Appendix A

The method of invariant imbedding

In a typical transport problem (classical or quantum), one is normally interested with quantities such as the density, the flux, the eigenvalues and the eigenfunctions of the Hamiltonian inside the medium or the sample. The invariant imbedding method, in contrast, directly deals with the external emergent quantities such as the reflection and the transmission of the system, and is ideally suited to Landauer's approach to electronic transport[172], who related these quantities to the transport properties. The invariant imbedding method was originally developed by Chandrasekhar in his work on radiative transfer in stellar atmospheres[2]. The invariant imbedding approach is, however, mostly applicable to one-dimensional systems (width $\ll$ length). For the general details of the approach, formulation and applications, the reader is referred to the excellent book by Bellman and Wing[173]. Here we will present the derivation of the invariant imbedding equations for the convenience of the reader.

We note that both the time-independent Schrodinger equation and the time-independent wave equation can be written as a Helmholtz equation:

$$\frac{\partial^2 \psi(x)}{\partial x^2} + k^2 \left[1 + \eta(x)\right] \psi(x) = 0, \tag{A.1}$$

where k is the wave vector in the medium. For the electronic case, $\eta(x) = -V(x)/E$, ($V(x)$ the potential energy), and in the case of light, $\eta(x)$ is the fluctuating part of the relative refractive index. Now consider a plane-wave with unit amplitude incident on the 1D sample from the right (see Fig. A.1a), where $R(L)$ and $T(L)$ are the reflection and the transmission coefficients of the sample. The invariant imbedding method is a 'kind' of a perturbation method where the length of the system is perturbed and we obtain equations for dR/dL and dT/dL.

The solutions to the Helmholtz equation(A.1) in the free space on the left (ψ_l)

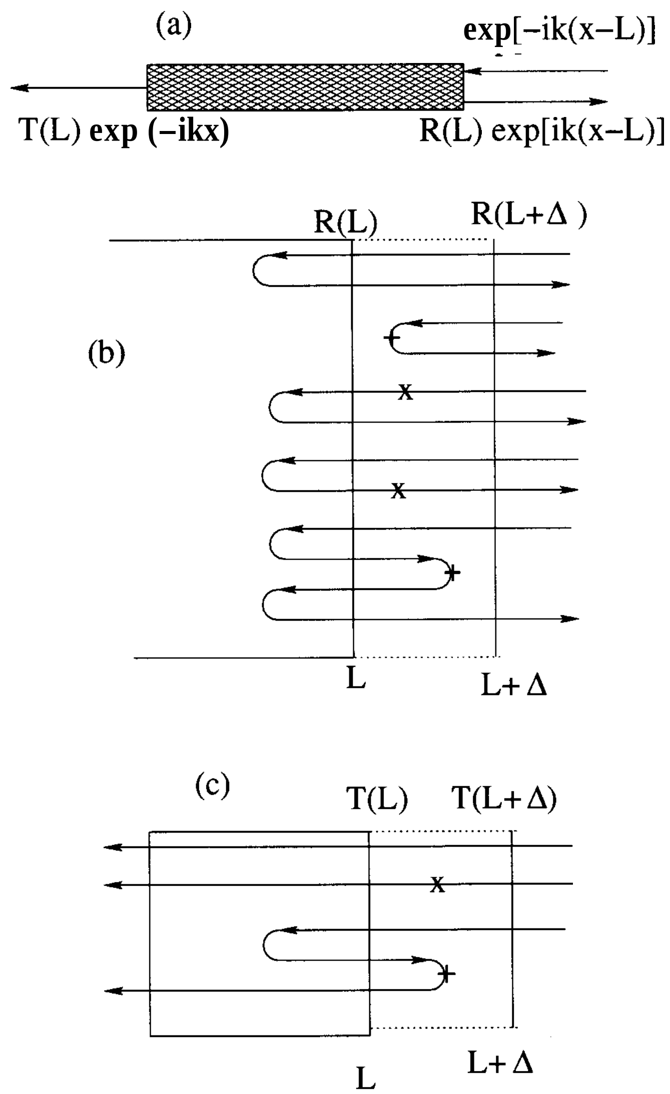

Figure A.1: Schematic pictures (a) scattering from a 1-D disordered sample, where a plane wave is incident from the right. (b) showing a sample of length L imbedded inside a sample of length L + A. the different elementary scattering processes the contribute to the reflection are shown. Free propagation is shown by arrows and the scattering processes by the crosses, and (c) The same as in (b), but showing the elementary processes for transmission and the right (ψ_r) sides of the sample are plane waves:

$$\psi_r(x) = \exp[-ik(x-L)] + R(L)\exp[ik(x-L)] \quad \text{(A.2)}$$

$$\psi_l(\mathrm{x}) = T(L)\exp(-ikx) \quad \text{(A.3)}$$

with boundary conditions $\psi_r(L) = 1 + R(L)$, $\psi_l(0) = T(L)$, $\psi_r' = -ik[1 - R(L)] = -ik[2 - \psi(L)]$ and $\psi_l' = -ikT(L) = -ik\psi(0)$, (the prime indicates differentiation with respect to x) arising from the conditions of continuity of the wave function and its derivative across the boundary. The Helmholtz equation has a solution in terms of an integral equation,

$$\psi(x;L) = \exp[-ik(x-L)] + \frac{ik}{2}\int_0^L dx'\,\eta(x')e^{ik|x-x'|}\psi(x';L) \quad , \quad \text{(A.4)}$$

whose form does not change any further with increase of sample length – the principle of invariance [2]. Now, we imbed the original sample of length L in a sample of length L + A and find the relationship between $R(L)$ and R(L + A).

We differentiate the Equation(A.4) with respect to L and obtain

$$\frac{\partial\psi(x;L)}{\partial L} = A(L)\psi(x;\mathrm{L}) + B(x;\mathrm{L}), \quad \text{(A.5)}$$

where $A(L) = ik + ik/2\ \eta(L)\psi(L;\mathrm{L})$ and $B(L) = ik/2\ \int_0^L \mathrm{dx'}\ e^{ik|x-x'|}\eta(x')B(x;\mathrm{L})$. Since $B(x;\mathrm{L})$ satisfies the same integral equation(A.4) as $\psi(x;\mathrm{L})$ but without the source term, we conclude that $B(x;\mathrm{L}) = 0$. Now, differentiating $\psi(L;\mathrm{L})$ with respect to L, we get

$$\begin{aligned}\frac{\partial\psi(L;L)}{\partial L} &= \frac{\partial\psi(x;L)}{\partial x}|_{x=L} + \frac{\partial\psi(x;L)}{\partial L}|_{x=L},\\ &= -ik[2-\psi(L;\mathrm{L})] + A(L)\psi(L;L).\end{aligned} \quad \text{(A.6)}$$

Using the boundary conditions $\psi(L;\mathrm{L}) = 1+R(L)$, we obtain the invariant imbedding equation for the reflection amplitude as

$$\frac{dR(L)}{dL} = 2ikR(L) + \frac{ik}{2}\eta(L)\left[1+R(L)\right]^2. \quad \text{(A.7)}$$

Similiarly, we can carry out the above procedure at the left end of the sample and obtain the invariant imbedding equation for the transmission as

$$\frac{dT(L)}{dL} = ikT(L) + \frac{ik}{2}\eta(L)\left[1+R(L)\right]T(L). \quad \text{(A.8)}$$

The initial conditions can depend on the problem, but are normally taken to be $T(0) = 1$, and $R(0) = 0$.

Another physically appealing method to derive the above equations is the following graphical method. Consider the Eqn.(A.4). The first term corresponds to free propagation, while the second term is due to scattering and can be further split into a product of three parts: (i)the scattering amplitude $[ik/2\ \eta(x)]$, (ii)the amplitude for propagation $[e^{ik|x-x'|} \simeq 1 + ik\Delta]$ for a small length A $= |x - x'|$, and (iii) the wave amplitude at x $[\psi(x; \mathrm{L})]$. Now, consider all the elementary processes to first order in A, as we imbed a sample of length L inside a sample of length L + A (see Fig. A.1b). We get for the reflection:

$$\begin{aligned} R(L+\Delta) &= (1+ik\Delta)\ R(L)\ (1+ik\Delta) + \frac{ik}{2}\eta(L)\Delta \\ &+ \frac{ik}{2}\eta(L)\Delta\ R(L)\ (1+ik\Delta) + (1+ik\Delta)\ R(L)\ \frac{ik}{2}\eta(L) \\ &+ (1+ik\Delta)\ R(L)\ \frac{ik}{2}\eta(L)\Delta\ R(L)\ (1+ik\Delta). \end{aligned} \tag{A.9}$$

