

# Functional Bosonization of Interacting Fermions in Arbitrary Dimensions

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We bosonize the long-wavelength excitations of interacting fermions in arbitrary dimension by directly applying a suitable Hubbard-Stratonovich transformation to the Grassmannian generating functional of the fermionic correlation functions. With this technique we derive a surprisingly simple expression for the single-particle Green's function, which is valid for arbitrary interaction strengths and can describe Fermi- as well as Luttinger liquids. Our approach sheds further light on the relation between bosonization and the random-phase approximation, and enables us to study screening in a non-perturbative way.

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Several groups [1-4] have recently constructed bosonization rules for interacting fermions in dimensions  $d > 1$ . The strategy adopted in these works follows closely the usual bosonization of one-dimensional systems [5], and is based on the observation that suitably defined local density operators approximately obey bosonic commutation relations in the Hilbert space of states with wave-vectors close to the Fermi surface. An alternative method to bosonize interacting fermions without calculating commutators is based on functional integration [6,7]. In this letter we shall further develop this approach, and show that it is in many respects more powerful than the usual operator bosonization.

Consider a system of interacting fermions on a  $d$ -dimensional hypercube with volume  $\mathcal{V}$ . The hamiltonian is given by  $\hat{H} = \hat{H}_0 + \hat{H}_{int}$ , with  $\hat{H}_0 = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} c_{\mathbf{k}}^\dagger c_{\mathbf{k}}$  and  $\hat{H}_{int} = \frac{1}{\mathcal{V}} \sum_{\mathbf{q}, \mathbf{k}, \mathbf{k}'} f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'} c_{\mathbf{k}+\mathbf{q}}^\dagger c_{\mathbf{k}-\mathbf{q}}^\dagger c_{\mathbf{k}} c_{\mathbf{k}'}$ , where  $c_{\mathbf{k}}$  annihilates an electron with wave-vector  $\mathbf{k}$ , and  $\epsilon_{\mathbf{k}}$  is some arbitrary energy dispersion [8]. We assume that the degrees of freedom far away from the Fermi surface have been integrated out, so that  $\mathbf{k}$  and  $\mathbf{k}'$  are restricted to a shell around the Fermi surface, with radial thickness small compared with the Fermi wave-vector  $k_F$ . Thus,  $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$  and  $\epsilon_{\mathbf{k}}$  differ from the bare parameters by finite renormalizations. Following Refs. [1-4], we partition the Fermi surface into disjoint patches of volume  $\Lambda^{d-1}$ . The precise shape of the patches is irrelevant as long as we are interested in fluctuations with wave-vectors  $|\mathbf{q}| \ll \Lambda$ , and the interaction  $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$  is dominated by momentum transfers  $|\mathbf{q}| \ll k_F$ . Throughout this work we shall assume that these restrictions are satisfied. Let us introduce a label  $\alpha$  to enumerate the patches in some arbitrary ordering, and denote by  $K^\alpha$  the set of  $\mathbf{k}$ -points in patch  $\alpha$ . For each  $\alpha$  we define local density operators

$\hat{R}_{\mathbf{q}}^\alpha = \sum_{\mathbf{k}} \Theta^\alpha(\mathbf{k}) c_{\mathbf{k}}^\dagger c_{\mathbf{k}+\mathbf{q}}$ , where  $\Theta^\alpha(\mathbf{k}) = 1$  if  $\mathbf{k} \in K^\alpha$ , and zero otherwise. Assuming that the variations of  $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$  are negligible if  $\mathbf{k}$  and  $\mathbf{k}'$  are restricted to given patches, we may introduce the coarse-grained interaction function  $f_{\mathbf{q}}^{\alpha\alpha'} = \langle \Theta^\alpha(\mathbf{k}) \Theta^{\alpha'}(\mathbf{k}') f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'} \rangle$  where  $\langle \dots \rangle$  denotes averaging with respect to  $\mathbf{k}$  and  $\mathbf{k}'$ .

