule, we have:

\[
\delta S_V = \int ds \delta x(s) \frac{\delta \int dt V(x(t))}{\delta x(s)} = \int ds \delta x(s) \int dt \partial_x V(x(t)) \delta(t-s) = \int dt \delta x(t) \partial_x V(x(t)).
\]

We could rewrite this information as:

\[
\frac{\delta \int dt V(x(t))}{\delta x(s)} = V'(x(s)).
\]

What about the kinetic term \( S_T[x] \equiv \int dt \frac{1}{2} m \dot{x}^2 \)? Here we need integration by parts:

\[
\frac{\delta}{\delta x(s)} S_T[x] = \frac{2}{2} m \int dt \dot{x}(t) \partial_x \frac{\delta x(t)}{\delta x(s)} = m \int dt \dot{x}(t) \partial_x \delta(t-s) = -m \int dt \ddot{x}(t) \delta(t-s) = -m \ddot{x}(s).
\]

If we set the total variation to zero, we get Newton’s equation:

\[
\frac{\delta}{\delta x(s)} \left( \int dt \left( \frac{1}{2} m \dot{x}^2 - V(x(t)) \right) \right) = -m \ddot{x}(s) + V'(x(s)).
\]

---

21If you are unhappy with thinking of what we just did as a use of the chain rule, think of time as taking on a discrete set of values \( t_i \) (this is what you have to do to define calculus anyway) and let \( x(t_i) \equiv x_i \). Now instead of a functional \( S_V[x(t)] \) we just have a function of several variables \( S_V(x_i) = \sum_i V(x_i) \). The basic equation of calculus of variations is even more obvious now:

\[
\frac{\partial x_i}{\partial x_j} = \delta_{ij}
\]

and the manipulation we did above is

\[
\delta S_V = \sum_j \delta x_j \partial_{x_j} S_V = \sum_j \delta x_j \partial_{x_j} \sum_i V(x_i) = \sum_j \sum_i \delta x_j V'(x_i) \delta_{ij} = \sum_i \delta x_i V'(x_i).
\]
5 Festival of rigor

Let us pause in our assault on field theory to collect some Facts that we know for sure about the free energy of short-ranged lattice models. As with any rigorous, formal results in physics, it will be crucial to understand the hypotheses.

5.1 Extensivity of the free energy

[Parisi pp. 41-42] The Ising model free energy is extensive, $F/N = f + \text{terms which go to zero as the number of sites } N \to \infty$. In particular, in the thermodynamic limit, the bulk free energy density $f$ doesn’t care about boundary conditions. This assumes that $J$ is short-ranged: $J_{r,0}$ is either of finite support (system-size-independent range), or falling off sufficiently rapidly in $r$.

Here is an RG-inspired proof of this result. We begin with a finite system, with $N$ sites.

First, notice that the hamiltonian $H(s)$ is bounded

$$-ND < H(s) < ND$$

for some constant $D$ (for the near-neighbor Ising model on a cubic lattice it’s $J$ for each link, so $D = dJ$).

We can bound the free energy, too, by realizing that the number of configurations is finite – for a finite lattice with $N$ sites, there are only $2^N$ of them. Each one contributes an energy below the maximum value, and above the minimum value. If all $2^N$ configurations achieved the max/min value, we get the smallest/biggest possible values of the partition function:

$$2^N e^{-\beta ND} \leq Z_N \leq 2^N e^{\beta ND}.$$

Taking log of the BHS gives

$$-\infty < -D - \frac{\log 2}{\beta} \leq f_N \leq D + \frac{\log 2}{\beta} < \infty$$

the important thing being that the free energy density is bounded on either side, independently of $N$.

Now here comes the RG bit. For definiteness, take free boundary conditions on an $L \times L \times \cdots L$ chunk of cubic lattice. (Free boundary conditions means that we just stop writing terms in the hamiltonian when the sites that would participate in them don’t...
exist.) Take $L \gg R$, the range of the interactions. Let $Z^F_L$ be the partition function for this chunk.

