Tel Aviv Siesta/TranSiesta Tutorial - 9 September 2014

Siesta internal details: H, S, grid, k-points...

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OUTLINE:

- Some general Info: Main References and Units in SIESTA
- Atomic Orbitals: Real Spherical Harmonics
- The Hamiltonian
- The Density
- The Real Space Grid
- Diagonalization
- The SCF Cycle
- The Total Energy
- Periodic Boundary Conditions and k-points
- The scaling of the calculation with system size

References

http://siesta.icmab.es → Documentation → Manuals
Tutorials
Publications

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **14** (2002) 2745–2779 PII: S0953-8984(02)30737-9

The SIESTA method for *ab initio* order-*N* materials simulation

**José M Soler[1], Emilio Artacho[2], Julian D Gale[3], Alberto García[4],
Javier Junquera[1,5], Pablo Ordejón[6] and Daniel Sánchez-Portal[7]**

Atomic units

$$e = m_e = \hbar = 1$$

$$\text{atomic mass unit} \; = \; m_e$$

$$\text{atomic length unit} \; = \; 1 \text{ Bohr} \; = \; 0.5292 \text{ Ang}$$

$$\text{atomic energy unit} \; = \; 1 \text{ Hartree} \; = \; 27.2 \text{ eV}$$

$$\text{SIESTA energy unit} \; = \; 1 \text{ Ry} \; = \; 0.5 \text{ Hartree} \; = \; 13.6 \text{ eV}$$

$$H_k = -\frac{1}{2}\nabla^2$$

$$V(\mathbf{r}) = \int \frac{\rho(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d^3\mathbf{r}'$$

$$\rho(\mathbf{r}) \equiv n(\mathbf{r}) > 0$$

Real spherical harmonics

$$Y_{lm}(\theta, \varphi) = C_{lm} P_l^m(cos\theta) \begin{cases} sin(m\varphi) & \text{if } m < 0 \\ cos(m\varphi) & \text{if } m \geq 0 \end{cases}$$

Normalization factors

Associated Legendre polynomials

l = 0

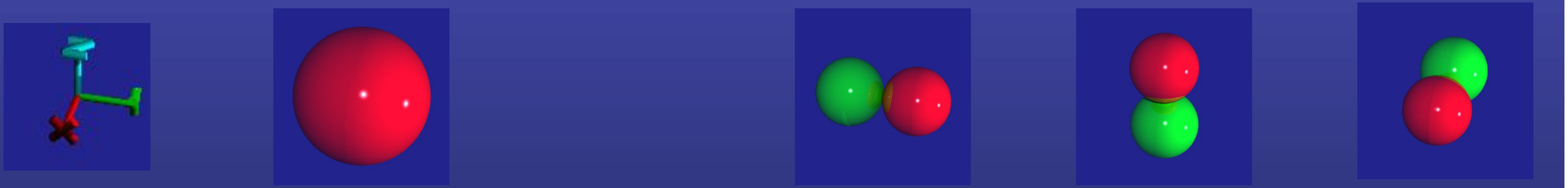
l = 1

m = 0

m = -1

m = 0

m = +1



Pictures courtesy of Victor Luaña

siesta.ORB_INDX output file

siesta.ORB_INDX   output file

```
      92       92 = orbitals in unit cell and supercell. See end of file.

     io     ia is    spec iao   n   l   m   z   p          sym       rc     isc       iuo
      1      1  1       O   1   2   0   0   1   F            s    4.574  0  0  0        1
      2      1  1       O   2   2   0   0   2   F            s    2.639  0  0  0        2
      3      1  1       O   3   2   1  -1   1   F           py    6.175  0  0  0        3
      4      1  1       O   4   2   1   0   1   F           pz    6.175  0  0  0        4
      5      1  1       O   5   2   1   1   1   F           px    6.175  0  0  0        5
      6 ...

 Column codes:
   io = Orbital index in supercell
   ia = Atom to which orbital belongs
   is = Atomic species index
 spec = ...
```

The one-particle Kohn-Sham hamiltonian

$$\hat{H} = \hat{T} + \sum_{\alpha} \hat{V}_{\alpha}^{PS} + V^{H}\left(\vec{r}\right) + V^{xc}\left(\vec{r}\right)$$

Kinetic energy operator

$$\hat{T} = -\frac{1}{2}\nabla^2$$

Hartree potential

$$V^{H}\left(\vec{r}\right) = \int d\vec{r}\,' \frac{\rho(\vec{r}\,')}{|\vec{r} - \vec{r}\,'|}$$

Exchange-correlation potential

(Assume LDA approach)

$$V^{xc}\left(\vec{r}\right) = V^{xc}\left[\rho\left(\vec{r}\right)\right]$$

Transforming the semilocal pseudopotential form into the fully nonlocal separable Kleinman-Bylander form

$$\hat{V}^{PS} = V^{local}\left(\vec{r}\right) + \hat{V}^{KB}$$

$$V^{local}\left(\vec{r}\right) \rightarrow -\frac{Z_{val}}{r}$$

$$\hat{V}^{KB} = \sum_{l=0}^{l_{max}^{KB}} \sum_{m=-l}^{l} \sum_{n=1}^{N_l^{KB}} |\chi_{lmn}^{KB}\rangle v_{ln}^{KB} \langle\chi_{lmn}^{KB}|$$

Exchange-correlation functional

Spin dependency:

- Unpaired electrons
- Non-singlet states
- Ferromagnetic solids

$$E_{xc}\left[\rho_{\uparrow}(\mathbf{r}),\rho_{\downarrow}(\mathbf{r})\right] \quad \Rightarrow \quad V_{xc}^{\uparrow\downarrow}(\mathbf{r})$$

fdf labels:

- SpinPolarized
- FixSpin
- TotalSpin
- XC.Functional
- XC.Authors

Local density approximation (LDA):

$$V_{xc}\left(\rho(\mathbf{r})\right)$$

- Unambiguous and purely nonempirical
- Generally bonds too short and strong
- Frequently too crude

$$V_{xc}\left(\rho(\mathbf{r}),\left|\nabla\rho(\mathbf{r})\right|\right)$$

Generalized gradient approximation (GGA):

- Many flavours with same functional form but different approximations
- Versions optimized for molecules OR for solids
- Generally bonds somewhat long and weak but much better than LDA
- Tendency to overestimate high-spin states
- Underestimates weak bonds (vdW)

$$V_{xc}(\mathbf{r}) = \int K\left(\rho(\mathbf{r}),\nabla\rho(\mathbf{r}),\rho(\mathbf{r}'),\nabla\rho(\mathbf{r}'),\left|\mathbf{r}-\mathbf{r}'\right|\right) d^3\mathbf{r}'$$

Van der Waals functionals (VDW):

- Much better for weak vdW interactions
- vdW bonds systematically too long

No hybrid functionals in Siesta!

