993SM - Laboratory of Computational Physics lecture 8 - part 1 April 20, 2022

Maria Peressi
Università degli Studi di Trieste - Dipartimento di Fisica
Sede di Miramare (Strada Costiera 11, Trieste)
e-mail: peressi@units.it
tel.: +39 040 2240242

Monte Carlo in quantum systems

VARIATIONAL MONTE CARLO (VMC)

M. Peressi - UniTS - Laurea Magistrale in Physics
Laboratory of Computational Physics - Unit VIII

Metropolis Sampling

(previous Lecture)

Using a method to generate a distribution $p(x)$, we can efficiently sample integrals of the form

$$\langle f \rangle = \frac{\int p(x) f(x)\, dx}{\int p(x)\, dx}$$

application in quantum systems:

$f(x)$: physical quantity; $p(x) = |\psi(x)|^2$

(if f(x) is a multiplicative operator)

Variational Monte Carlo

A stochastic way of calculating **expectation values of observables** in many-body (in general) systems using a **trial wavefunction** $\psi_\alpha(\{R\})$ which depends on a set of parameters $\{\alpha\}$.
(notation: here {R} or simply R indicates a set of many-body coordinates)

=> Which are the parameters $\{\alpha\}$ that give

✔ the most reliable expectation value?

✔ the best trial wavefunction?

A method based on:
variational principle + Monte Carlo evaluation of integrals
using importance sampling based on the Metropolis algorithm

Variational Monte Carlo

1) Start from a trial wavefunction (wfc) with a set of parameters $\{\alpha\}$.

2) Calculate the expectation value of the many-body hamiltonian $\mathcal{H}$ or in general of other observables $\mathcal{O}$ on the wfc, transforming the integral into a form suitable for MC integration

3) Change parameters and recalculate the expectation value on the new wfc.

4) Iterate to reach the best estimate of the expectation value

With VMC one can obtain exact properties only if the trial wavefunction is an **exact** wavefunction of the system; it is a **variational** method to find the ground state.

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Variational Monte Carlo

1) Start from a trial wavefunction (wfc) with a set of parameters $\{\alpha\}$.

done in Lecture VII for a single-particle problem (harmonic oscillator)

2) Calculate the expectation value of the many-body hamiltonian $\mathcal{H}$ or in general of other observables $\mathcal{O}$ on the wfc, transforming the integral in a form suitable for MC integration

3) Change parameters and recalculate the expectation value on the new wfc.

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With VMC one can obtain exact properties only if the trial wavefunction is an **exact** wavefunction of the system; it is a **variational** method to find the ground state.

Quantum averages - I

(Ground) state average:

$$< \mathcal{O} >_\psi = \frac{\int \psi^*(R)\mathcal{O}\psi(R)dR}{\int |\psi(R)|^2 dR}$$

R: compact notation for the whole set of variables of the many-body wfc

Quantum averages - I

(Ground) state average:

$$\psi(R)\psi^{-1}(R)$$

$$< \mathcal{O} >_{\psi} = \frac{\int \psi^*(R)\mathcal{O}\psi(R)dR}{\int |\psi(R)|^2 dR}$$

Quantum averages - I

(Ground) state average:

$\psi(R)\psi^{-1}(R)$

$$< \mathcal{O} >_\psi = \frac{\int \psi^*(R)\mathcal{O}\psi(R)dR}{\int |\psi(R)|^2 dR}$$

$$= \int \left[\frac{|\psi(R)|^2}{<\psi|\psi>}\right] \left[\frac{\mathcal{O}\psi(R)}{\psi(R)}\right] dR \equiv \int w(R)\mathcal{O}_L(R)dR$$

probability (weighting factor)

"local" operator

Quantum averages - II

integrals in many variables {R} =>
suitable for importance sampling - Monte Carlo integration:

$$< \mathcal{O}_L >= \int w(R)\mathcal{O}_L(R)dR \approx \frac{1}{M}\sum_{i=1}^{M}\mathcal{O}_L(R_i)$$

provided that the configurations i are distributed with the probability

$$w(R_i) = \frac{|\psi(R_i)|^2}{\langle\psi|\psi\rangle}$$

error ~ $1/\sqrt{M}$

VMC on one trial wfc - I

Details for the calculation of quantum averages:

2) Calculate the expectation value of the many-body hamiltonian $\mathcal{H}$ on the wfc transforming the integral into a form suitable for MC integration

---

2a) Equilibration phase:

a walker consisting of an initially random set of particle positions {*R*} is propagated according to the Metropolis algorithm, in order to equilibrate and start sampling $|\psi(\{R\})|^2$. If the problem is many-body, a new configuration can be obtained by moving just one particle and the others are unchanged.

2b) Accumulation phase:

New configurations are generated and energies and other observables are accumulated for statistical analysis.

VMC on one trial wfc - II

I. **Equilibration phase:**
   1. Generate initial configuration using random positions for the particles.
   2. For every particle* in the configuration:
      1. Propose a move from **r** to **r'** ← brute force sampling
      2. Compute $w = |\Psi(\mathbf{r}')/\Psi(\mathbf{r})|^2 = |\Psi(\mathbf{r}')|^2/|\Psi(\mathbf{r})|^2$
      3. Accept or reject move accordingly to Metropolis probability $\min(1, w)$
   3. Repeat configuration moves until equilibrated

2. **Accumulation phase:**
   1. For every particle in the configuration:
      1. Propose a move from **r** to **r'**
      2. Compute $w = |\Psi(\mathbf{r}')/\Psi(\mathbf{r})|^2$
      3. Accept or reject move accordingly to Metropolis probability $\min(1, w)$
      4. Accumulate the contribution to the local energy and other observables at **r** (if move is rejected) or **r'** (if move is accepted)
   2. Repeat configuration moves until sufficient data are accumulated

In this algorithm, a new configuration is considered when one particle is moved, individually.