Now we try to double the (linear) size of the system, by gluing together the right number ($2^d$) of smaller chunks of size $L$. Gluing just means that we add the terms in the Hamiltonian which couple the sites across the interface. The number of terms we have to add is $L^d - 1$ for each interface (each pair of chunks) we glue, and we have to glue $2^d$ interfaces. The magnitude of the contribution of each term is bounded by $D$. Therefore

$$\left( Z^F_L \right)^{2^d} (2e^{-\beta D})^{2^d L^d - 1} R \leq Z^F_{2L} \leq \left( Z^F_L \right)^{2^d} (2e^{+\beta D})^{2^d L^d - 1} R.$$  

Taking the log and dividing by $(2L)^d$ gives

$$f_L + \tilde{D} L^{-1} R \geq f_{2L} \geq f_L - \tilde{D} L^{-1} R$$

(where $\tilde{D} \equiv D + T \ln 2$), which can be written as

$$|f_{2L} - f_L| \leq \frac{c}{L}$$

for some positive number $c$ which does not depend on $L$.

This means that the sequence $\{f_{2^n L}\}_n$ converges as $n \to \infty$ (for a big enough initial $L$). The same argument can be used to show that the effect of changing boundary conditions can be bounded on either side. Suppose we change terms in the Hamiltonian in a way which is localized near the boundary and where the magnitude of the change of each term is bounded by some $\Delta$. Then if $Z^B_L$ is the resulting partition function,

$$Z^B_L e^{-\beta L^d - 1 \tilde{\Delta}} \leq Z^F_L \leq Z^B_L e^{\beta L^d - 1 \tilde{\Delta}}.$$  

Again when we take the log and divide by the volume $L^d$, the terms proportional to $\tilde{\Delta} \equiv \Delta + T \ln 2$ are suppressed by a factor of $L$.

**Thermodynamic limit**

We conclude that in a system in $d$ dimensions of linear size $L$, with short-range interactions, the free energy takes the form:

$$F = L^d f_b + L^{d-1} f_\partial + \mathcal{O}(L^{d-2})$$

$$f_b = \lim_{L \to \infty} \frac{F}{L^d}, \quad f_\partial = \lim_{L \to \infty} \frac{F - L^d f_b}{L^{d-1}}.$$  

$f_\partial$ is a boundary free energy density.

Two questions to ponder:
1. What should we hold fixed in the limit \( L \to \infty \)? In a fluid, we might want to fix the density of particles, \( \rho = \frac{N_{\text{particles}}}{L} \). If we instead fix \( N_{\text{particles}} \), we get a boring fluid.

2. How can the thermodynamic limit fail to exist? We consider a class of examples where it might fail next.

### 5.2 Long-range interactions

**Charged system.** Consider a bunch of stuff with a net electric charge, at \( T = 0 \). Imagine we can fix the charge density \( \rho \), and take \( d = 3 \) so that the inter-charge potential is \( U(r) = \frac{A}{r} \). The self-energy of a sphere of this stuff is (integrating the contributions from shells of radius \( r \), which only care about contributions from inside)

\[
E(R) = \int_0^R \left( \frac{4}{3} \pi r^2 \rho \right) \frac{A}{r} (4\pi r^2 \rho dr) \sim A \rho^2 R^5.
\]

So the ‘bulk free energy density’ is

\[
E_b = \frac{E(R)}{V(R)} \sim A \rho^2 R^2 \overset{R \to \infty}{\to} \infty.
\]

So a Coulomb-like force is too long-ranged for the thermodynamic limit to exist. More physically, the conclusion (5.1) means (for \( A > 0 \), repulsive interactions) that the system (with a fixed number of particles or fixed charge) can lower its energy by expanding into a larger volume – it explodes.

