Statistical Field Theory: Example Sheet 3

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0. Apply the RG procedure to the theory with effective free energy

$$F[\phi] = \int d^dx \left[\frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}\mu^2\phi^2 + g_4\phi^4\right]$$

Step 1 of the RG procedure will generate a term $g_6\phi^6$. What is the simplest Feynman diagram that contributes to this term? Determine g_6 to $O(g_4^2)$. What is the next-lowest dimension operator generated by this Feynman diagram? Draw some more Feynman diagrams that contribute to g_6.

1. The $O(N)$ model consists of N scalar fields, $\boldsymbol{\phi} = (\phi_1, \ldots, \phi_N)$, with a free energy

$$F_1[\boldsymbol{\phi}] = \int d^dx \; \left[\frac{1}{2}(\nabla\boldsymbol{\phi})^2 + \frac{\mu^2}{2}(\boldsymbol{\phi}\cdot\boldsymbol{\phi}) + g(\boldsymbol{\phi}\cdot\boldsymbol{\phi})^2\right]$$

which is invariant under $O(N)$ rotations. In $d = 4 - \epsilon$ dimensions, the beta functions for the $O(N)$ model are

$$\begin{aligned}\frac{d\mu^2}{ds} &= 2\mu^2 + \frac{N+2}{2\pi^2}\frac{\Lambda^4}{\Lambda^2+\mu^2}\tilde{g} \\ \frac{d\tilde{g}}{ds} &= \epsilon\tilde{g} - \frac{N+8}{2\pi^2}\frac{\Lambda^4}{(\Lambda^2+\mu^2)^2}\tilde{g}^2\end{aligned}$$

where $\tilde{g} = \Lambda^{-\epsilon}g$ is the dimensionless coupling. What is the critical exponent ν at the Wilson-Fisher fixed point? Assuming that $\eta \sim \mathcal{O}(\epsilon^2)$, determine the critical exponents α, β, γ and δ to leading order in ϵ.

2. Along the flow from the Gaussian to the Wilson-Fisher fixed point, we have $\mu^2 \sim \mathcal{O}(\epsilon)$. To leading order in ϵ, the second beta function in question 1 becomes

$$\frac{d\tilde{g}}{ds} \approx \epsilon\tilde{g} - \frac{N+8}{2\pi^2}\tilde{g}^2 = -A\tilde{g}(\tilde{g}-\tilde{g}_\star)$$

for a suitable A and $\tilde{g}_\star$ that you should determine. Show that if the coupling initially sits at g_0, it evolves as

$$g = \frac{g_\star}{1-(1-g_\star/g_0)e^{-\epsilon s}}$$

3*. The $O(N)$ model is deformed by adding a term which breaks the $O(N)$ symmetry,

$$F_2[\boldsymbol{\phi}] = F_1[\boldsymbol{\phi}] + \int d^dx\ \lambda \sum_{a=1}^{N} \phi_a^4$$

Show that the free energy is positive definite only if $g + \lambda > 0$.

To leading order in ϵ, the coupled beta functions for the dimensionless couplings $\tilde{g} = \Lambda^{-\epsilon} g$ and $\tilde{\lambda} = \Lambda^{-\epsilon}\lambda$ are

$$\begin{aligned} \frac{d\tilde{g}}{ds} &= \epsilon\tilde{g} - \frac{N+8}{2\pi^2}\tilde{g}^2 - \frac{3}{\pi^2}\tilde{g}\tilde{\lambda} \\ \frac{d\tilde{\lambda}}{ds} &= \epsilon\tilde{\lambda} - \frac{6}{\pi^2}\tilde{g}\tilde{\lambda} - \frac{9}{2\pi^2}\tilde{\lambda}^2 \end{aligned}$$

Show that these equations have four fixed points: the Gaussian fixed point, the Heisenberg fixed point (with $\tilde{\lambda} = 0$), the Ising fixed point (with $\tilde{g} = 0$) and the cubic fixed point with $\tilde{g}, \tilde{\lambda} \neq 0$. Check that the cubic fixed point lies within the regime of parameters for which the free energy is positive definite.

Determine the stability of each fixed point in the (g, λ) plane. [*Hint*: to determine the signs of the eigenvalues of a 2×2 matrix, you need look only at the determinant and trace.] Plot that RG flows between the four fixed points. You should find that you have to distinguish between the cases $N > 4$ and $N < 4$.

4. The free energy for the Sine-Gordon model in $d = 2$ dimensions, with UV cut-off Λ, is given by

$$F[\phi] = \int d^2x\ \frac{1}{2}(\nabla\phi)^2 - \lambda_0 \cos(\beta_0\phi)$$

What is the naive (i.e. "engineering") dimension of β_0 and λ_0?