(∗) If the problem is many-body, **r** and **r'** are single-particle coordinates and therefore differ from **R**.

The variational principle - I

For the ground state:
if $\psi(R)$ is a trial wavefunction and E_0 is the exact ground state eigenvalue, we have:

$$< E >_\psi \quad \geq E_0$$

and the "=" holds if and only if the trial wavefunction is the exact ground state wavefunction ($\psi \equiv \psi_0$).

The variational principle - II

Basic idea for VMC:

calculate $\langle \mathcal{O} \rangle$ over different trial wavefunctions

and choose the best...

VMC - standard procedure - I

1) Start from a trial wavefunction with a set of parameters α_0

2) Calculate the expectation value of the operator $\mathcal{O}$ with a MC integration:

$$\langle \mathcal{O}_L \rangle_{\alpha_0} = \frac{\int |\psi_{\alpha_0}(R)|^2 \mathcal{O}_L(R) dR}{\int |\psi_{\alpha_0}(R)|^2 dR} = \int w_{\alpha_0}(R) \mathcal{O}_L(R) dR \approx \frac{1}{M} \sum_{i=1}^{M} \mathcal{O}_L(R_i^{\{\alpha_0\}})$$

3) Change the set of parameters α and recalculate from scratch the expectation value on the new wfc:

$$\langle \mathcal{O}_L \rangle_{\alpha} = \frac{\int |\psi_{\alpha}(R)|^2 \mathcal{O}_L(R) dR}{\int |\psi_{\alpha}(R)|^2 dR} = \int w_{\alpha}(R) \mathcal{O}_L(R) dR \approx \frac{1}{M} \sum_{i=1}^{M} \mathcal{O}_L(R_i^{\{\alpha\}})$$

($\mathcal{O}_L(R)$ changes (contains the new parameters) but also the $w(R)$ and hence the set of points $\{R_i\}$ change)

4) Iterate to reach the best estimate of the expectation value

VMC - standard procedure - II

Two problems:

1) time consuming

2) stochastic errors can be comparable to differences between expectation values for different sets of parameters

solution?

"reweighting" technique

A better idea: use the same sampling for similar trial wfc, $\psi_\alpha, \psi_{\alpha_0}$.

Start from α_0. Define: $r_\alpha(R) \equiv \dfrac{|\psi_\alpha(R)|^2}{|\psi_{\alpha_0}(R)|^2}$

Remembering that : $w_\alpha(R) = \dfrac{|\psi_\alpha(R)|^2}{\int |\psi_\alpha(R)|^2 dR}$, and similar for w_{α_0}, we have :

$$\langle \mathcal{O}_L \rangle_\alpha = \frac{\int |\psi_\alpha(R)|^2 \mathcal{O}_L(R) dR}{\int |\psi_\alpha(R)|^2 dR} = \frac{\int r_\alpha(R) |\psi_{\alpha_0}(R)|^2 \mathcal{O}_L(R) dR}{\int r_\alpha(R) |\psi_{\alpha_0}(R)|^2 dR} =$$

$$= \frac{\int r_\alpha(R) w_{\alpha_0}(R) \mathcal{O}_L(R) dR}{\int r_\alpha(R) w_{\alpha_0}(R) dR} \approx \frac{\sum_i r_\alpha(R_i) \mathcal{O}_L(R_i)}{\sum_i r_\alpha(R_i)}$$

where the set {R_i} of M points is generated according to $w_{\alpha_0}(R)$

(Check that: $A(\alpha, \alpha_0) \equiv \dfrac{\left(\sum_i r_\alpha(R_i)\right)^2}{\sum_i r_\alpha^2(R_i)} \approx M$; if not, generate other points)

"zero-variance" property

(when applicable, very useful!)

if a trial wavefunction is the exact one,

the variance of the numerical estimate of $<\mathcal{O}>$ ($<\mathcal{H}>$)

is zero:

$$\sigma^2 \equiv < \psi | (\mathcal{H} - < \mathcal{H} >)^2 | \psi > = 0$$

the criterion to find the best parameter set is precisely defined!

(remark: applicable also to excited states if the exact excited state wfc is contained in the trial wfc set)

possible problems/remarks

- nodes of the trial wfc: not a real problem, provided the trial moves are large enough to overcome nodes
- $\mathcal{H}(R)\psi(R)$ must be defined everywhere
- $\psi(R)$ must have the proper symmetry (bosons or fermions) and proper boundary conditions

Trial wavefunction

The reliability of the VMC estimates
are crucially dependent
on the quality of the trial wfc

Trial wavefunctions for many-body systems

The choice of trial wavefunction is critical in VMC calculations. All observables are evaluated with respect to the probability distribution $|\Psi_T(\mathbf{R})|^2$. The trial wavefunction, $\Psi_T(\mathbf{R})$, must well approximate an exact eigenstate for all $\mathbf{R}$ in order that accurate results are obtained. Improved trial wavefunctions also improve the importance sampling, reducing the cost of obtaining a certain statistical accuracy.