But wait: there are Coulomb-like forces in the world, and here we are in the thermodynamic limit. A fatal assumption above is that there was only one sign of the charge. If we allow charge of both signs, we can have the phenomenon of *screening*. Screening makes a microscopically long-range force short-ranged. That last sentence has a lot of RG physics in it, and it’s worth absorbing more. This is an opportunity to say something about “running couplings”.

---

**Screening: mean field theory of Debye and Huckel.**

[McComb] We take a uniform background of + charges, fixed in place. (This is sometimes called ‘jellium’.) Their number density is \( n_\infty \). We add to this *mobile* − charges (‘electrons’), with equal average number density.

Suppose we stick in a test (−) charge at the origin. At temperature \( T \), what is the probability of finding an electron a distance \( r \) from the test charge? If we knew the electrostatic potential \( \phi(r) \), the classical equilibrium probability would be

\[
p(r) = Z^{-1} e^{-\epsilon \phi(r) / T}.
\]
In vacuum, $\phi(r)$ would be $\xi$. We will determine it self-consistently. The electron number density is proportional to the probability $p(r)$, and must approach the average density far away (where $\phi \to 0$), so

$$n(r) = n_\infty e^{-\beta \phi(r)}.$$ 

Now we can impose Gauss’ law:

$$-\nabla^2 \phi(r) = 4\pi \rho(r) = 4\pi e(n(r) - n_\infty) = 4\pi e n_\infty (e^{-\beta \phi(r)} - 1) \approx -4\pi \beta e^2 n_\infty \phi(r) + O(e\beta \phi)^2.$$ 

This is just the equation we solved in (4.12) to find the correlation function $G(r)$ away from the critical point, at finite $\xi^{-2} = 4\pi \beta e^2 n_\infty$, and the solution is

$$\phi(r) = \frac{e}{r} e^{-r/\xi_D} \equiv \frac{e_{\text{eff}}(r)}{r}.$$ 

The name of the correlation length in this case is

$$\xi_D \equiv \sqrt{\frac{T}{4\pi e^2 n_\infty}},$$

the Debye screening length. In the second equality in (5.3) I introduced a distance-dependent effective charge $e_{\text{eff}}(r)$: how much charge you see depends how closely you look.

The continuum approximation we’ve used here is consistent with classical corpuscles if the average interparticle distance is small compared to the screening length:

$$n_\infty^{-1/3} \ll \xi_D$$

which is true when $e^3 \sqrt{N} \ll T^{3/2}$, i.e. at high enough temperature, consistent with our approximation in (5.2).

You might worry that a collection of charges of both signs, once we let them all move around, might either implode or explode. This paper by Lieb, called The Stability of Matter, is very interesting and not too forbidding. The early sections are about the stability of matter to implosion, which is a short-distance issue (whose resolution crucially involves quantum mechanics and the Pauli principle and hence is off-limits here); but Section V contains a ‘rigorous version of screening’ which removes the concern that matter should want to explode like in (5.1).
Other power laws. Suppose instead of Coulomb interactions in \(d = 3\), we have particles interacting pairwise via a potential \(U(r) = \frac{A}{r^\sigma}\) in \(d\) dimensions. Then the energy of a collection of particles with density \(\rho(r)\), in a ball of radius \(R\), \(B_R\) is

\[
E(R) = \frac{1}{2} \int_{B_R} d^d r \int_{B_R} d^d r' \rho(r) U(r - r') \rho(r')
\]

\[
\simeq \rho A \frac{L^2}{2} \int_{B_R} d^d r \int_{B_R} d^d r' \frac{1}{|r - r'|^\sigma}
\]

\[
= A \frac{L^2}{2} R^{2d - \sigma} C(d, \sigma) \tag{5.4}
\]

where

\[
C(d, \sigma) \equiv \int_{B_1} \frac{d^d x d^d y}{|x - y|^{\sigma}}
\]