Retaining only terms to first order in A, we immediately get Equation(A.7) in the limit A $\to 0$. Similiarly, we have for the transmission (see Fig. A.1c),

$$T(L+\Delta) = (1+ik\Delta)\ T(L) + \frac{ik}{2}\eta(L)\Delta\ T(L) + R(L)\ \frac{ik}{2}\eta(L)\Delta(L)\ T(L), \tag{A.10}$$

and in the limit A $\to$ 0 obtain the same invariant imbedding Eqn.(A.8) for the transmission.

The invariant imbedding equations are an exact transformation of the Helmholtz equation. The method transforms a boundary value problem into a initial value problem, which might be easier to solve. It can be readily generalized to the multichannel problem and to media which are non-linear[173].

Appendix B

The Novikov theorem

In stochastic problems, one is typically faced with functionals of random processes. The Novikov theorem [100] is a very useful theorem for dealing with functionals of random functions f (t), with a Gaussian distribution. The functions can also be correlated so that ⟨f (t)⟩ = 0 and ⟨f (t)f (t')⟩ = F(t,t'), where ⟨ ⟩ indicates averaging over all the stochastic realizations.

The Novikov theorem states that, if $R_t[f]$ be an arbitrary functional of f (t), then the quantity

$$\langle f(t)R_t[f]\rangle = \int F(t,t')\langle\frac{\delta R_t[f]}{\delta f(t')}\rangle dt', \tag{B.1}$$

where δ/δf (t) is the functional derivative with respect to f (t).
The proof involves expanding the functional R_t in a Taylor expansion

$$R_t[f] = R_t[0] + \sum_{n=1}^{\infty} R^{(n)}_{1\cdots n}(t_1,t_2,\cdots,t_n)f_1f_2\cdots f_n dt_1dt_2\cdots dt_n \tag{B.2}$$

where $f_i =$ f (t_i) and $R^{(n)}_{1\cdots n}(t_1,t_2,\cdots,t_n) = \delta^n R_t[f=0]/\delta f_1\ \delta f_2\cdots\delta f_n$. We note that $R^{(n)}_{1\cdots n}(t_1,t_2,\cdots,t_n)$ is symmetric in its arguments taken together with its indices. Due to the Gaussian nature of the fluctuations, we can split the n^{th} moment into a pair-wise product and get

$$\langle f_\alpha f_1 f_2 \cdots f_n\rangle = \sum_{1=1}^{\mathrm{n}} F(t_\alpha,t_i)\langle f_1\cdots f_{i-1}f_{i+1}\cdots f_n\rangle \tag{B.3}$$

Using this in the expansion for $R_t[f]$ and the symmetry of the functional derivatives, we have for the left hand side of the equation(B.1)

$$\langle f(t)R_t[f]\rangle = \sum_{n=1}^{\infty}\frac{1}{n-1!}\int dt_1 F(t,t_1)\ \left[\int\cdots\int R^{(n)}_{1\cdots n}(t_1,t_2,\cdots,t_n)\langle f_2\cdots f_n\rangle dt_2\cdots dt_n\right] \tag{B.4}$$

Similiarly using the symmetry of the functional derivatives, it is straightforward to verify that

$$\langle\frac{\delta R_t[f]}{\delta f(t_1)}\rangle = \sum_{n=1}^{\infty} \frac{1}{n-1!} \int \cdots \int R^{(n)}_{1\cdots n}(t_1, t_2, \cdots, t_n)\langle f_2 \cdots f_n\rangle dt_2 \cdots dt_n, \tag{B.5}$$

and hence the theorem is proved.