Typical form chosen for the many-body trial wfc:

$$\psi = \exp\left[\sum_{i<j}^{N} -u(r_{ij})\right] \; det[\theta_k(r_i, \sigma_i)]$$

Jastrow or two-body correlation function

Slater determinant on single-particle spin-orbitals

Programs & scripts:

on moodle2

metropolis_gaussian.f90
(see also: metropolis_sampling.f90, Unit VII)
metropolis_parabola.f90
metropolis_parabola_vs_a.f90
job_gaussian
job_parabola

Exercises

1) Harmonic oscillator solved with VMC : (a particularly simple example, where everything could be done also analytically, used to test the numerical algorithm)

$$\mathcal{H} = E_{kin} + E_{pot} = \frac{1}{2}p^2 + \frac{1}{2}x^2 \qquad (\hbar = 1,\ m = 1)$$

1.a) Trial wfc.:

$$\psi(x) = Ae^{-\beta x^2} \quad \text{or } Ae^{-x^2/(4\sigma^2)} \quad \text{with : } \beta = \frac{1}{4\sigma^2}$$

$$\begin{cases} E_{pot,L}(x) \equiv \dfrac{E_{pot}\psi(x)}{\psi(x)} = \dfrac{1}{2}x^2 \\ E_{kin,L}(x) \equiv \dfrac{E_{kin}\psi(x)}{\psi(x)} = \dfrac{-\frac{1}{2}\frac{d^2}{dx^2}\psi(x)}{\psi(x)} = -2\beta^2 x^2 + \beta \end{cases}$$

$$\begin{cases} \langle E_{pot}\rangle = \dfrac{\langle\psi|\frac{1}{2}x^2|\psi\rangle}{\langle\psi|\psi\rangle} = \dfrac{\int \frac{1}{2}x^2|\psi(x)|^2dx}{\int |\psi(x)|^2dx} = \dfrac{1}{2}\sigma^2 = \dfrac{1}{8\beta} \\ \langle E_{kin}\rangle = \dfrac{\langle\psi|-\frac{1}{2}\nabla^2|\psi\rangle}{\langle\psi|\psi\rangle} = \dfrac{\int \left(\frac{1}{4\sigma^2} - \frac{x^2}{8\sigma^4}\right)|\psi(x)|^2dx}{\int |\psi(x)|^2dx} = \dfrac{1}{8\sigma^2} = \dfrac{1}{2}\beta \end{cases}$$

Determining the ground state

$$\langle E_{pot,L} \rangle = \frac{1}{8\beta}, \qquad \langle E_{kin,L} \rangle = \frac{1}{2}\beta \qquad \frac{d\langle E_{tot,L}(\beta) \rangle}{d\beta} = 0 \Longrightarrow \beta = \frac{1}{2}, E_{tot} = \frac{1}{2}$$

($\alpha = \sqrt{2}/2$)

But also, looking at the variance:

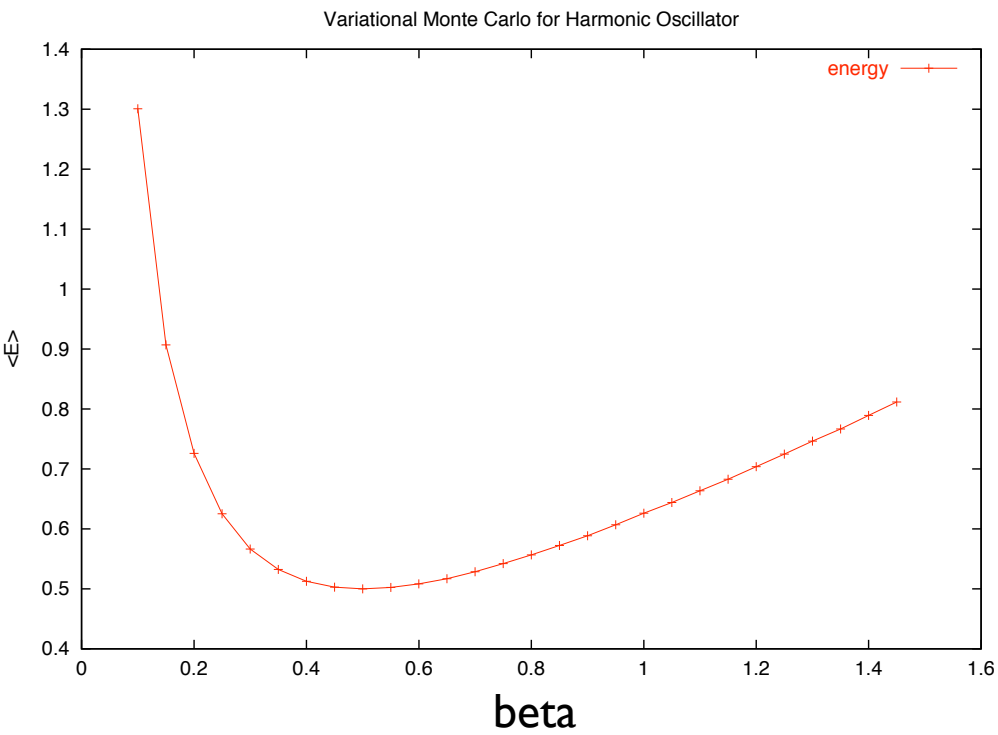
$$\sigma_E^2 = \langle E_{tot,L}^2 \rangle - \langle E_{tot,L} \rangle^2 =$$