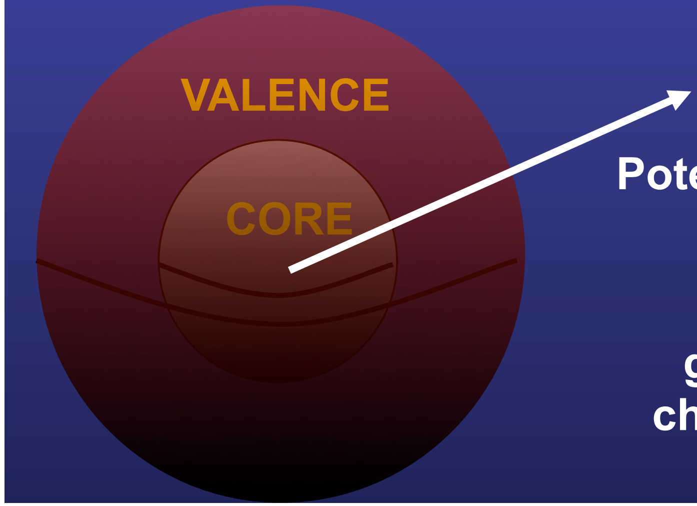
The neutral-atom potential

$$\rho(\mathbf{r}) = \rho_{atom}(\mathbf{r}) + \delta\rho(\mathbf{r}) \quad \Rightarrow \quad V_H(\mathbf{r}) = V_H^{atom}(\mathbf{r}) + \delta V_H(\mathbf{r})$$

Neutral atom potential

$$V^{local}(\vec{r}) \rightarrow -\frac{Z_{val}}{r}$$

$$V_I^{NA}(\vec{r}) \equiv V_I^{local}(\vec{r}) + V_I^{atom}(\vec{r})$$

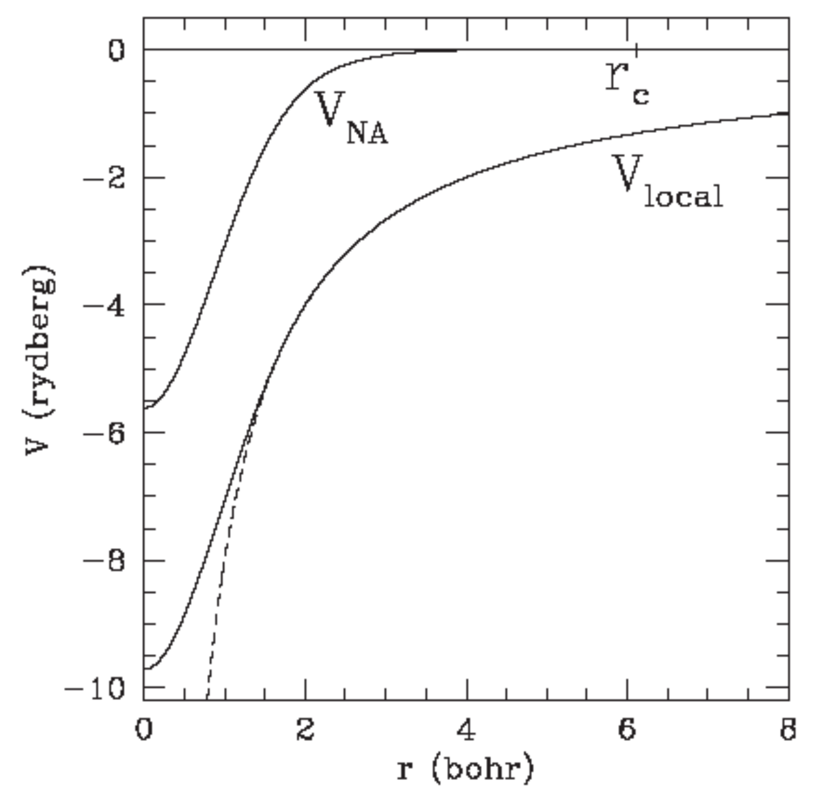


$$V_I^{NA}(\vec{r}) = 0$$

Potential outside the sphere vanishes

(Gauss theorem ⇒ generated by the total charge inside the sphere = 0 if neutral atom)

Vanishes exactly ar r_c

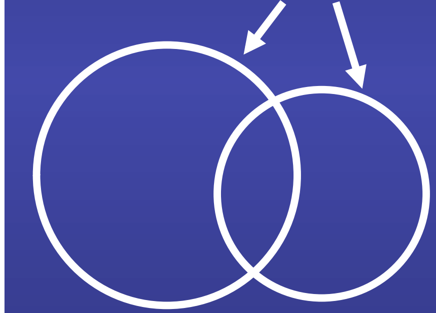


Two- and three-center matrix elements

$$\hat{H} = \overbrace{\hat{T} + \hat{V}^{NL}}^{\text{Two center integrals}} + \overbrace{V^{NA}(\vec{r}) + \delta V^{H}(\vec{r}) + V^{xc}(\vec{r})}^{\text{Three center integrals}}$$

$$\langle \phi_\nu \,|\, \nabla^2 \,|\, \phi_\mu \rangle$$

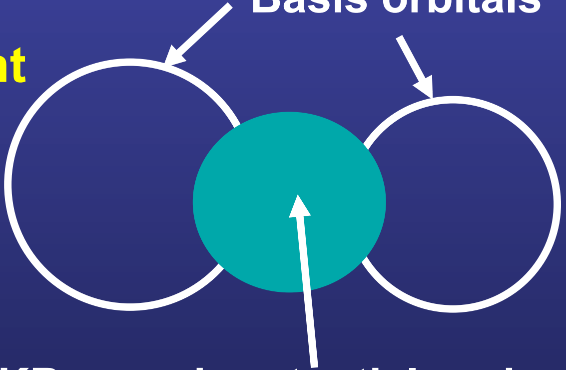
Basis orbitals



Non self-consistent

$$\langle \phi_\nu \,|\, \chi^{KB}_{lmn} \rangle \langle \chi^{KB}_{lmn} \,|\, \phi_\mu \rangle$$

Basis orbitals



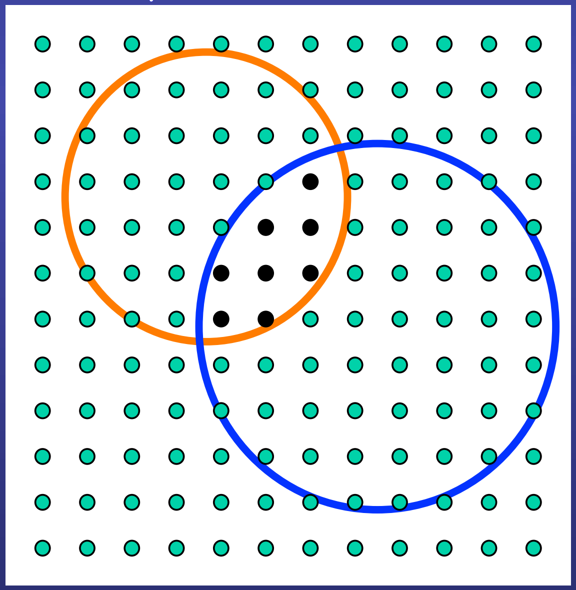
KB pseudopotential projector

Computed in reciprocal space and tabulated

$$\langle \phi_\nu \,|\, V(\vec{r}) \,|\, \phi_\mu \rangle$$

$\phi_\mu(\vec{r})$

Self-consistent



$\phi_\nu(\vec{r})$

Three-dimensional real space grid

The density matrix, a basic ingredient of SIESTA

Expansion of the eigenvectors in a basis of localized atomic orbitals

$$\psi_i\left(\vec{r}\right) = \sum_{\mu} \phi_{\mu}\left(\vec{r}\right) c_{\mu i}$$

$$\rho\left(\vec{r}\right) = \sum_{i} \underset{\uparrow}{n_i} \left|\, \psi_i\left(\vec{r}\right)\right|^2$$

