QUANTUM FIELD THEORY IN CONDENSED MATTER PHYSICS

Wolfgang Belzig
“Wahlpflichtfach” 4h lecture + 2h exercise
Lecture: Mon & Thu, 10-12, P603
Tutorial: Mon, 14-16 (P912) or 16-18 (P712)
50% of exercises needed for exam
Language: “English” (German questions allowed)
EXERCISE GROUPS

- Two groups @ 14h (P912) and 16h (P712)
- Distribution: see list
- Exercise sheets usually 5-8 days before exercise (see webpage for preview)
- Question on exercise to one of the tutors (preferably the one who is responsible)
- Plan: 18.4. Milena Filipovic; 2.5. Martin Bruderer; 9.5. Fei Xu
  16.5. Cecilia Holmqvist; 23.5. Peter Machon
LITERATURE

- G. Rickayzen: Green’s functions and Condensed Matter
- J. Rammer: Quantum Field Theory of Non-equilibrium States
- G. Mahan: Quantum Field Theoretical Methods
- Fetter & Walecka: Quantum Theory of Many Particle Systems
A. Introduction, the Problem
B. Formalities, Definitions
C. Diagrammatic Methods
D. Disordered Conductors
E. Electrons and Phonons
F. Superconductivity
G. Quasiclassical Methods
H. Nonequilibrium and Keldysh formalism
I. Quantum Transport and Quantum Noise
Solid state physics: Many electrons and phonons interacting with the lattice potential and among each other (band structure, disorder, electron-electron interaction, electron-phonon interaction)

We need to explain:

- Why some materials are conductors, semiconductors, insulators, superconductors or ferromagnets
- Thermodynamic quantities, transport coefficients, electric and magnetic susceptibilities
- All phenomena follow from the same Hamiltonian, but with different microscopic parameters (number of electrons per atom, lattice structure, nucleus masses...)
Due to the huge number of degrees of freedom ($M$ states, $N$ particles: $M^N$), a wave function treatment is not feasible.

Quantum fields ($\Psi(x), c_k^\dagger, \ldots$) are more suitable, since they can represent a large number of identical particles.

The central objects are expectation values of quantum field operators - Greens function

$$G(x, x') = \langle \Psi(x)\Psi^\dagger(x') \rangle$$

Physical observable are obtained directly from the Greens functions, e.g. density

$$n(x) = G(x, x)$$
Often approximations are based on some perturbation expansion up to some finite order (first or second).

In many practical problems we need non-perturbative solutions:

Exponential decay

\[ n \sim e^{-t/\tau} \approx 1 - t/\tau \]

goes negative

Critical temperature

\[ k_B T_c \sim \hbar \omega_c e^{-1/NV} \]

not expandable in \( V \)
A. Introduction, the Problem
B. Formalities, Definitions
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I. Quantum Transport and Quantum Noise
A. INTRODUCTION

1. Greens functions (general definition, Poisson equation, Schrödinger equation, retarded, advanced and causal)
   Linear response (general theory of response functions, Kubo formula, Greens function)

2. Statement of the problem (physical problem, 2\textsuperscript{nd} quantization, field operators, electron-phonon interaction, single particle potentials)
THE HAMILTONIAN

\[ H = \sum_j \left( \frac{\vec{p}_j^2}{2M_j} + U_j(\vec{R}_j) \right) \]

\[ + \sum_i \left( \frac{\vec{p}_i^2}{2m} + U_i(\vec{r}_i) \right) \]

\[ + \frac{1}{2} \sum_{i \neq j} \frac{e^2}{|\vec{r}_i - \vec{r}_j|} + \sum_{ij} V_{ij}(\vec{R}_j, \vec{r}_i) \]