To bosonize  $\hat{H}$ , we consider the imaginary-time correlation function

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{1}{\mathcal{V}} \int_0^\beta dt e^{-t\omega - t'} \langle \hat{R}_{\mathbf{q}}^\alpha(t) \hat{R}_{-\mathbf{q}}^{\alpha'}(0) \rangle \quad (1)$$

where  $\beta = 1/T$  is the inverse temperature and  $\mathbf{q} = [\mathbf{q}, i\omega_{\mathbf{q}}]$  denotes wave-vector  $\mathbf{q}$  and bosonic Matsubara frequency  $\omega_{\mathbf{q}} = 2\pi n\omega T$ . Below it will become evident that bosonization of  $\hat{H}$  is equivalent to the calculation of a functional  $S_{eff}[\rho]$  of a complex field  $\rho_{\mathbf{q}}^\alpha$ , such that Eq.1 can be written as a bosonic functional integral

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} \frac{\int \mathcal{D}\{\rho\} \rho_{\mathbf{q}}^\alpha \rho_{-\mathbf{q}}^{\alpha'} e^{-S_{eff}(\rho)}}{\int \mathcal{D}\{\rho\} e^{-S_{eff}(\rho)}} \quad (2)$$

We now derive  $S_{eff}[\rho]$  in arbitrary dimension. Starting point is the representation of  $\Pi_{\mathbf{q}}^{\alpha\alpha'}$  as a functional integral over Grassmann fields  $c_{\mathbf{k}}$  [9]

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} \frac{\int \mathcal{D}\{c\} \hat{R}_{\mathbf{q}}^\alpha \hat{R}_{-\mathbf{q}}^{\alpha'} e^{-S_1(c) - S_2(c)}}{\int \mathcal{D}\{c\} e^{-S_1(c) - S_2(c)}} \quad (3)$$

with  $S_1\{c\} = \beta \sum_{\mathbf{k}} [-i\omega_{\mathbf{k}} + \xi_{\mathbf{k}}] c_{\mathbf{k}}^\dagger c_{\mathbf{k}}$ , and  $S_2\{c\} = \frac{\beta}{\mathcal{V}} \sum_{\mathbf{q}} \sum_{\alpha, \alpha'} \hat{R}_{\mathbf{q}}^\alpha f_{\mathbf{q}}^{\alpha\alpha'} \hat{R}_{-\mathbf{q}}^{\alpha'}$ . Here  $\omega_{\mathbf{k}} = \pi(2n+1)T$  are fermionic Matsubara frequencies,  $\xi_{\mathbf{k}} = \epsilon_{\mathbf{k}} - \mu$  is the energy measured relative to the chemical potential  $\mu$  of the interacting system, and  $\hat{R}_{\mathbf{q}}^\alpha = \sum_{\mathbf{k}} \Theta^\alpha(\mathbf{k}) c_{\mathbf{k}}^\dagger c_{\mathbf{k}+\mathbf{q}}$ . We now decouple  $S_2\{c\}$  by means of a Hubbard-Stratonovich transformation that involves two auxiliary fields  $\phi_{\mathbf{q}}^\alpha$  and  $\rho_{\mathbf{q}}^\alpha$  [7]. Completing squares and using the invariance of the integration measure with respect to shifts [9], it is not difficult to show that

$$e^{-S_2(c, \phi)} = \int \mathcal{D}\{\rho\} \mathcal{D}\{\phi\} e^{-S_2(c, \phi) - S_3(\phi, \rho) - S_{int}(\rho)} \quad (4)$$

$$S_2\{c, \phi\} = \sum_{\mathbf{k}, \mathbf{k}'} c_{\mathbf{k}}^\dagger V_{\mathbf{k}\mathbf{k}'} c_{\mathbf{k}'}, \quad V_{\mathbf{k}\mathbf{k}'} = i \sum_{\alpha} \Theta^\alpha(\mathbf{k}) \phi_{\mathbf{k}-\mathbf{k}'}^\alpha \quad (5)$$

$$S_3\{\phi, \rho\} = -i \sum_{\alpha} \sum_{\mathbf{q}} \phi_{-\mathbf{q}}^\alpha \rho_{\mathbf{q}}^\alpha \quad (6)$$

$$S_{int}\{\rho\} = \frac{1}{2} \sum_{\alpha} \sum_{\alpha'} \rho_{-\mathbf{q}}^\alpha f_{\mathbf{q}}^{\alpha\alpha'} \rho_{\mathbf{q}}^{\alpha'}, \quad f_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} f_{\mathbf{q}}^{\alpha\alpha'} \quad (7)$$

# Bosonization Of Interacting Fermions In Arbitrary Dimensions

**Puja Mehta**



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