Occupation of state ψ_i

Inserting the expansion into the definition of the density

$$\rho\left(\vec{r}\right) = \sum_{\mu\nu} \rho_{\mu\nu} \phi_{\nu}^{*}\left(\vec{r}\right) \phi_{\mu}\left(\vec{r}\right)$$

where, with $c_{i\nu} \equiv c_{\nu i}^{*}$, the **density matrix** is defined

$$\rho_{\mu\nu} = \sum_{i} c_{\mu i} n_i c_{i\nu}$$

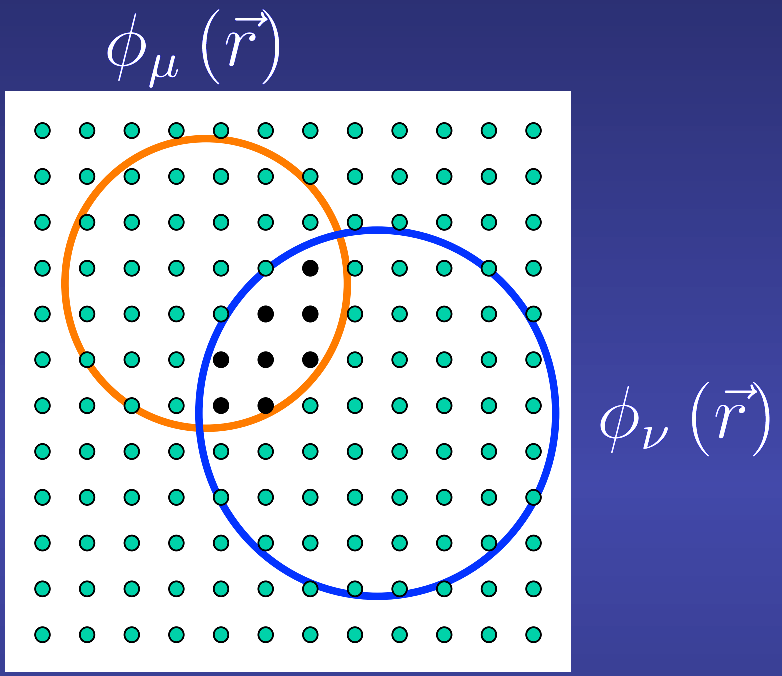
Three dimensional grid to compute Hartree, exchange correlation and neutral atom potentials

$$\rho\left(\vec{r}\right)=\sum_{\mu\nu}\rho_{\mu\nu}\phi_{\nu}^{*}\left(\vec{r}\right)\phi_{\mu}\left(\vec{r}\right)$$

$$\rho\left(\vec{r}\right)\rightarrow V^{xc}\left(\vec{r}\right)$$

$$\delta\rho\left(\vec{r}\right)=\rho\left(\vec{r}\right)-\rho_{atoms}\left(\vec{r}\right)$$

$$\delta\rho\left(\vec{r}\right)\xrightarrow{FFT}\delta V^{H}\left(\vec{r}\right)$$

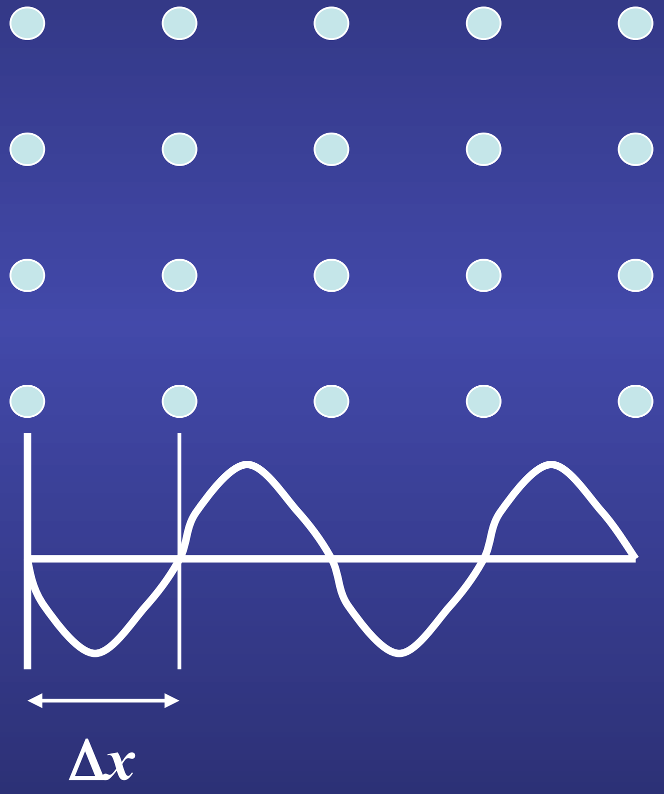


$$V\left(\vec{r}\right)=V^{NA}\left(\vec{r}\right)+\delta V^{H}\left(\vec{r}\right)+V^{xc}\left(\vec{r}\right)$$

$$\int d\vec{r}\ \phi_{\nu}^{*}\left(\vec{r}\right)V\left(\vec{r}\right)\phi_{\nu}\left(\vec{r}\right)\approx\sum_{i}\phi_{\nu}^{*}\left(\vec{r}\right)V\left(\vec{r}\right)\phi_{\nu}\left(\vec{r}\right)\Delta\vec{r}$$

Fineness of the grid controlled by a single parameter, the “MeshCutoff”

E_{cut} : maximum kinetic energy of the plane waves that can be represented in the grid without aliasing



$$\Delta x \Longrightarrow k_c = \frac{\pi}{\Delta x} \Longrightarrow E_c = \frac{\hbar^2 k_c^2}{2m_e}$$