- **Ions in the harmonic potential**
- **Electrons in the periodic potential**
- **Electron-electron and Elektron-phonon interaction**
THE HAMILTONIAN

\[ H = \sum_{\vec{q}\lambda} \omega_{\vec{q}\lambda} \left( a_{\vec{q}\lambda}^{\dagger} a_{\vec{q}\lambda} + \frac{1}{2} \right) \]

\[ + \sum_{\vec{k}\sigma} \epsilon_{\vec{k}\sigma} c_{\vec{k}\sigma}^{\dagger} c_{\vec{k}\sigma} \]

\[ + \sum_{\vec{k}\vec{k}'\vec{q}\sigma\sigma'} c_{\vec{k}+\vec{q}\sigma}^{\dagger} c_{\vec{k}'-\vec{q}\sigma'}^{\dagger} V(\vec{q}) c_{\vec{k}'\sigma'} c_{\vec{k}\sigma} \]

\[ + \sum_{\vec{k}\vec{q}\sigma\lambda} g_{\vec{q}\lambda} c_{\vec{k}+\vec{q}\sigma}^{\dagger} c_{\vec{k}\sigma} \left( a_{-\vec{q}\lambda}^{\dagger} + a_{\vec{q}\lambda} \right) \]

Ions in the harmonic potential

Electrons in the periodic potential

Electron-electron and Elektron-phonon interaction
SUMMARY OF A.

1. Greens functions obey differential equations with generalized delta-perturbation

2. Analytical properties of GF are related to causality

3. Linear response response of a quantum system (Kubo formula) related to a retarded function

4. Many-body Hamiltonian in second quantization: electrons, phonons, potentials, interaction
A. Introduction, the Problem
B. **Formal Matters**
C. Diagrammatic Methods
D. Disordered Conductors
E. Electrons and Phonons
F. Superconductivity
G. Quasiclassical Methods
H. Nonequilibrium and Keldysh formalism
I. Quantum Transport and Quantum Noise
B. FORMAL MATTERS

1. Definitions of double-time GF (retarded, advanced, causal, temperature), higher order GF
2. Analytical properties (spectral representation, spectral function, Matsubara frequencies)
3. Single particle Greens functions, spectral function, density of states, quasiparticles
4. Equation of motion for Greens functions
5. Wicks theorem
I. DEFINITIONS

Two-time Greens functions for two operators $A$ and $B$

Retarded Greens function

$$G^R(t,t') = -\frac{i}{\hbar} \left\langle \left[ \hat{A}_H(t), \hat{B}_H(t') \right] \right\rangle \theta(t-t')$$

$$\langle \cdots \rangle = \text{Tr}(\hat{\rho} \cdots)$$

$$\hat{\rho} = \frac{1}{Z} e^{-\beta (\hat{H} - \mu \hat{N})}$$

$$\left[ \hat{A}, \hat{B} \right]_\epsilon = \hat{A}\hat{B} + \epsilon \hat{B}\hat{A}$$

$$\epsilon = \begin{cases} 
-1 & \text{Bose operators} \\
+1 & \text{Fermi operators} 
\end{cases}$$

**Bose:** $\hat{a}_k, \hat{a}_k^\dagger, \hat{\rho}(\vec{r}) = \hat{\psi}^\dagger(\vec{r})\hat{\psi}(\vec{r}), \hat{j}(\vec{r}), \hat{H}, \hat{N}$

**Fermi:** $\hat{c}_k, \hat{c}_k^\dagger, \hat{\psi}^\dagger(\vec{r}), \hat{\psi}(\vec{r})$
I. DEFINITIONS

Temperature Greens function \( t \to -i\tau \)
\[
\hat{A}_H(t) \to \hat{A}(-i\tau) = \hat{A}(\tau) = e^{iH\tau}\hat{A}e^{-iH\tau}
\]
\[
G(\tau, \tau') = -\frac{1}{\hbar}\left\langle T\left(\hat{A}(-i\tau)\hat{B}(-i\tau')\right)\right\rangle
\]

Time-ordering operator
\[
T\left(\hat{A}(\tau)\hat{B}(\tau')\right) = \hat{A}(\tau)\hat{B}(\tau')\theta(\tau - \tau') - \epsilon\hat{B}(\tau')\hat{A}(\tau)\theta(\tau' - \tau)
\]
“Later times to the left”

Higher-order Greens function
\[
G(\tau_1, \tau_2, \tau_3, \ldots) \sim \left\langle T\left(\hat{A}(\tau_1)\hat{B}(\tau_2)\hat{C}(\tau_3)\ldots\right)\right\rangle
\]
B. FORMAL MATTERS