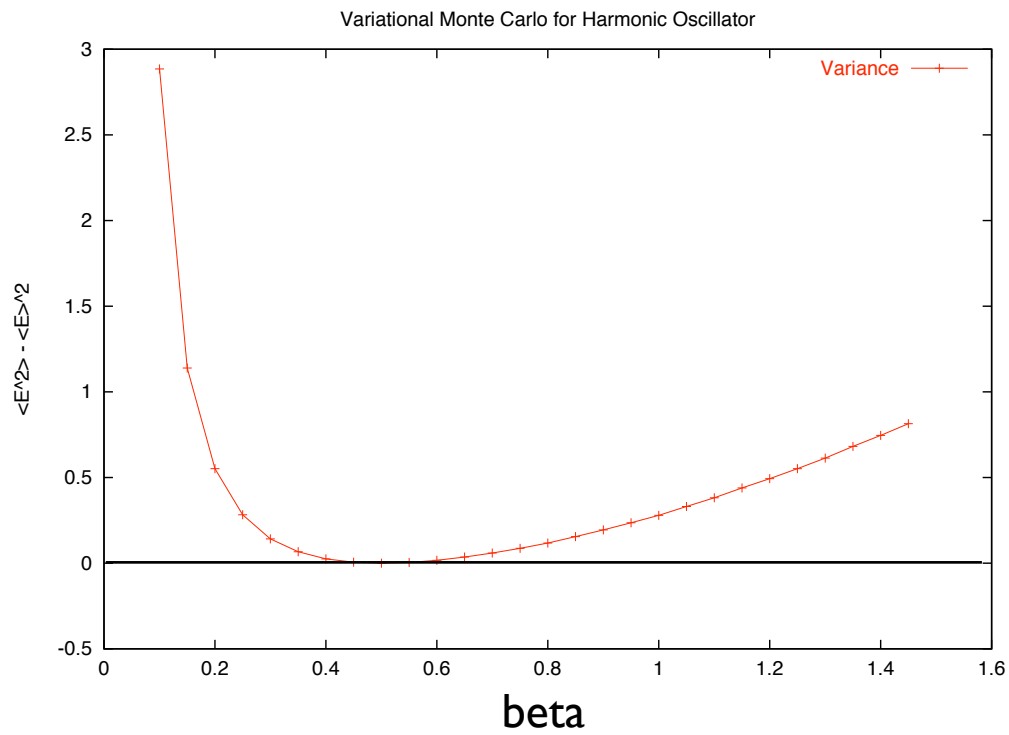
$$= \left\langle \left(\frac{1}{2}x^2 - 2\beta^2 x^2 + \beta \right)^2 \right\rangle - \left(\frac{1}{8\beta} + \frac{1}{2}\beta \right)^2 =$$

$$= \frac{1}{32\beta^2} + \frac{1}{2}\beta^2 - \frac{1}{4}$$

For the exact ground state: $\beta = \frac{1}{2} \quad \Rightarrow \quad \sigma_E = 0$

Notice the zero-variance property for this problem:





$$300 \text{ walkers}^{(*)} \text{ and } \texttt{MCSteps} = 10{,}000$$

(*) In this simple case, even a single walker is enough.

Many independent walkers starting at different random points in the configuration space could be necessary for a better sampling **in more complicate systems** (a single walker might have trouble locating all of the peaks in the distribution; using a large number of randomly located walkers improves the probability that the distribution will be correctly generated)

Exercises

1) Harmonic oscillator solved with VMC:

$$\mathcal{H} = E_{kin} + E_{pot} = \frac{1}{2}p^2 + \frac{1}{2}x^2$$

1.b) Trial wfc.:

(reasonable choice:
satisfies boundary conditions; correct symmetry; only one parameter)

$$\psi(x) = \begin{cases} B(a^2 - x^2), & \text{for } |x| < a; \\ 0, & \text{for } |x| > a. \end{cases} \quad \text{Normalization: } \int_{-a}^{a} B^2(a^2 - x^2)^2 dx = 1 \implies B^2 = \frac{15}{16a^5}$$

$$E_L(x) = \frac{\mathcal{H}\psi(x)}{\psi(x)} = \left(\frac{1}{a^2 - x^2} + \frac{1}{2}x^2\right)$$

(in this case the problem can be analytically solved:)