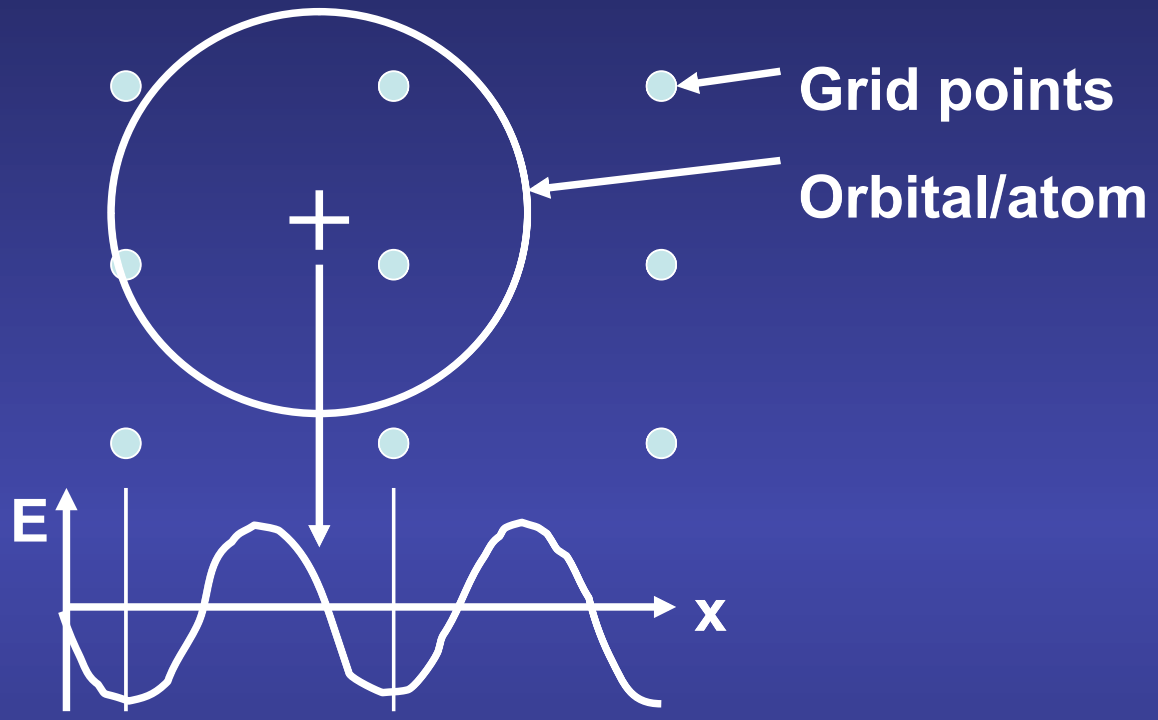
$$E_{cut} = \left(\frac{\pi}{\Delta x}\right)^2 / \, 2$$

fdf label:
- MeshCutoff

In the **grid**, we represent the **density** ⇒ grid cutoff **not directly comparable** with the **plane wave cutoff** to represent wave functions

(Strictly speaking, the density requires a value four times larger)

The grid breaks traslation symmetry, the "eggbox" effect

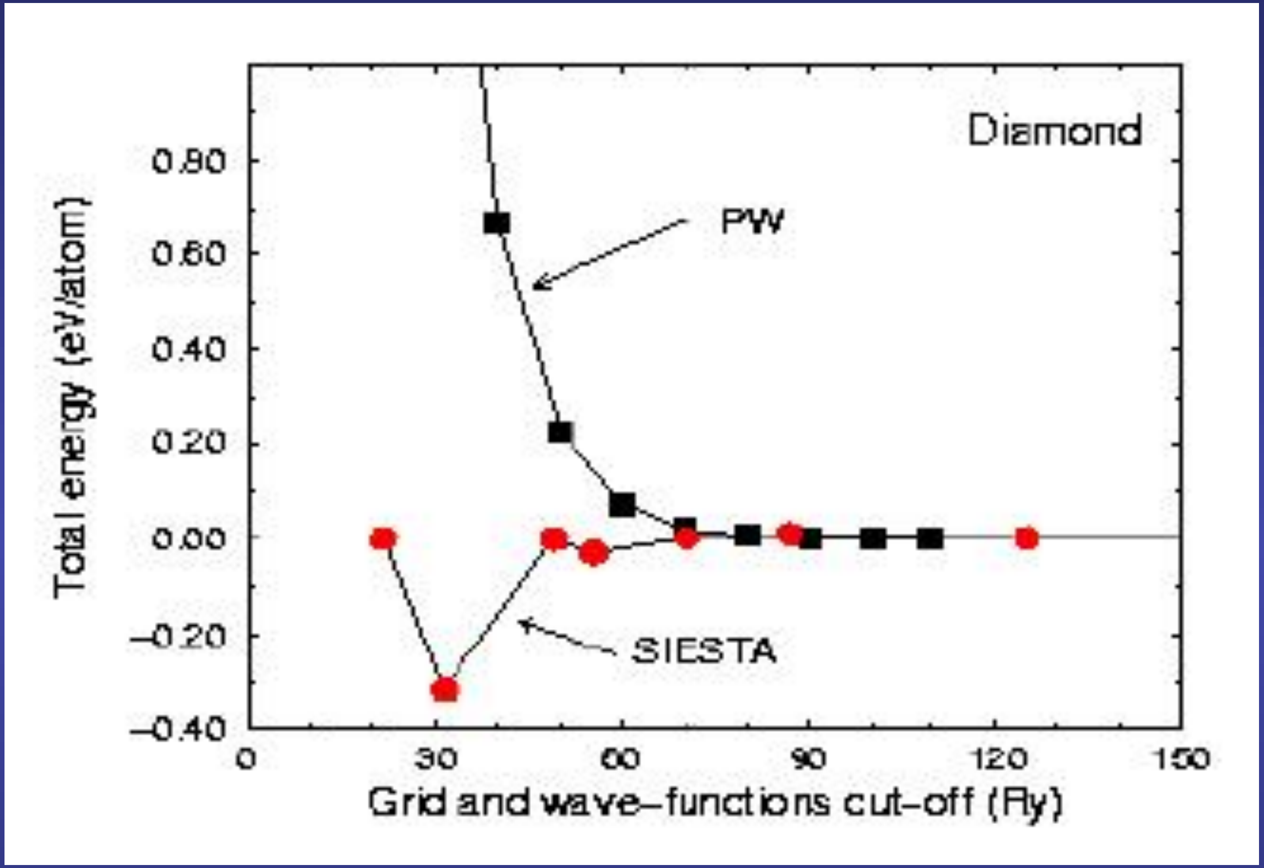


Affects more to forces than to energy

Solutions:

- Increase cutoff (computational effort in time and memory)
- "Grid-cell sampling"
- Filter the atomic orbitals [E. Anglada *et al.* Phys. Rev. B 73, 115122 (2006)]

Convergence of the results with the grid cutoff



$$E_{cut} = \left(\frac{\pi}{\Delta x}\right)^2 / 2$$

Solving Schrödinger's equation

$$\hat{H}\psi_i\left(\vec{r}\right) = E_i\psi_i\left(\vec{r}\right)$$

Expansion of the eigenvectors in a basis of localized atomic orbitals

$$\psi_i\left(\vec{r}\right) = \sum_{\mu}\phi_{\mu}\left(\vec{r}\right)c_{\mu i}$$

Inserting the expansion of the eigenvector into the Kohn-Sham equation

$$\sum_{\mu}c_{\mu i}\hat{H}\phi_{\mu}\left(\vec{r}\right) = E_i\sum_{\mu}c_{\mu i}\phi_{\mu}\left(\vec{r}\right)$$