1. Definitions of double-time GF (retarded, advanced, causal, temperature), higher order GF
2. **Analytical properties (spectral representation, spectral function, Matsubara frequencies)**
3. Single particle Greens functions, spectral function, density of states, quasiparticles
4. Equation of motion for Greens functions
5. Wicks theorem
**MATSUBARA GREEN’S FUNCTION**

Definition of temperature GF

\[ \tilde{A}(\tau) = \hat{A}(-i\tau) = e^{H\tau}A e^{-H\tau} \]

\[ G(\tau) = \begin{cases} -\langle \tilde{A}(\tau)\tilde{B} \rangle & \tau > 0 \\ \epsilon \langle \tilde{B}\tilde{A}(\tau) \rangle & \tau < 0 \end{cases} \]

For \( 0 < \tau \leq \beta \) we find the symmetry relation

\[ G(\tau - \beta) = -\epsilon G(\tau) \]

Definition of Matsubara GF for \( -\beta < \tau \leq \beta \)

\[ \tilde{G}(\omega_v) = \int_0^\beta d\tau e^{i\omega_v \tau} G(\tau) \]

\[ G(\tau) = \frac{1}{\beta} \sum_v e^{-i\omega_v \tau} \tilde{G}(\omega_v) \]

Symmetry implies

\[ \omega_v = \frac{\pi}{\beta} \begin{cases} 2v & \epsilon = -1 \text{ for bosons} \\ (2v + 1) & \epsilon = +1 \text{ for electrons} \end{cases} \]

\[ \nu = 0, \pm 1, \pm 2, \ldots \]
SPECTRAL REPRESENTATION

Matsubara GF can be represented as

\[ \tilde{G}(\omega_v) = \int dx \frac{A(x)}{i\omega_v - x} \]

SAME function as before

\[ A(x) = \frac{1 + e^{-\beta \omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_m + E_n) \]

Matsubara GF can be found from G as

\[ \tilde{G}(\omega_v) = G(i\omega_v) \]
Matsubara GF can be represented as

\[ \tilde{G}(\omega_v) = \int dx \frac{A(x)}{i\omega_v - x} \]

SAME function as before

\[ A(x) = \frac{1 + e^{-\beta\omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_m + E_n) \]

Matsubara GF can be found from \( G \) as

\[ \tilde{G}(\omega_v) = G(i\omega_v) \]

**Inverse question:** Can we determine \( G \) from MGF?

No, since \( G'(\omega) = G(\omega) + (1 + e^{\beta\omega}) f(\omega) \) has the same MGF

\[ \tilde{G}(\omega_v) = G(i\omega_v) = G'(i\omega_v) \]

for an arbitrary analytical function \( f(\omega) \)

Unique definition through condition

\[ \lim_{|\omega| \to \infty} G(\omega) \sim 1 / \omega \]
THE SPECTRAL FUNCTION

\[ A(x) = \frac{1 + \epsilon e^{-\beta \omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_n + E_m) \Rightarrow G(\omega) = \int_{-\infty}^{\infty} dx \frac{A(x)}{\omega - x} \]
\[ A(x) = \frac{1 + \epsilon e^{-\beta \omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_n + E_m) \rightarrow G(\omega) = \int_{-\infty}^{\infty} dx \frac{A(x)}{\omega - x} \]

\[ \tilde{G}(\omega_v) = G(i\omega_v) = \int_{-\infty}^{\infty} dx \frac{A(x)}{i\omega_v - x} \]
\[ A(x) = \frac{1 + \epsilon e^{-\beta \omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_n + E_m) \rightarrow G(\omega) = \int_{-\infty}^{\infty} dx \frac{A(x)}{\omega - x} \]

\[ G^R(E) = G(E + i\delta) = \int_{-\infty}^{\infty} dx \frac{A(x)}{E - x + i\delta} \]

\[ \tilde{G}(\omega_v) = G(i\omega_v) = \int_{-\infty}^{\infty} dx \frac{A(x)}{i\omega_v - x} \]
THE SPECTRAL FUNCTION