In the last step we scaled out the system-size dependence of the integral by defining \(r \equiv R x, r' \equiv R y\). This \(C\) is just a dimensionless number – if it’s finite. In that case, the ‘bulk energy density’ (free energy density at \(T = 0\)) is

\[
\varepsilon_{\text{bulk}} \equiv \frac{E(R)}{V(R)} = \frac{R^{2d - \sigma} A \rho^2 C/2}{R^d V_d} \sim R^{d - \sigma}
\]

which is finite as \(R \to \infty\) (the would-be thermodynamic limit) if \(\sigma > d\). \((V_d\) is the volume of the unit \(d\)-ball.) So \(\sigma > d\) is a sufficiently fast falloff of the interactions to allow for a thermodynamic limit.

When is \(C(d, \sigma)\) finite? What I really mean by this is: the power law form of \(U(r) \sim r^{-\sigma}\) surely only holds for \(r \gg a\), some UV cutoff – for example the size of the particles. The real question is: when can we ignore this approximation for purposes of computing \(C\)? Changing integration variables to \(u \equiv x - y, v = x + y\),

\[
C = V_d \Omega_{d-1} \int_{a/R}^1 \frac{u^{d-1}}{u^\sigma} du \begin{cases} 
\frac{V_d \Omega_{d-1}}{d - \sigma} \left(1 - \left(\frac{a}{R}\right)^{d - \sigma}\right), & d \neq \sigma \\
\propto \log \frac{R}{a}, & d = \sigma.
\end{cases}
\]

5.3 (Anti-)convexity of the free energy

[Goldenfeld §2.6] We’re going to prove some facts about the nearest-neighbor Ising model, with Hamiltonian

\[
H(s) = -J \sum_{\langle ij \rangle} s_i s_j - h \sum_i s_i. \tag{5.5}
\]

Many of them are true more generally.
(1) With the additive normalization in (5.5), the bulk free energy density is negative:

\[ f < 0.\]

This statement is sensitive to the additive normalization of \( H \) — if we add a big positive constant to \( H \), we can change this fact. The normalization (5.5) is special because there is no constant term, in the sense that

\[ \sum_s H(s) = 0 \quad (5.6) \]

— it is normal-ordered.

Proof of (1): Begin with \( N < \infty \) sites. The free energy density is \( f = F/N = -\frac{T}{N} \log Z \), so the claim \( f < 0 \) means \( Z > 1 \). The partition function \( Z = \sum_s e^{-\beta H(s)} \) is a sum of \( 2^N \) positive terms (for \( 0 < T < \infty \)). And \( Z > 1 \) because there exists a configuration \( s^* \) which by itself contributes a term \( e^{-\beta H(s^*)} > 1 \). For example, for \( J > 0, h > 0 \), it happens when \( s^*_i = 1, \forall i \). But more generally, it follows from the normal-ordering condition (5.6) since \( H(s) \) is not identically zero, so there must be configurations with both signs of \( H(s) \), and at least one which has \( H(s^*) < 0 \). ■

(2) The entropy density is

\[ s = -\partial_T f \geq 0. \]

The proof of this statement follows from the identity

\[ -\partial_T F = -\sum_s \rho_\beta(s) \log \rho_\beta(s) \]

where \( \rho_\beta(s) \equiv e^{-\beta H(s)}Z^{-1} \) is the equilibrium probability distribution at temperature \( T \). Since \( 0 \leq \rho \leq 1 \), this is a sum of positive terms. ■

Here is a Definition: A function \( f(x) \) is anti-convex in \( x \) if

\[ f(tx_1 + (1-t)x_2) \geq sf(x_1) + (1-t)f(x_2), \quad \forall t \in [0,1]; \]

that is, if the graph of the function is above any chord. If \( f \) is anti-convex then I’ll call \(-f\) convex.