Multiplying by ϕ_{ν}^{*} at the left in both sides and integrating over all space

$$\sum_{\mu}c_{\mu i}\int d\vec{r}\;\phi_{\nu}^{*}\left(\vec{r}\right)\hat{H}\phi_{\mu}\left(\vec{r}\right) = E_i\sum_{\mu}c_{\mu i}\int d\vec{r}\phi_{\nu}^{*}\left(\vec{r}\right)\phi_{\mu}\left(\vec{r}\right)$$

Transposing everything to the left hand side term

$$\sum_{\mu}\left(\int d\vec{r}\;\phi_{\nu}^{*}\left(\vec{r}\right)\hat{H}\phi_{\mu}\left(\vec{r}\right) - E_i\int d\vec{r}\phi_{\nu}^{*}\left(\vec{r}\right)\phi_{\mu}\left(\vec{r}\right)\right)c_{\mu i} = 0$$

Solving Schrödinger's equation

$$\sum_{\mu} \left(H_{\nu\mu} - E_i S_{\nu\mu} \right) c_{\mu i} = 0$$

$$S_{\nu\mu} = \langle \phi_\nu \,|\, \phi_\mu \rangle = \int d\vec{r}\ \phi^*_\nu(\vec{r})\,\phi_\mu(\vec{r})$$

$$H_{\nu\mu} = \langle \phi_\nu \,|\, \hat{H} \,|\phi_\mu \rangle = \int d\vec{r}\ \phi^*_\nu(\vec{r})\,\hat{H}\phi_\mu(\vec{r})$$

"Generalized" Eigenvalue Problem

$$\boxed{\mathbf{H}\vec{c} = \varepsilon\,\mathbf{S}\vec{c}}$$

(Note: in TranSiesta, Green's functions are used inestead of Eigenvalues / Eigenvectors)

If diagonalization, the generalized eigenvalue problem is solved using standard mathematical libraries

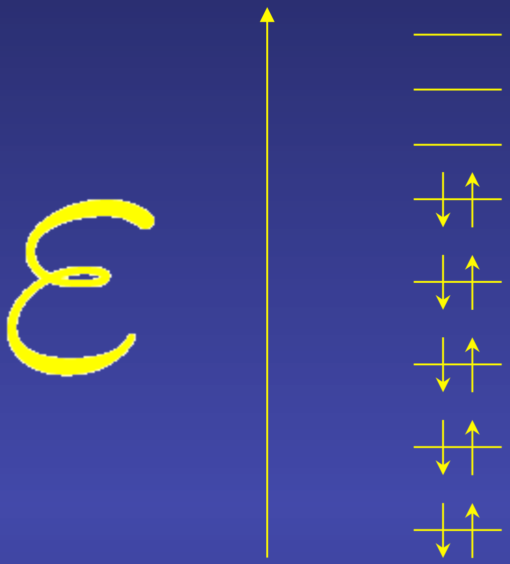
$$\underset{N\times N}{\begin{pmatrix} & & \\ & H & \\ & & \end{pmatrix}}\underset{N\times 1}{\begin{pmatrix} C \end{pmatrix}} = E_{n\vec{k}}\underset{N\times N}{\begin{pmatrix} & & \\ & S & \\ & & \end{pmatrix}}\underset{N\times 1}{\begin{pmatrix} C \end{pmatrix}}$$

Serial:	Parallel:
BLAS	BLACS
LAPACK	SCALAPACK

Freely available in http://www.netlib.org

Most machine vendors have their own implementations available for their own platforms (acml, mkl,…).

The one-particle eigenstates are filled following the "Aufbau" principle: from lower to higher energies



$$n^{\sigma}\left(\vec{r}\right)=\sum_{i} f_{i}^{\sigma}\left|\psi_{i}^{\sigma}\left(\vec{r}\right)\right|^{2}$$

Occupation numbers

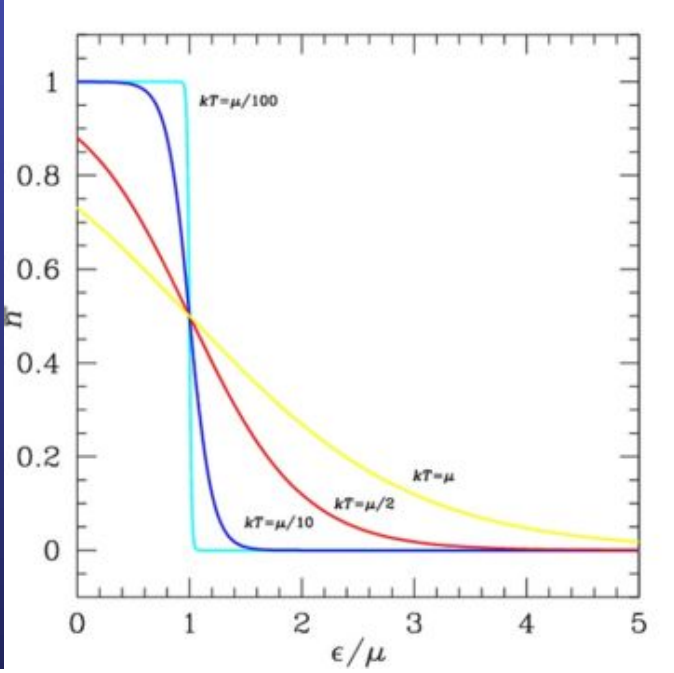
The ground state has one (or two if spin independent) in each of the orbitals with the lowest eigenvalues

A smearing of the electronic occupation might be done:

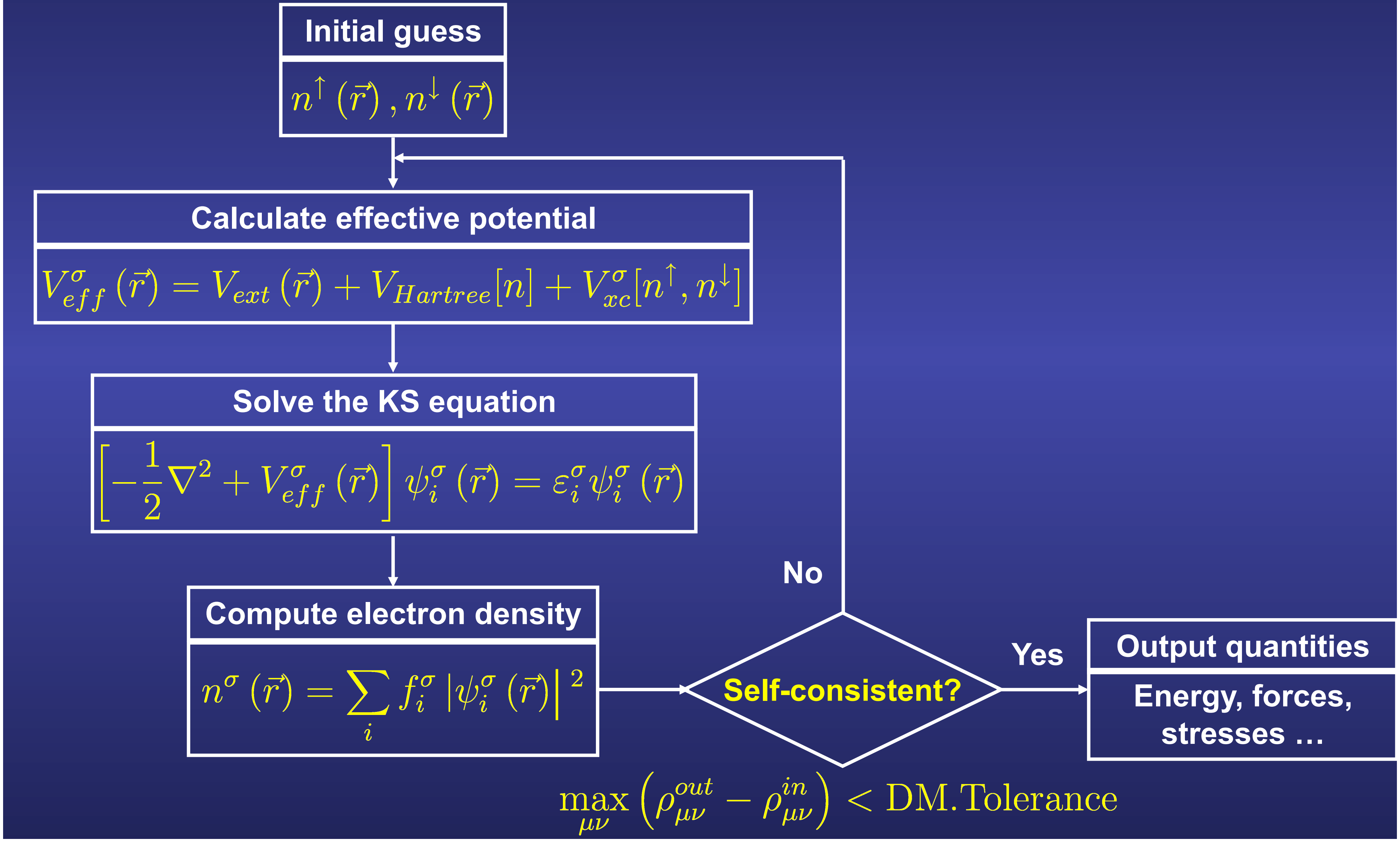
Fermi-Dirac (OccupationFunction FD)

ElectronicTemperature

Methfessel Paxton (OccupationFunction MP)



The Kohn-Sham equations must be solved self-consistently
The potential (input) depends on the density (output)



Initial guess

$$n^{\uparrow}(\vec{r}), n^{\downarrow}(\vec{r})$$

Calculate effective potential

$$V_{eff}^{\sigma}(\vec{r}) = V_{ext}(\vec{r}) + V_{Hartree}[n] + V_{xc}^{\sigma}[n^{\uparrow}, n^{\downarrow}]$$

Solve the KS equation

$$\left[-\frac{1}{2}\nabla^2 + V_{eff}^{\sigma}(\vec{r})\right]\psi_i^{\sigma}(\vec{r}) = \varepsilon_i^{\sigma}\psi_i^{\sigma}(\vec{r})$$

Compute electron density

$$n^{\sigma}(\vec{r}) = \sum_i f_i^{\sigma}\left|\psi_i^{\sigma}(\vec{r})\right|^2$$

Self-consistent?

No

Yes

Output quantities

Energy, forces, stresses …

$$\max_{\mu\nu}\left(\rho_{\mu\nu}^{out} - \rho_{\mu\nu}^{in}\right) < \mathrm{DM.Tolerance}$$

SCF convergence

Charge sloshing:

$E_1<E_2 \Rightarrow n_1>n_2 \Rightarrow E_1>E_2 \Rightarrow n_1<n_2$

Simple mixing:

$\rho_{n+1} = (1-w)\,\rho^{in} + w\,\rho^{out}$

Pulay mixing:

$\rho^{in} \rightarrow \rho^{out} = \rho^{in} + \Delta\rho$

$\Delta\rho_{n+1} = w_{n-2}\,\Delta\rho_{n-2} + w_{n-1}\,\Delta\rho_{n-1} + w_n\,\Delta\rho_n = \min$

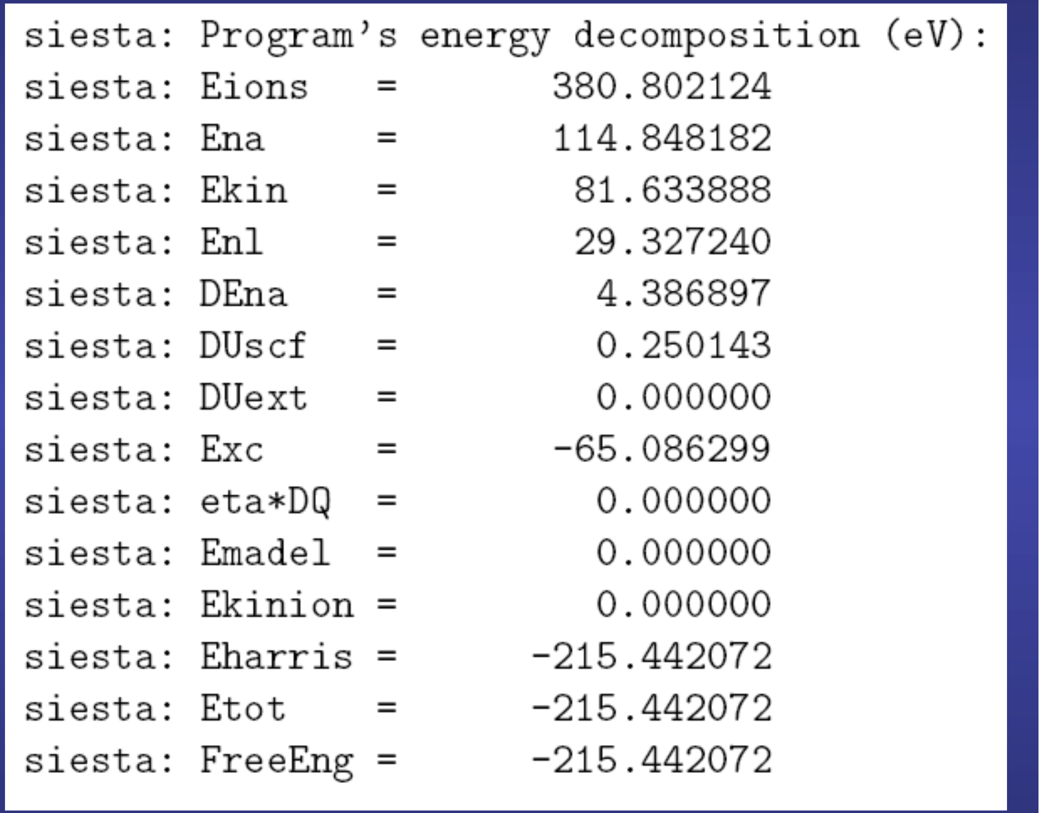
$\rho_{n+1} = w_{n-2}\,\rho_{n-2} + w_{n-1}\,\rho_{n-1} + w_n\,\rho_n + w\,\rho^{out}$

fdf labels:

- ElectronicTemperature
- OccupationFunction
- MixHamiltonian
- DM.UseSaveDM
- DM.MixingWeight
- DM.NumberPulay
- DM.Tolerance
- MaxSCFiterations

Kohn-Sham energy in SIESTA

$$\begin{aligned}
E^{KS} = & \sum_{\mu\nu} T_{\mu\nu}\rho_{\nu\mu} && \textbf{Ekin} \\
& + \sum_{\mu\nu} V^{KB}_{\mu\nu}\rho_{\nu\mu} && \textbf{Enl} \\
& \left.\begin{aligned} & +\frac{1}{2}\sum_{IJ} U^{NA}_{IJ}\left(R_{IJ}\right) \\ & + \sum_{I<J} \delta U^{local}_{IJ}\left(R_{IJ}\right) \end{aligned}\right\} && \textbf{Ena} \\
& - \sum_{I} U^{local}_{I} && \textbf{Eions} \\
& + \int V^{NA}\left(\vec{r}\right)\delta\rho\left(\vec{r}\right)d\vec{r} && \textbf{DEna} \\
& + \frac{1}{2}\int \delta V_H(\vec{r})\delta\rho(\vec{r})d\vec{r} && \textbf{DUscf} \\
& + \int \varepsilon^{xc}\left(\vec{r}\right)\rho\left(\vec{r}\right)d\vec{r} && \textbf{Exc}
\end{aligned}$$