We note that the theorem further simplifies for a 6-correlated white-noise, *i.e.*, for $F(t,t') = f_0^2\delta(t-t')$, and we have

$$\langle f(t)R_t[f]\rangle = f_0^2/2\langle\frac{\delta R_t[f]}{\delta f(t')}\rangle \tag{B.6}$$

The factor of 1/2 comes from taking only half the weight of the 6-function for t $> t'$.

Appendix C

The "formulae of differentiation" of Shapiro and Loginov

The "formulae of differentiation" of Shapiro and Loginov[101] is very useful for dealing with functionals of stationary random processes $f(t)$, such as Gaussian, Poisson arid Markov processes, having an exponential correlation, *i.e.*, $\langle f(t)\rangle = 0$ and $\langle f(t)f(t')\rangle = f_0^2 \exp(-\Gamma|t-t'|)$, where $\langle\ \rangle$ indicates averaging over all the stochastic realizations. If $R_t[f]$ be an arbitrary functional of $f(t)$, the "formula of differentiation" is

$$\frac{d}{dt}\langle f(t)R_t[f]\rangle = \langle f(t)\frac{d}{dt}R_t[f]\rangle - \Gamma\langle f(t)R_t[f]\rangle \tag{C.1}$$

The proof again involves expanding the functional $R_t[f]$ in a functional Taylor series [equation(B.2)]. Again, from the symmetry of the functional derivatives, we note that the formula of differentiation given by equation(C.1) would hold if,

$$\frac{d}{dt}\langle f f_1 f_2 \cdots f_n\rangle = -\Gamma\langle f f_1 f_2 \cdots f_n\rangle \tag{C.2}$$

This property can be verified to hold in the following cases.

The Exponentially correlated Gaussian process, with $\langle f(t)\rangle = 0$ and $\langle f(t)f(t')\rangle = f_0^2 \exp(-\Gamma|t-t'|)$.

The Poisson process, when $f(t) = \sum_k \xi_k g(t-t_k)$, i.e., a series of pulses of form $g(t)$, where t_k is uniformly distributed in $(-\infty,\infty)$ (Poisson distribution) and ξ_k is described by an arbitrary probability distribution $P(\xi_k)$. ξ_k and t_k are independent random processes.

The Telegraph process, where $f(t)$ can take on two values f_1 and f_2 that alternate randomly. The average $\langle f(t)\rangle = 0$, if $\Gamma_1 f_1 + \Gamma_2 f_2 = 0$, where Γ_1 and Γ_2 are the probabilities per unit time of the transitions $f_2 \to f_1$ and $f_1 \to f_2$ respectively. In this case, $\langle f(t)f(t')\rangle = (\Gamma_1 f_1^2 + \Gamma_2 f_2^2)/\Gamma \exp(-\Gamma|t-t'|)$, where $\Gamma = \Gamma_1 + \Gamma_2$. The formula of differentiation holds in this case. We note that $f_1 = -f_2$ and $\Gamma_1 = \Gamma_2$, then the resulting process is the dichotomic Markov process.

List of publications based on the work in this thesis

1. S. Anantha Ramakrishna, E. Krishna Das, G.V. Vijayagovindan and N. Kumar, "Super-reflection of light form a random amplifying medium with disorder in the complex refractive index : Statistics of fluctuations", Phys. Rev. B 62, 256 (2000); cond-mat/9908303.

2. S. Anantha Ramakrishna and N. Kumar, "Imaginary potential as a counter of delay time for wave reflection from a one-dimensional random potential ", Phys. Rev. B 61, 3163 (2000); cond-mat/9906098.

3. S. Anantha Ramakrishna and N. Kumar, "Correcting the quantum clock: The sojourn time" (To be communicated), cond-mat/0009269.

4. S. Anantha Ramakrishna and N. Kumar, "Diffusion of particles moving with constant speed", Phys. Rev. E **60**, 1361 (1999); cond-mat/9903020.

5. V. Gopal, S. Anantha Ramakrishna, A.K. Sood and N. Kumar, "Photon propagation in thin disordered slabs", Pramana J. Phys. (Communicated); cond-mat/9903016.

6. S. Anantha Ramakrishna and N. Kumar, "A note on the generalization of the Telegrapher process to describe photon migration in higher dimensions" (To be communicated), cond-mat/0006483.

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