Convex implies continuous, as you can see from the picture at right of a function which jumps. If \( f \) is anti-convex,
\( \partial_x f \) is non-increasing (and in particular the derivative exists almost everywhere). \( f \) can have cusps.

\( \text{(3) } \ln Z(\beta, h, J) \) is anti-convex in its arguments.

Proof of (3): The proof relies on a Hölder inequality. Given two sequences \( \{g_k\}, \{h_k\} \) of non-negative numbers \( g_k, h_k \geq 0 \), and \( t \in [0, 1] \),

\[
\sum_k (g_k)^t (h_k)^{1-t} \leq \left( \sum_k g_k \right)^t \left( \sum_k h_k \right)^{1-t}.
\]

This follows from the convexity of the logarithm\(^{22}\).

Here's the idea for \( f(\beta) \):

\[
Z(t\beta_1 + (1-t)\beta_2) = \sum_s e^{-t\beta_1 H(s)} e^{-(1-t)\beta_2 H(s)}
\]

Hölder \[
\leq \left( \sum_s e^{-\beta_1 H(s)} \right)^t \left( \sum_s e^{-\beta_2 H(s)} \right)^{1-t}
\]

\[
= Z(\beta_1)^t Z(\beta_2)^{1-t}.
\]

Taking logs gives:

\[
\ln Z(t\beta_1 + (1-t)\beta_2) \geq t \ln Z(\beta_1) + (1-t) \ln Z(\beta_2).
\]

The limit as \( N \to \infty \) of a family of convex functions is also convex.

A useful alternative viewpoint: anticonvexity follows by showing that all second derivatives of \( f \) are negative. For example,

\[
\frac{\partial^2 f}{\partial \beta^2} = -\frac{1}{\beta N} \langle (H - \langle H \rangle)^2 \rangle \leq 0
\]

\(^{22}\) Here's the idea:

\[
ab = e^{\log ab} = e^{\frac{1}{p} \log a^p + \frac{1}{q} \log b^q}
\]

\[
\leq \frac{1}{p} e^{\log a^p} + \frac{1}{q} e^{\log b^q} = \frac{a^p}{p} + \frac{b^q}{q}
\]

for \( \frac{1}{p} + \frac{1}{q} = 1 \), where we used the fact that \( e^x \) is anticonvex \((e^{tx} + (1-t)y) \leq te^x + (1-t)e^y\), as illustrated at right. Apply this inequality with

\[
a = \left( \frac{g_k}{\sum g} \right)^{\frac{1}{p} \equiv t}, \quad b = \left( \frac{h_k}{\sum h} \right)^{\frac{1}{q} \equiv 1-t}
\]

and sum the BHS over \( k \).

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is proportional to minus the specific heat, aka the variance of the energy. Similar statements hold for other variations, such as the magnetic susceptibility

\[ \partial_h^2 f = -c \langle (s - \langle s \rangle)^2 \rangle \leq 0. \]

So the condition of convexity is related to the stability of the equilibrium.

Note that \( f \) being anticonvex in \( \beta \) means \( f \) is convex as a function of \( T \).
5.4 Spontaneous symmetry breaking

[Goldenfeld p. 56, Parisi p. 15]

Orders of limits. I made a big deal earlier (in §3) about the impossibility of spontaneous symmetry breaking (SSB) in finite volume. There is more to say about this. What does the free energy density (in the thermodynamic limit) look like as a function of $h$ near $h = 0$? It must be

$$f(h) = f(0) - m_s |h| + O(h^{\sigma>1})$$

so that the magnetization is

$$m = -\partial_h f = \begin{cases} m_s + O(h^{\sigma-1}), & h > 0, \\ -m_s + O(h^{\sigma-1}), & h < 0. \end{cases}$$

(If $\sigma$ were not larger than one, the magnetization would diverge as $h \to 0$ and that’s not happening, since it’s bounded. I also imposed $f(h) = f(-h)$ by Ising symmetry.)