\[ A(x) = \frac{1 + e^{-\beta \omega}}{Z} \sum_{nm} e^{-\beta E_n} A_{nm} B_{mn} \delta(x - E_n + E_m) \rightarrow G(\omega) = \int_{-\infty}^{\infty} \frac{A(x)}{\omega - x} \mathrm{d}x \]

\[ G^R(E) = G(E + i\delta) = \int_{-\infty}^{\infty} \frac{A(x)}{E - x + i\delta} \mathrm{d}x \]

\[ G^A(E) = G(E - i\delta) = \int_{-\infty}^{\infty} \frac{A(x)}{E - x - i\delta} \mathrm{d}x \]

\[ \tilde{G}(\omega_v) = G(i\omega_v) = \int_{-\infty}^{\infty} \frac{A(x)}{i\omega_v - x} \mathrm{d}x \]
Kramers-Kronig relations (from analyticity of $G$ in upper half-plane)

$$\text{Re} G^R(E) = \frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Im} G(E')}{E' - E}$$

$$\text{Im} G^R(E) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Re} G(E')}{E' - E}$$

Real and imaginary parts of response functions are related
CONSEQUENCES OF ANALYTICAL PROPERTIES

Kramers-Kronig relations (from analyticity of $G$ in upper half-plane)

\[
\begin{align*}
\Re G^R(E) &= \frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\Im G(E')}{E' - E} \\
\Im G^R(E) &= -\frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\Re G(E')}{E' - E}
\end{align*}
\]

Real and imaginary parts of response functions are related

Fluctuation-Dissipation relation (for Bose operators and $A=B$)

\[
\Im G^R(E) = \frac{\pi}{2} \left( e^{-\beta E} - 1 \right) \int_{-\infty}^{\infty} dt e^{iEt} \langle B(t)B^\dagger \rangle
\]
CONSEQUENCES OF ANALYTICAL PROPERTIES

Kramers-Kronig relations (from analyticity of $G$ in upper half-plane)

\[
\text{Re} G^R(E) = \frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Im} G(E')}{E' - E} \quad \text{Im} G^R(E) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Re} G(E')}{E' - E}
\]

Real and imaginary parts of response functions are related

Fluctuation-Dissipation relation (for Bose operators and $A=B$)

\[
\text{Im} G^R(E) = \frac{\pi}{2} (e^{-\beta E} - 1) \int_{-\infty}^{\infty} dte^{iEt} \langle B(t)B^\dagger(t) \rangle
\]

Dissipation (c.f. exercise)
Kramers-Kronig relations (from analyticity of $G$ in upper half-plane)

\[
\text{Re} G^R(E) = \frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Im} G(E')}{E' - E} \\
\text{Im} G^R(E) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} dE' \frac{\text{Re} G(E')}{E' - E}
\]

Real and imaginary parts of response functions are related

Fluctuation-Dissipation relation (for Bose operators and $A=B$)

\[
\text{Im} G^R(E) = \frac{\pi}{2} \left( e^{-\beta E} - 1 \right) \int dt e^{iEt} \langle B(t)B^\dagger \rangle
\]

Dissipation (c.f. exercise)  Fluctuations (spectral density)
B.3 SINGLE PARTICLE GREEN’S FUNCTION

Definition:

\[ G(\vec{r}, \tau; \vec{r}', \tau') = -\left\langle T\left( \bar{\Psi}(\vec{r}, \tau)\bar{\Psi}(\vec{r}', \tau') \right) \right\rangle \]

\[ \bar{\Psi}(\vec{r}, \tau) = e^{H\tau}\Psi(\vec{r})e^{-H\tau} \quad \bar{\Psi}(\vec{r}, \tau) = e^{H\tau}\Psi^{\dagger}(\vec{r})e^{-H\tau} \]