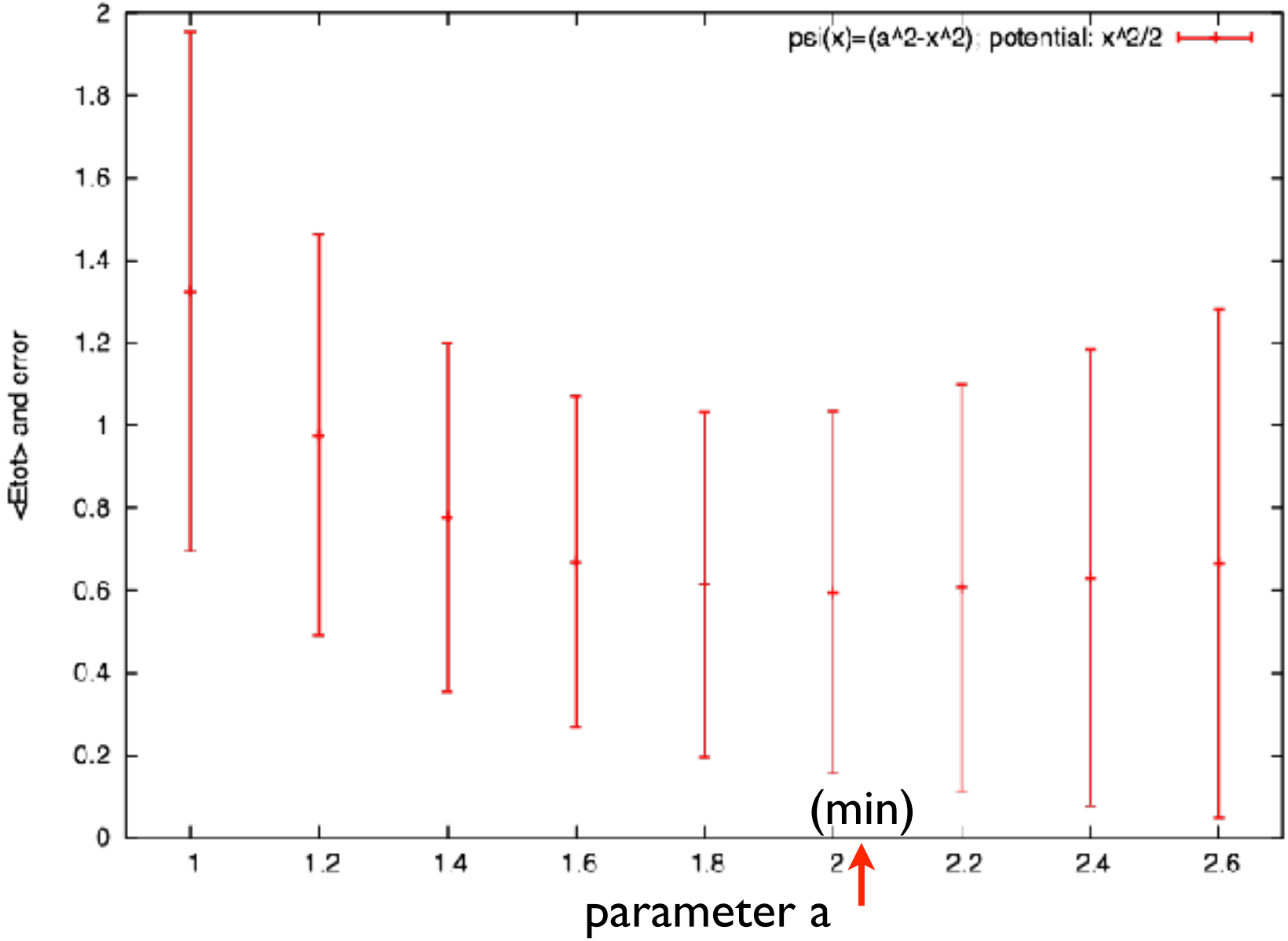
$$\langle E_{tot,L} \rangle = \int_{-a}^{a} \frac{|\psi(x)|^2}{\langle\psi|\psi\rangle} E_L(x) dx = \int_{-a}^{a} B^2(a^2 - x^2)^2 \left(\frac{1}{a^2 - x^2} + \frac{1}{2}x^2\right) dx$$

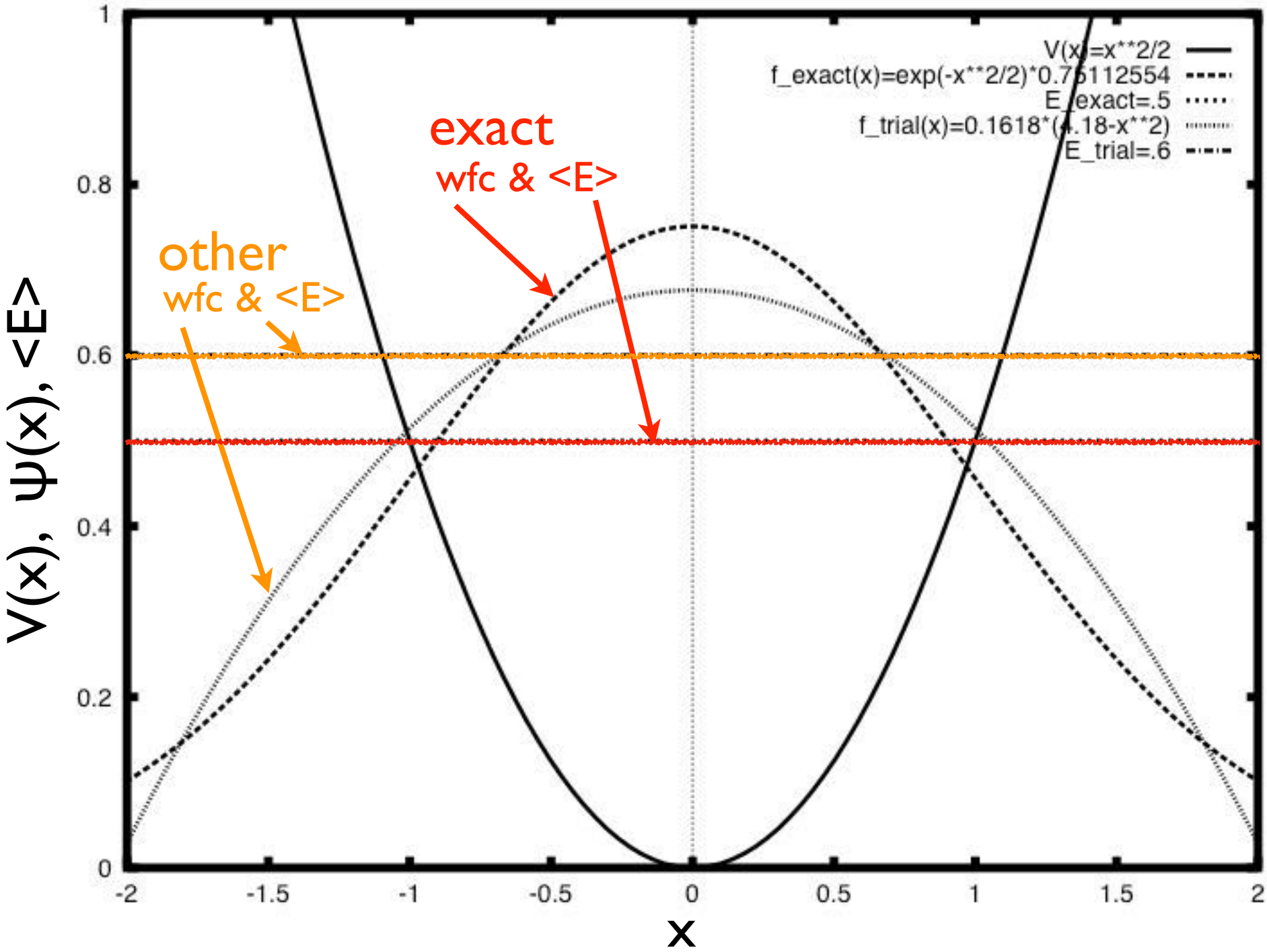
$$= \int_{-a}^{a} B^2(a^2 - x^2) dx + \frac{B^2}{2} \int_{-a}^{a} x^2(a^2 - x^2)^2 dx = \frac{5}{4a^2} + \frac{a^2}{14}$$