But before the thermodynamic limit, $f(h)$ is a smooth function. This means the two limits $h \to 0, N \to \infty$ are clashing violently:

$$\lim_{N \to \infty} \lim_{h \to 0} \frac{1}{N} \partial_h F = 0 \quad \text{but} \quad \lim_{h \to 0} \lim_{N \to \infty} \frac{1}{N} \partial_h F = \pm m_s.$$

Yang-Lee singularities. Here is a toy model of how this can come about. Suppose our system of volume $V$ is so tightly bound that only two configurations matter, the one where all $N$ spins point up, $m = +V$, and the one where they all point down, $m = -V$. (All the rest of the configurations have such a large energy that we can ignore their contributions to $Z$.) So a single spin $s = \pm 1$ determines the whole configuration.

Then, in a field, we have

$$Z(h) = \sum_{s=\pm 1} e^{-\beta hVs} = 2 \cosh \beta hV$$

and

$$f(h) = -\frac{T}{V} \log (2 \cosh \beta V), \quad m(h) = \partial_h f = \tanh \beta hV \quad V \to \infty \quad m(h) = \text{sign}(h).$$

Where in $h$ is the free energy $F \propto \log(Z)$ singular? When $Z(h) = 0$. For $V < \infty$, the zeros of the partition function happen at pairs of imaginary values of $h$

$$Z(h_n = 0) \quad \text{at} \quad h_n = \frac{(2n + 1)\pi i}{2\beta V}$$

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which in the thermodynamic limit $V \to \infty$ accumulate and pinch the real axis. (They are shown for $\beta V = 1, 2, 5$ in the figure at right.) These zeros are named after Yang and Lee.

**Ergodicity breaking.** There are many points of view from which SSB seems paradoxical. For example if the equilibrium probability density is

$$p_0(s) = Z^{-1} e^{-\beta H(s)}$$

then the Ising symmetry $H(s) = H(-s)$ implies directly that the magnetization vanishes:

$$m = \langle s \rangle = \langle -s \rangle = \sum_s P_0(s)s = 0.$$  

What gives? Consider, at small $h > 0$ and finite $N$, the ratio of the probabilities of two configurations: a reference configuration $s$, and the one related to it by a global spin reversal. If $m(s) \equiv \frac{1}{N} \sum_i s_i$ is the magnetization in this configuration, then

$$\frac{p(s)}{p(-s)} = \frac{e^{-\beta(-hNm(s))}}{e^{\beta(hNm(s))}} = e^{2\beta hNm(s)} \xrightarrow{N \to \infty} \infty.$$  

In the thermodynamic limit, if $h \neq 0$ one of these configurations is infinitely more probable than the other! This is true no matter how small $h$ is, even if $h = 0^+$. If we reverse the sign of $h$, the other configuration wins. We’ve learned that

$$\lim_{h \to 0^\pm} \lim_{N \to \infty} p_0(s) \equiv p_\pm(s)$$

is a different, restricted ensemble compared to the symmetric distribution $p_0$. It is restricted in the sense that $p_+(s|m(s) < 0) = 0$ – states with the wrong sign of magnetization have no weight. So in this limit, our distribution only samples a subset of the configuration space – it is not *ergodic*. This is a toy example of ergodicity breaking, a concept which is much more useful in the physics of glassy systems. Very roughly, from the usual point of view of ergodicity as underlying statistical mechanics, in terms of time evolution, the claim is that starting from an initial configuration, the probability of evolving to a configuration with the opposite sign of the magnetization goes like $e^{-\beta \Delta F}$ where the change in free energy is $\Delta F \sim N \sigma > 0 \xrightarrow{N \to \infty} \infty$. So we are also claiming that SSB means that the $N \to \infty$ limit and the $t \to \infty$ limit do not commute. (If we take $t \to \infty$ first, the system will explore all the configurations.)