Spectral representation

\[ \tilde{G}(\vec{r}, \vec{r}'; \omega_v) = \beta \int_0^\beta d\tau e^{i\omega_v \tau} G(\vec{r}, \vec{r}'; \tau) = \int dx \frac{A(\vec{r}, \vec{r}', x)}{i\omega_v - x} \]

\[ A(\vec{r}, \vec{r}'; x) = \frac{1 + \epsilon e^{-\beta\omega}}{Z} \sum_{nm} e^{-\beta E_m} \Psi_{nm}(\vec{r})\Psi_{mn}^{\dagger}(\vec{r}')\delta(x - E_m + E_n) \]
MOMENTUM REPRESENTATION

\[
G(\vec{k}, \tau) = -\left\langle T \left( \tilde{c}_{\vec{k}}(\tau) \tilde{c}_{\vec{k}} \right) \right\rangle
\]

\[
\tilde{G}(\vec{k}, \omega_v) = \frac{\beta}{0} d\tau e^{i\omega_v \tau} G(\vec{k}, \tau) = \int_{-\infty}^{\infty} dx \frac{A(\vec{k},x)}{i\omega_v - x}
\]

\[
A(\vec{k},x) = \frac{1 + e^{-\beta x}}{Z} \sum_{nm} e^{-\beta E_m} \left| c_{\vec{k}nm} \right|^2 \delta(x - E_m + E_n)
\]

Free particles

\[
\tilde{G}(\vec{k}, \omega_v) = \frac{1}{i\omega_v - \epsilon_{\vec{k}}}
\]

Density of states

\[
N(E, \vec{k}) = -\frac{1}{\pi} \text{Im} G^R(\vec{k}, E) = A(\vec{k}, E)
\]

\[
N(E, \vec{k}) = \delta(\epsilon_{\vec{k}} - E)
\]

\[
N(E) = -\frac{1}{\pi} \text{Im} \sum_{\vec{k}} G^R(\vec{k}, E) = \sum_{\vec{k}} A(\vec{k}, E)
\]
WICK’S THEOREM

Recursion relation for GF of noninteracting particles

\[
G_{0}^{(n)} (1, 2, \ldots, n; 1', 2', \ldots, n') = \\
\sum_{i=1}^{n} (-\epsilon)^{i-1} G_{0} (1, i') G_{0}^{(n-1)} (\setminus 1', \ldots, \setminus i, \ldots, n') G_{0} (2, 2')
\]

Example:

\[
G_{0}^{(2)} (1, 2; 1', 2') = G_{0} (1, 1') G_{0} (2, 2') - \epsilon G_{0} (1, 2') G_{0} (1', 2)
\]
WICK’S THEOREM II

For Fermions

\[ G_0^{(n)}(1, 2, \ldots, n; 1', 2', \ldots, n') = \begin{bmatrix}
  G_0(1, 1') & G_0(1, 2') & \cdots & G_0(1, n') \\
  G_0(2, 1') & G_0(2, 2') & & \vdots \\
  \vdots & \vdots & \ddots & \vdots \\
  G_0(n, 1') & \cdots & \cdots & G_0(n, n')
\end{bmatrix} \]
B. FORMAL MATTERS - SUMMARY

1. Definitions of different GFs: retarded, advanced, causal, temperature (Wick rotation, imaginary time)
2. Analytical properties, all GF determined by the same spectral function $A(x)$, Matsubara GF and frequencies
3. Single particle Green’s function, density of states, relation to observables, quasiparticles as poles of the 1P-GF
4. Equation of motion: 1P-GF obeys differential equation like ordinary GF, interaction couples 1P-GF, 2P-GF,..., NP-GF
5. Wicks theorem: NP-GF for non-interacting particles can be decomposed into products of 2P-GF
C. DIAGRAMMATIC METHODS

- Systematic perturbation theory in external potential, two-particle interaction or/and electron-phonon interaction
- Symbolic language in terms of Feynman diagrams enables efficient algebraic manipulations
C. DIAGRAMMATIC METHODS

1. Single-particle potential
2. Interacting particles
3. Translational invariant problems
4. Selfenergy and Correlations
5. Screening and random phase approximation (RPA)
C. 1 SINGLE-PARTICLE POTENTIAL

Dictionary:

\[ G(1,2) \quad G_0(1,2) \quad U(1) \]

Dyson equation:

\[ G(1,2) = G_0(1,2) + \int d3 G_0(1,3) U(3) G(3,2) \]
C. 1 SINGLE-PARTICLE POTENTIAL

Dictionary:

\[ G(1, 2) \quad G_0(1, 2) \quad U(1) \]