$$\frac{d\langle E_{tot,L}(a) \rangle}{da} = 0 \implies a^2 = \sqrt{\frac{35}{2}}, \quad E_{tot} \approx 0.6$$

$a \approx 2.04$

Notice: the zero-variance property does not hold for this class of trial wfc's!
and the energy minimum does not correspond to the variance minimum




V(x), ψ(x), <E>
x
V(x)=x**2/2
f_exact(x)=exp(-x**2/2)*0.75112554
E_exact=.5
f_trial(x)=0.1618*(4.18-x**2)
E_trial=.6
exact
wfc & <E>
other
wfc & <E>
1
0.8
0.6
0.4
0.2
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

Exercises

2) Anharmonic oscillator solved with VMC:

$$\mathcal{H} = E_{kin} + E_{pot} = \frac{1}{2}p^2 + \frac{1}{2}x^2 + \frac{1}{8}x^4$$

Trial wfc.:

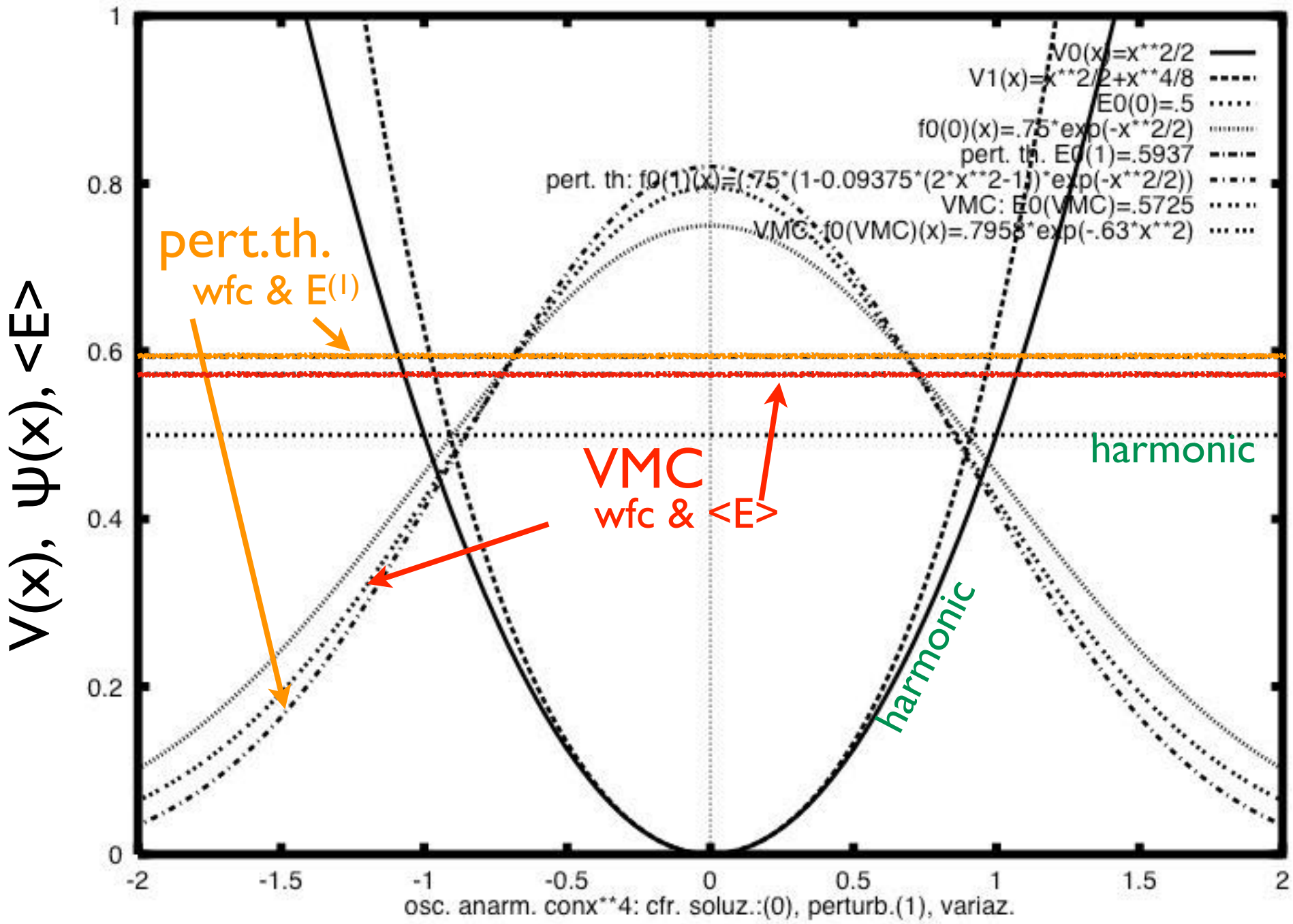
$$\psi(x) = Ae^{-\beta x^2}$$

(also in this case the problem can be analytically solved:)

$$\langle E_{tot,L} \rangle = \left(\frac{1}{2} - 2\beta^2\right)\frac{1}{4\beta} + \beta + \frac{3}{128\beta^2}$$

$$\frac{d\langle E_{tot,L}\rangle}{d\beta} = 0 \quad \Longrightarrow \quad \beta\left(4\beta^2 - 1\right) = \frac{3}{8} \quad \Longrightarrow \quad \beta \approx 0.63, \quad E_{tot} \approx 0.5725$$

(better than 1st order perturbation theory)


V(x), ψ(x), <E>
V0(x)=x**2/2
V1(x)=x**2/2+x**4/8
E0(0)=.5
f0(0)(x)=.75*exp(-x**2/2)
pert. th. E0(1)=.5937
pert. th: f0(1)(x)=.75*(1-0.09375*(2*x**2-1))*exp(-x**2/2))
VMC: E0(VMC)=.5725
VMC: f0(VMC)(x)=.7958*exp(-.63*x**2)
pert.th.
wfc & E(1)
VMC
wfc & <E>
harmonic
harmonic
1
0.8
0.6
0.4
0.2
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
osc. anarm. conx**4: cfr. soluz.:(0), perturb.(1), variaz.

managing input/output

job_parabola Note: it must be **executable!**

make it with: ($prompt)> chmod u+x job_parabola

run with: ($prompt)> ./job_parabola

```
for sigma in 0.5  0.6  0.7  0.8  0.9  1.; do
cat > input << EOF
1000
$sigma
0.
5.
EOF

./a.out < input >> dati
```

(>> means “append”)

3) Hydrogen atom solved with VMC:

$$H = -\frac{\hbar^2}{2m}\nabla^2 - \frac{e^2}{r}$$

A 3D problem which can be reduced to 1D, using the radial part of the laplacian operator in polar coordinates:

$$H = -\frac{\hbar^2}{2m}\left[\frac{\mathrm{d}^2}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}}{\mathrm{d}r}\right] - \frac{e^2}{r}$$

Use atomic units $(\hbar = 1,\ m = 1,\ e^2 = 1 \implies E\ in\ Hartree\ )$

Consider a s-type trial wfc with a radial part: $\psi_\alpha(r) = e^{-\alpha r}$

$$E_L(r) = \frac{H\psi_\alpha(r)}{\psi_\alpha(r)} = -\frac{1}{2}\left[\alpha^2 - \frac{2\alpha}{r}\right] - \frac{1}{r}$$

3) Hydrogen atom solved with VMC:

$$E_L(r) = \frac{H\psi_\alpha(r)}{\psi_\alpha(r)} = -\frac{1}{2}\left[\alpha^2 - \frac{2\alpha}{r}\right] - \frac{1}{r}$$

$$\Rightarrow \quad \langle E_L \rangle = \int_0^\infty \frac{\psi_\alpha^2(r)}{\langle \psi_\alpha | \psi_\alpha \rangle} E_L(r) d\mathbf{r} = \int_0^\infty \frac{4\pi r^2 \psi_\alpha^2(r)}{\langle \psi_\alpha | \psi_\alpha \rangle} E_L(r) dr$$

NOTES: using spherical coordinates and 1D integral, pay attention to:

- Generation of new position: must be $r \geq 0$
- Probability of being btw r and r+dr: is $\propto 4\pi r^2$

3) Hydrogen atom solved with VMC:

The harmonic oscillator program **metropolis_gaussian.f90** or what you have done can be adapted to this problem by changing the form of the trial wave function and local energy:

Accumulate $$E_L(r) = \frac{H\psi_\alpha(r)}{\psi_\alpha(r)} = -\frac{1}{2}\left[\alpha^2 - \frac{2\alpha}{r}\right] - \frac{1}{r}$$

generating points and accepting or rejecting them according to the ratio

$$w = \left(\frac{r'}{r}\right)^2 \left|\frac{\psi(r')}{\psi(r)}\right|^2$$

3) Hydrogen atom solved with VMC:

Hints:

- use nmcs = 100.000
- Max variation of r = 4 Bohr; adapt it to keep the acceptance ratio of the order of 50%

=> use also the zero variance property!