**Cluster decomposition failure.** If we prepare the system in an initial configuration with a mixture of $\pm$ (or average over possible initial conditions with the appropriate weight), as

$$p_q(s) = qp_+(s) + (1-q)p_-(s), \quad q \in [0, 1]$$

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then our expectation for the connected correlations are

\[
\langle s_i s_j \rangle_c^q \equiv \frac{\langle s_i s_j \rangle_q - \langle s_i \rangle_q \langle s_j \rangle_q}{|r_i - r_j| \to \infty}
\]

\[
m^2 - (2q - 1)^2 m^2 = 4q(1 - q)m^2 \neq 0.
\]

They don’t vanish for arbitrarily-separated points! The demand that they should is called the cluster decomposition principle; it is an implementation of the notion of ‘locality’. SSB means that cluster decomposition fails for the symmetric distribution. Only the (non-symmetric) ‘pure states’ with \( q = 0, 1 \) satisfy this demand (this is the definition of ‘pure state’ in this context).

### 5.5 Phase coexistence

[Goldenfeld, §4] First, let’s recall some thermodynamics facts. I will speak in the language of fluids, but with appropriate substitutions of letters, it can be translated into physics of magnets or other examples. At fixed volume, the free energy which is minimized in equilibrium is the Hemholtz one (the one we’ve been talking about), \( F(T, V, N) = E - TS \). If instead we fix the pressure \( P \), the quantity which is minimized in equilibrium is the Legendre transform of \( F \), named for Gibbs:

\[
G(T, P, N) = F + PV,
\]

in terms of which the first law of thermodyanmics is

\[
dG = -SdT + VdP + \mu dN.
\]

The Gibbs-Duhem relation (basically, integrating the first law) says \( E = -PV + TS + \mu N \), so that in fact \( G = \mu N \) is just proportional to the chemical potential.

Let’s consider a situation at fixed \( P \) where there is a first order transition, between two phases \( I, II \) (for example, liquid and gas) where the order parameter is the volume, or the density (equivalently at fixed \( N \), since \( V = N/\rho \)). Along the phase boundary, where they exchange dominance, we must have

\[
G_I = G_{II}.
\]

Hence also \( \mu_I = \mu_{II} \); this is a condition for chemical equilibrium of the two phases.

---

\(^{23}\)For some intuition for the sense in which arbitrarily-separated points are correlated in these ensembles, see the homework.
Moving along the phase boundary, the condition (5.8) says

\[
G_I(T + dT, P + dP, N) = G_{II}(T + dT, P + dP, N) - dT \frac{\partial T G_I}{\partial T} |_{P} + dP \frac{\partial P G_I}{\partial P} |_{P} - S_I
\]

and therefore we get the Clausius-Clapeyron equation for the slope of the coexistence curve

\[
\left. \frac{dP}{dT} \right|_{\text{coexistence}} = \frac{S_I - S_{II}}{V_I - V_{II}}.
\]

The difference in the numerator is proportional to the latent heat of the transition, \( T \Delta S = T(S_I - S_{II}) \). If phases I and II are not somehow topologically distinguished (for example, by a different symmetry-breaking pattern), then there can be a critical endpoint of the line of first-order transitions, where \( \Delta S \to 0, \Delta V \to 0 \), at some \((T_c, P_c)\).

The consequence of a first-order transition depends on what is held fixed as the transition is traversed. If we heat a fluid at constant pressure \( P < P_c \) (for example atmospheric pressure), starting from \( T < T_c \) (moving along the red vertical line in the figure, and doing so slowly enough that we stay in the equilibrium phase diagram at every step) then first the fluid expands and warms up. When it reaches the coexistence curve \( T_{\text{coexistence}}(P) \), it starts to boil. While this happens, the energy goes into the latent heat converting I into II, and the temperature stays fixed: we are sitting at the point \((T_{\text{coexistence}}(P), P)\) on the coexistence curve in the \((P,T)\) phase diagram, while the fraction \( x \) of the fluid which is gas grows:

\[
V = xV_I + (1-x)V_g, \quad x = x(t)
\]

is some protocol-dependent function. Although \( V_I \neq V_g \), the volume of fluid itself does not jump. How do I know this? Bear with me a moment, the proof is at Eq. (5.9).
If instead we compress the fluid at constant $T$, starting at $T > T_c$ in the gas phase:

$$-\frac{1}{V} \partial_V P \big|_T \equiv \kappa_T > 0$$

a positive compressibility says that it fights back. It fights back until the volume reaches $V = V_l(T)$, which is when $P = P_{\text{coexistence}}(T)$, beyond which the fluid starts to condense.

What do these isothermal curves look like? Let $v = V/N = 1/\rho$ be the volume fraction per particle. For an ideal gas, recall that $Pv = T$. This is correct in general at high temperature. For lower temperatures, van der Waals suggests some appealing simple corrections which account for an interparticle interaction described by a potential like we discussed in §3.6:

- each particle wants some amount of personal space, and therefore excludes some fixed volume $b$: $v \to v - b$.
- the energy per particle is decreased by the long-range attractive part of the potential by an amount proportional to the density:

$$\frac{E}{N} \to \frac{E}{N} - a \rho \quad \implies \quad P = \partial_V F \to P - \frac{a}{v^2}.$$  

So the vdW equation of state is

$$P = \frac{T}{v - b} - \frac{a}{v^2}$$

for some constants $a, b$ (in the plot at right we see $a = 2, b = 5$ and $T = 1, 1.5, 2$ from bottom to top). This has two nice new features for our present purposes:

- It has a critical $T = T_c$ below which there is a line of first order phase transitions. The critical point appears when $P(v) = \text{const}$ goes from having one solution ($T > T_c$, like the ideal gas), to having three. When this happens, $\partial_v P = \partial^2_v P = 0$, so that locally $P \sim (v_c - v)^3$ is locally cubic. In fact, for the vdW equation of state, this condition is exactly a cubic equation for $v$: $P_0 v^3 - v^2 (bP_0 + T) + av - ab = 0$.

- (Relatedly), it has regions where $\kappa_T = -\frac{1}{V} \partial_V P \big|_T < 0$ which says that if you try to squeeze it, it doesn’t fight back, but rather tries to help you squeeze it further. Creepy! (The same thing happened in our study of the Landua-Ginzburg free energy in §4.1 and this led to the picture of the swallowtail.)
Note by the way that the vdW equation is a masterpiece of estimation: $a, b$ can be determined from high-temperature data and they give a (not bad) estimate of the location of the critical point.

What is the free energy doing while this is going on? At coexistence, in equilibrium, $\mu_l = \mu_g$, and the first law says

$$d\mu = -\frac{S}{N}dT + \frac{V}{N}dP$$

so

$$0 = \mu_l - \mu_g = \int_{\text{liquid}}^{\text{gas}} d\mu = \int_{\text{gas}} \frac{V(P)}{N}dP$$

so the area under the $V(P)$ curve is zero (and is the change in the Gibbs free energy), along any path in equilibrium. This is true even for infinitesimal paths. Therefore, the actual equilibrium trajectory of the free energy is a straight line between $V_g$ and $V_p$. This is the Maxwell construction. It saves the convexity of the free energy.

The creepy self-squeezing regions of the equation-of-state curve are exactly the ones which are removed by the phase-coexistence region.

At left here, I've made some pictures where a decreasing fraction of the dots are colored red, in an attempt to depict the history of the volume fraction of one phase in the other as the coexistence region is traversed. What's wrong with this picture? How could you make it more realistic?

Notice that we are making a strong demand of equilibrium here, effectively taking $t \to \infty$ before $N \to \infty$. This failure of commutativity of these limits is the same issue as in our discussion of ergodicity-breaking above.
6 Field Theory