Dyson equation:

\[ G(1, 2) = G_0(1, 2) + \int d^3 G_0(1, 3) U(3) G(3, 2) \]

Rules for order-n contribution:

- Draw all topologically distinct and connected diagrams with 2 external and n internal vertices.
- Associate a line with \( G_0 \) and each internal vertex with \( U \) and integrate over all internal coordinates.
C. 2 TWO-PARTICLE INTERACTION

\[ H = H_0 + V \]
\[ S_0(\tau) = T \exp \left[ -\int_0^\tau H_0(\tau') \right] \]
\[ V_I(\tau) = S_0^{-1}(\tau)VS_0(\tau) \]
\[ S_I(\tau) = T \exp \left[ -\int_0^\tau V_I(\tau') \right] \]

ready for expansion....
C. 2 TWO-PARTICLE INTERACTION

\[ H = H_0 + V \]
\[ V_I(\tau) = S_0^{-1}(\tau)VS_0(\tau) \]
\[ S_0(\tau) = T \exp \left[ -\int_0^\tau H_0(\tau') \right] \]
\[ S_I(\tau) = T \exp \left[ -\int_0^\tau V_I(\tau') \right] \]

Expression for 1P-GF in interaction picture

\[
G(1,2) = \frac{\left\langle T \left[ S_I(\beta) \bar{\psi}_I(1) \bar{\psi}_I(2) \right] \right\rangle_0}{\left\langle T \left[ S_I(\beta) \right] \right\rangle_0}
\]

ready for expansion....
C. 2 TWO-PARTICLE INTERACTION

Dictionary:

\[ G(1,2) \quad G_0(1,2) \quad -V(1,2) \]
C. 2 TWO-PARTICLE INTERACTION

Dictionary:

\[ G(1,2) \quad G_0(1,2) \quad -V(1,2) \]

Rules for order-n contribution:

- Draw all topologically distinct and **connected** diagrams with 2 external and 2n internal vertices
- Connect all vertices with direct solid lines and all internal vertices with dashed lines
- Integrate over all internal coordinates
- ...

\[ \begin{align*}
G(1,2) & \quad G_0(1,2) \quad -V(1,2) \\
\end{align*} \]
C. 3 TRANSLATIONAL INVARIANCE

\[ G(k, \omega_v) \quad G_0(k, \omega_v) - V(q) \]
C. 3 TRANSLATIONAL INVARIANCE

\[ G(k, \omega_v) - G_0(k, \omega_v) - V(q) \]

Feynman rules for order-n contribution im momentum and frequency space:

- Draw the same diagrams as in real space
- Associate lines with Fourier-transformed GF and V
- Momentum conservation at vertices
- Sum over internal momenta and frequencies
- ...

\[
\begin{align*}
\text{Diagram 1} & = \\
\text{Diagram 2} & + \\
\text{Diagram 3} & + \\
\end{align*}
\]
C. 4 SELFENERGY AND CORRELATIONS

Summing all diagram which can be cut by cutting a single line

\[ G = G_0 + G_0 \Sigma G \]

Dyson equation

Physical implications
- real part of selfenergy implies energy shifts
- imaginary part leads to finite lifetime

Hartree-Fock approximations
- leads to (diverging) real self energy
- neglects correlations in 2P-GF
C. 5 SCREENING AND RANDOM PHASE APPROXIMATION (RPA)

Dressing the interaction

\[ \Pi(k, \omega_n) = \frac{V_0(q)}{1 - \Pi(q, \omega_n)V_0(q)} \]

Physical implications

- screening of the interaction by creation of electron-hole pairs
- equivalent diagram occurs in charge response to external potential -> relation to dielectric function

Consequences: Finite life time & Thomas-Fermi screening
C. DIAGRAMMATIC METHODS

- Systematic perturbation theory for Greens functions in external potential, two-particle interaction or/and electron-phonon interaction
- Symbolic language in terms of Feynman diagrams enables efficient algebraic manipulations
- Selfenergy leads to an improved approximation by summing infinite series of certain diagram classes
- Hartree-Fock diagrams provide a first rough approximation
- Screening of the interaction and finite lifetime in the RPA