Alternative approach keeping the full 3D problem:

- consider cartesian (x,y,z) coordinates
- no need of limiting the walk; probability automatically set correctly

He atom solved with VMC:

If we use atomic units with $\hbar = m_e = e = 1$, the Hamiltonian for the motion of the two electrons can be written

$$H = -\frac{1}{2}\nabla_1^2 - \frac{1}{2}\nabla_2^2 - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{r_{12}} \, ,$$

where $r_{12} = |\mathbf{r}_{12}| = |\mathbf{r}_1 - \mathbf{r}_2|$. The terms $-2/r_i$ represent the negative (attractive) potential energy between each electron with charge -1 and the Helium nucleus with charge $+2$, and the term $+1/r_{12}$ represents the positive (repulsize) potential energy between the two electrons.

A simple choice of variational trial wave function

(1) H without e-e interaction, ψ without correlation

If the repulsive term $1/r_{12}$ were not present, then the Hamiltonian would be that of two independent Hydrogen-like atoms. It can be shown that the energy and ground state wave function of a Hydrogen-like atom whose nucleus has charge Z are given by

$$E_0 = -\frac{Z^2}{2} \, , \qquad \psi_0 \sim e^{-Zr} \, .$$

The wave function of the combined atom with two non-interacting electrons would be the product of two such wave functions:

$$\boxed{\psi(\mathbf{r}_1, \mathbf{r}_2) \sim e^{-2r_1} e^{-2r_2}} \, .$$

This suggests a trial wave function of the form

$$\Psi_{\mathrm{T},\alpha} = e^{-\alpha r_1} e^{-\alpha r_2} \, ,$$

similar to what was done for the Hydrogen atom. If the electron-electron interaction is neglected, then the average energy with this wave function can be calculated

$$\left\langle -\frac{1}{2}\nabla_1^2 - \frac{1}{2}\nabla_2^2 - \frac{2}{r_1} - \frac{2}{r_2} \right\rangle = 2 \times \frac{\alpha^2}{2} - 2 \times \alpha \, ,$$

He atom solved with VMC:

(2) H with interaction, ψ without correlation

which has a minimum at $\alpha = 1$, which gives $\langle E \rangle = -1$. The experimentally measured ground state energy is $E_0 = -2.904$.

In fact, the average energy can be evaluated exactly for this trial wave function even if the electron-electron interaction is included:

$$\left\langle -\frac{1}{2}\nabla_1^2 - \frac{1}{2}\nabla_2^2 - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{r_{12}} \right\rangle = \alpha^2 - \frac{27}{8}\alpha \ ,$$

which has a minimum at $\alpha = 27/16$, which gives $\langle E \rangle = -2.8477$. This shows that the repulsion between the electrons is important and lowers the energy.

(3) H with interaction, ψ with correlation, extremely simple form

Padé-Jastrow wave function

The textbook suggest using a trial wave function

$$\Psi(\mathbf{r}_1, \mathbf{r}_2) = e^{-2r_1} e^{-2r_2} e^{\frac{r_{12}}{2(1+\alpha r_{12})}},$$

with α as a variational parameter. The local energy with this wave function can be calculated

$$E_{\rm L}(\mathbf{r}_1, \mathbf{r}_2) = -4 + \frac{\alpha}{(1+\alpha r_{12})} + \frac{\alpha}{(1+\alpha r_{12})^2} + \frac{\alpha}{(1+\alpha r_{12})^3} - \frac{1}{4(1+\alpha r_{12})^4} + \frac{\hat{\mathbf{r}_{12}} \cdot (\hat{\mathbf{r}_1} - \hat{\mathbf{r}_2})}{(1+\alpha r_{12})^2} \ .$$

```
double eLocal(double *rElectron1, double *rElectron2) {

    // value of trial wave function for walker n
    double r1 = 0, r2 = 0, r12 = 0;
    for (int d = 0; d < 3; d++) {
        r1 += rElectron1[d] * rElectron1[d];
        r2 += rElectron2[d] * rElectron2[d];
        r12 += (rElectron1[d] - rElectron2[d]) *
               (rElectron1[d] - rElectron2[d]);
    }
    r1 = sqrt(r1);
    r2 = sqrt(r2);
    r12 = sqrt(r12);
    double dotProd = 0;
    for (int d = 0; d < 3; d++) {
        dotProd += (rElectron1[d] - rElectron2[d]) / r12 *
                   (rElectron1[d] / r1 - rElectron2[d] / r2);
    }
    double denom = 1 / (1 + alpha * r12);
    double denom2 = denom * denom;
    double denom3 = denom2 * denom;
    double denom4 = denom2 * denom2;
    double e = - 4 + alpha * (denom + denom2 + denom3)
               - denom4 / 4 + dotProd * denom2;
    return e;
}
```

```
double Psi(double *rElectron1, double *rElectron2) {

    // value of trial wave function for walker n
    double r1 = 0, r2 = 0, r12 = 0;
    for (int d = 0; d < 3; d++) {
        r1 += rElectron1[d] * rElectron1[d];
        r2 += rElectron2[d] * rElectron2[d];
        r12 += (rElectron1[d] - rElectron2[d])
               * (rElectron1[d] - rElectron2[d]);
    }
    r1 = sqrt(r1);
    r2 = sqrt(r2);
    r12 = sqrt(r12);
    double Psi = - 2*r1 - 2*r2 + r12 / (2 * (1 + alpha*r12));
    return exp(Psi);

}
```