Decompose the Fourier modes of the field as $\phi_{\mathbf{k}} = \phi^-_{\mathbf{k}} + \phi^+_{\mathbf{k}}$ where $\phi^+_{\mathbf{k}}$ has support on $\Lambda/\zeta < k < \Lambda$. Let $\phi^-(\mathbf{x})$ and $\phi^+(\mathbf{x})$ be the inverse Fourier transform of $\phi^-_{\mathbf{k}}$ and $\phi^+_{\mathbf{k}}$ respectively. Show that, after integrating out $\phi^+_{\mathbf{k}}$, the free energy for ϕ^- becomes, to leading order in λ_0,

$$F'[\phi^-] = \int d^2x\ \frac{1}{2}(\nabla\phi^-)^2 - \lambda_0 \left\langle \cos\beta_0(\phi^- + \phi^+)\right\rangle_+$$

where you should define the meaning of $\langle\ \rangle_+$. Evaluate this expectation value to show that,

$$F'[\phi^-] = \int d^2x\ \frac{1}{2}(\nabla\phi^-)^2 - \lambda_0\,\zeta^{-\beta_0^2/4\pi}\cos(\beta_0\phi^-)$$

Hence show that the $\cos(\beta\phi)$ potential is relevant when $\beta_0^2 < 8\pi$ and irrelevant when $\beta_0^2 > 8\pi$.

[*Hint*: Write $\cos(\phi^- + \phi^+) = \frac{1}{2}(e^{i\phi^-}e^{i\phi^+} + e^{-i\phi^-}e^{-i\phi^+})$ and use Wick's identity (from Q8 on Sheet 2). You will also need the position space correlation function

$$\langle\phi^+(\mathbf{x})\phi^+(\mathbf{y})\rangle_+ = \int_{\Lambda/\zeta}^{\Lambda}\frac{d^2k}{(2\pi)^2}\ \frac{e^{-i\mathbf{k}\cdot(\mathbf{x}-\mathbf{y})}}{k^2}$$

You should make use of this in the limit $\mathbf{x}\to\mathbf{y}$.]

5*. The free energy for a $d = 2$ membrane fluctuating in three dimensional space is

$$\begin{aligned} F[h] &= \int d^2x\ \frac{r_0}{2}(\nabla h)^2 + \frac{\lambda_0}{2}\left(1+(\nabla h)^2\right)^{-5/2}(\nabla^2 h)^2 \\ &\approx \int d^2x\ \frac{r_0}{2}(\nabla h)^2 + \frac{\lambda_0}{2}(\nabla^2 h)^2 - \frac{5\lambda_0}{4}(\nabla h)^2(\nabla^2 h)^2 + \ldots \end{aligned}$$

What is the engineering dimension of the height h, the tension r_0 and the bending modulus λ_0.

Write $F[h] = F_0[h] + F_I[h]$, where F_0 consists of the two quadratic terms, and $F_I[h]$ is the quartic term. Decompose the Fourier modes as $h_{\mathbf{k}} = h^-_{\mathbf{k}} + h^+_{\mathbf{k}}$ where $h^+_{\mathbf{k}}$ has support on $\Lambda/\zeta < k < \Lambda$. Using $e^{-F_0[h^+_{\mathbf{k}}]}$ as a probability distribution, show that

$$\langle h^+_{\mathbf{k}_1}\,h^+_{\mathbf{k}_2}\rangle_+ = \frac{1}{r_0k_1^2 + \lambda_0k_1^4}\,(2\pi)^2\delta(\mathbf{k}_1+\mathbf{k}_2)$$

Write $F_I[h_{\mathbf{k}}]$ in Fourier space. Expand $h_{\mathbf{k}} = h^-_{\mathbf{k}} + h^+_{\mathbf{k}}$ and identify the term in $F_I[h_{\mathbf{k}}]$ that will renormalise the interaction $(\nabla^2h)^2$. Focus only on this term (which means you should ignore the effect of field renormalisation) and derive the beta function

$$\frac{d\lambda}{ds} \approx -\frac{5}{4\pi}$$

where, as usual, the scale is parameterised by $\zeta = e^s$. Do the fluctuations of the membrane on short distance scales render it more or less flexible on long distance scales?

6. This question is harder but is a good way to test your skills at integrating out fields. A system in d spatial dimensions is described by two local order parameters, $\phi_1(\mathbf{x})$ and $\phi_2(\mathbf{x})$. The free energy is invariant under a $\mathbf{Z}_2^2$ symmetry, in which $\phi_1 \mapsto -\phi_1$ and, independently, $\phi_2 \mapsto -\phi_2$. The leading terms are

$$F[\phi_1, \phi_2] = \int d^dx \, \sum_{i=1}^{2} \left[\frac{1}{2} \nabla\phi_i \cdot \nabla\phi_i + \frac{\mu_i^2}{2}\phi_i^2 + g_i \phi_i^4 \right] + \lambda \phi_1^2 \phi_2^2$$

Set $\mu_i^2 = 0$ for $i = 1, 2$. Show that, in $d = 4 - \epsilon$ dimensions, the beta functions are given by

$$\begin{aligned} \frac{dg_i}{ds} &= \epsilon g_i - (36 g_i^2 + \lambda^2) I \qquad \text{for } i = 1, 2 \\ \frac{d\lambda}{ds} &= \epsilon \lambda - (8\lambda^2 + 12\lambda g_1 + 12 \lambda g_2) I \end{aligned}$$

for some constant I. What are the fixed points? Show that the stable fixed point has enhanced $O(2)$ symmetry.