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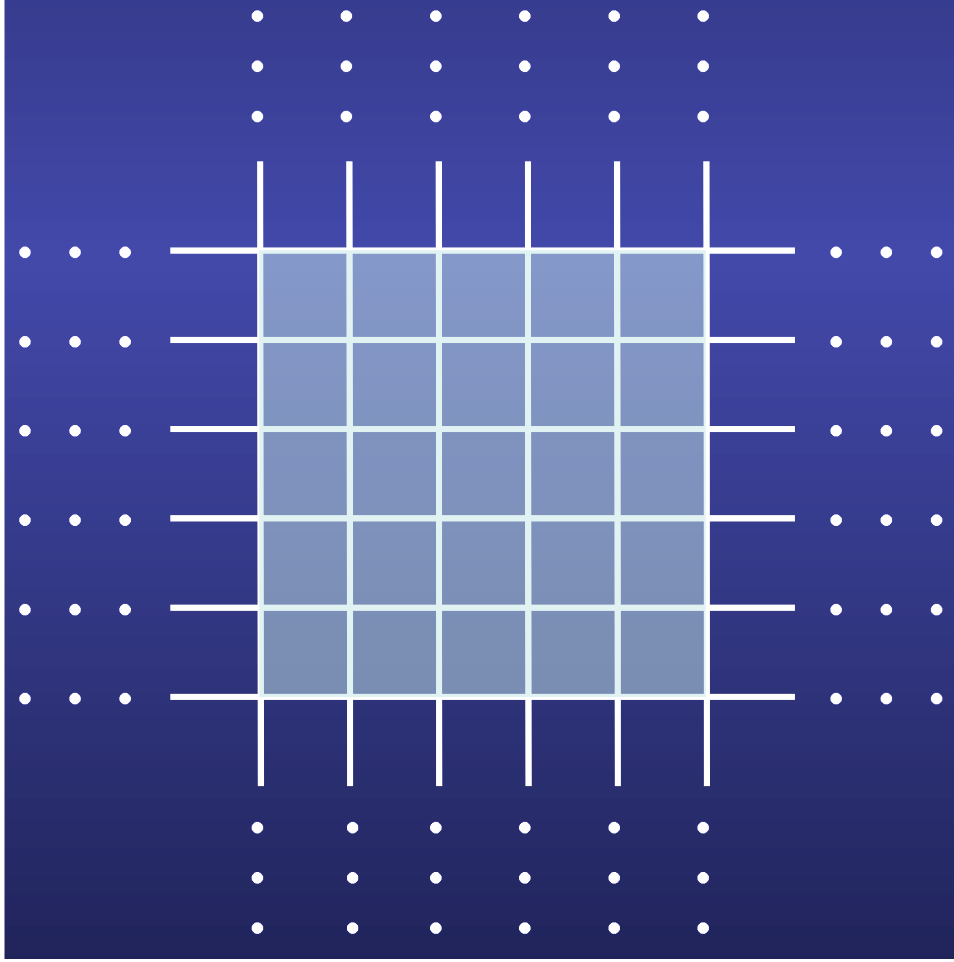
siesta: Program's energy decomposition (eV):
siesta: Eions   =       380.802124
siesta: Ena     =       114.848182
siesta: Ekin    =        81.633888
siesta: Enl     =        29.327240
siesta: DEna    =         4.386897
siesta: DUscf   =         0.250143
siesta: DUext   =         0.000000
siesta: Exc     =       -65.086299
siesta: eta*DQ  =         0.000000
siesta: Emadel  =         0.000000
siesta: Ekinion =         0.000000
siesta: Eharris =      -215.442072
siesta: Etot    =      -215.442072
siesta: FreeEng =      -215.442072
```

+ Sum extra terms if a net charge (Emadel), an external electric field (DUext), Order-N solver (eta*DQ) are used, or if the nuclei are moving (Ekinion)

How can we simulate an infinite periodic solid?
Periodic (Born-von Karman) boundary conditions

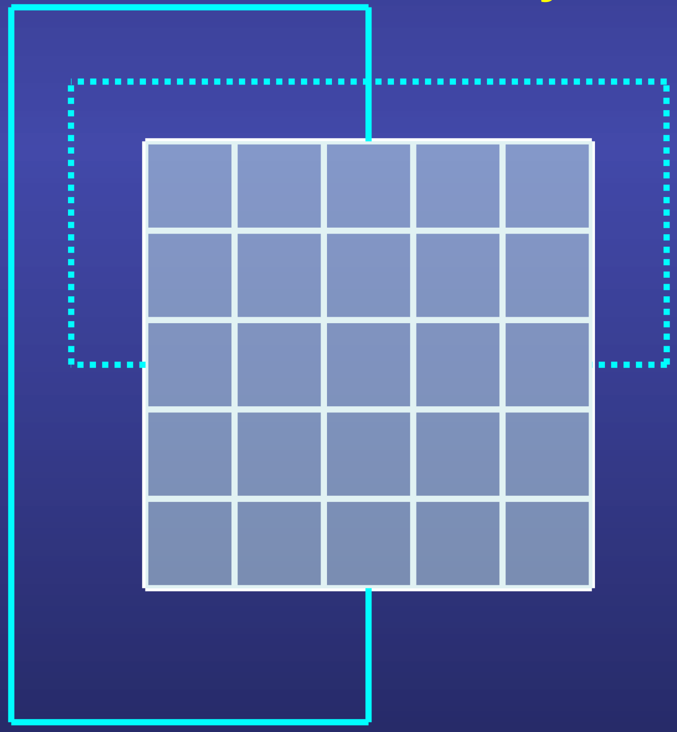
We should expect that the bulk properties to be unaffected by the presence of its surface.

A natural choice to emphasize the inconsequence of the surface by disposing of it altogether

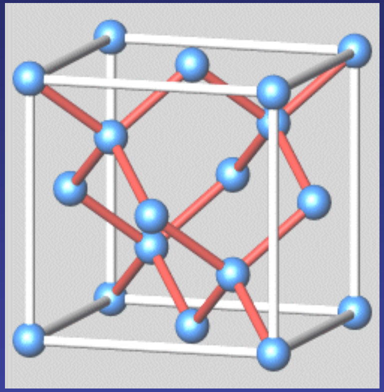


Supercell +

Born-von Karman boundary conditions



Electrons in a periodic potential



$$V(\vec{r}) = V(\vec{r} + \vec{R})$$

Bloch Theorem:

$$\psi_{n,\vec{k}}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} u_{n,\vec{k}}(\vec{r}) \qquad u_{n,\vec{k}}(\vec{r} + \vec{R}) = u_{n,\vec{k}}(\vec{r})$$

Periodicity in reciprocal space

$\vec{G}$ ≡**Reciprocal lattice vector**

$$\left\{ \begin{array}{l} \psi_{n,\vec{k}+\vec{G}}(\vec{r}) = \psi_{n,\vec{k}}(\vec{r}) \\ \\ \varepsilon_{n,\vec{k}+\vec{G}} = \varepsilon_{n,\vec{k}} \end{array} \right.$$

Instead of computing an infinite number of electronic wave functions

Finite number of wave functions at an infinite number of k-points in the 1BZ

K-dependent matrix elements

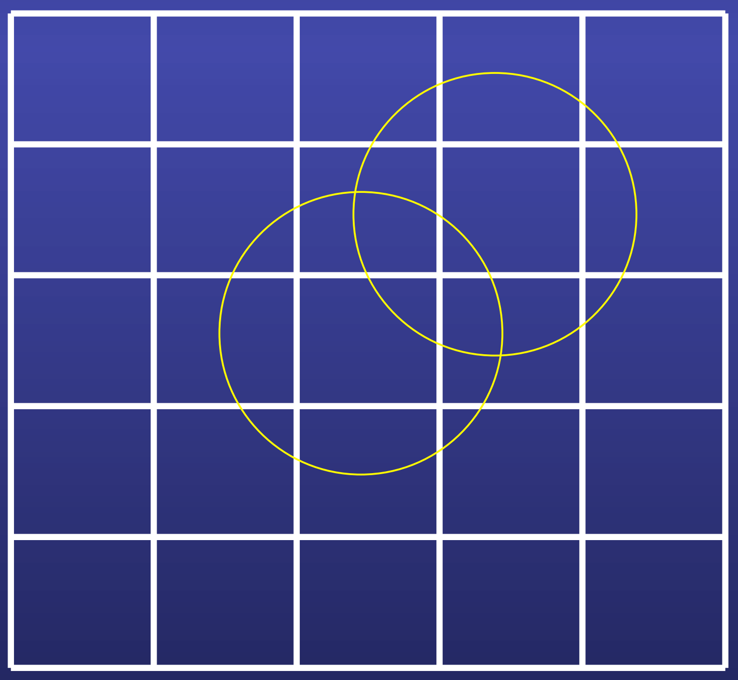
$$\psi_{\mathbf{k}j}(\mathbf{r}) = \sum_{\mu\mathbf{R}} c_{\mu\mathbf{k}j}\phi_{\mu\mathbf{R}}(\mathbf{r})e^{i\mathbf{k}(\mathbf{R}+\mathbf{r}_\mu)}$$

$$\sum_\nu \left(H_{\mu\nu\mathbf{k}} - E_j S_{\mu\nu\mathbf{k}}\right)c_{\nu\mathbf{k}j} = 0$$

$$H_{\mu\nu\mathbf{k}} = \sum_{\mathbf{R}'} \left\langle \phi_{\mu\mathbf{R}} \middle| \mathbf{H} \middle| \phi_{\nu\mathbf{R}'} \right\rangle e^{i\mathbf{k}(\mathbf{R}+\mathbf{r}_\mu-\mathbf{R}'-\mathbf{r}_\nu)}$$

$$S_{\mu\nu\mathbf{k}} = \sum_{\mathbf{R}'} \left\langle \phi_{\mu\mathbf{R}} \mid \phi_{\nu\mathbf{R}'} \right\rangle e^{i\mathbf{k}(\mathbf{R}+\mathbf{r}_\mu-\mathbf{R}'-\mathbf{r}_\nu)}$$

SIESTA supercell



Many magnitudes require integration of Bloch functions over Brillouin zone (1BZ)

Charge density

$$\rho(\vec{r}) = \sum_i \int_{BZ} n_i(\vec{k}) |\psi_{i\vec{k}}(\vec{r})|^2 d\vec{k}$$

Band structure energy

$$E_{BS} = \sum_i \int_{BZ} n_i(\vec{k}) \varepsilon_i(\vec{k}) d\vec{k}$$

In principle: we should know the eigenvalues and/or eigenvectors at all the k-points in the first BZ

In practice: electronic wave functions at k-points that are very close together will be almost identical $\Rightarrow$

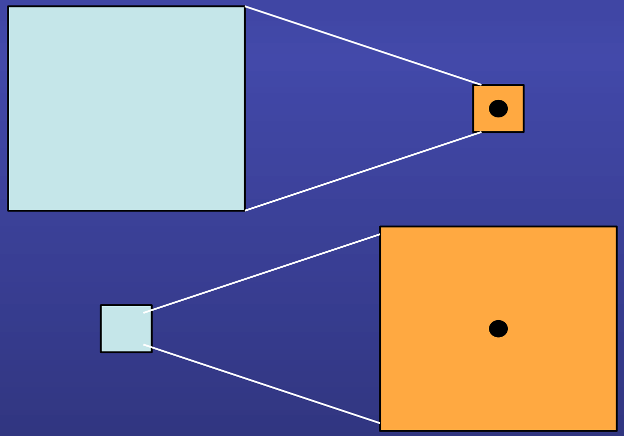
It is possible to represent electronic wave functions over a region of k-space by the wave function at a single k-point.

$$\int d\vec{k} \longrightarrow \sum_{\vec{k}} \Delta\vec{k}$$

k-points Sampling

Essential for:

Small cells



Real space ↔ Reciprocal space

$$\underbrace{\text{Metals} \qquad \text{Magnetic systems}}_{}$$

Good description of the Bloch states at the Fermi level

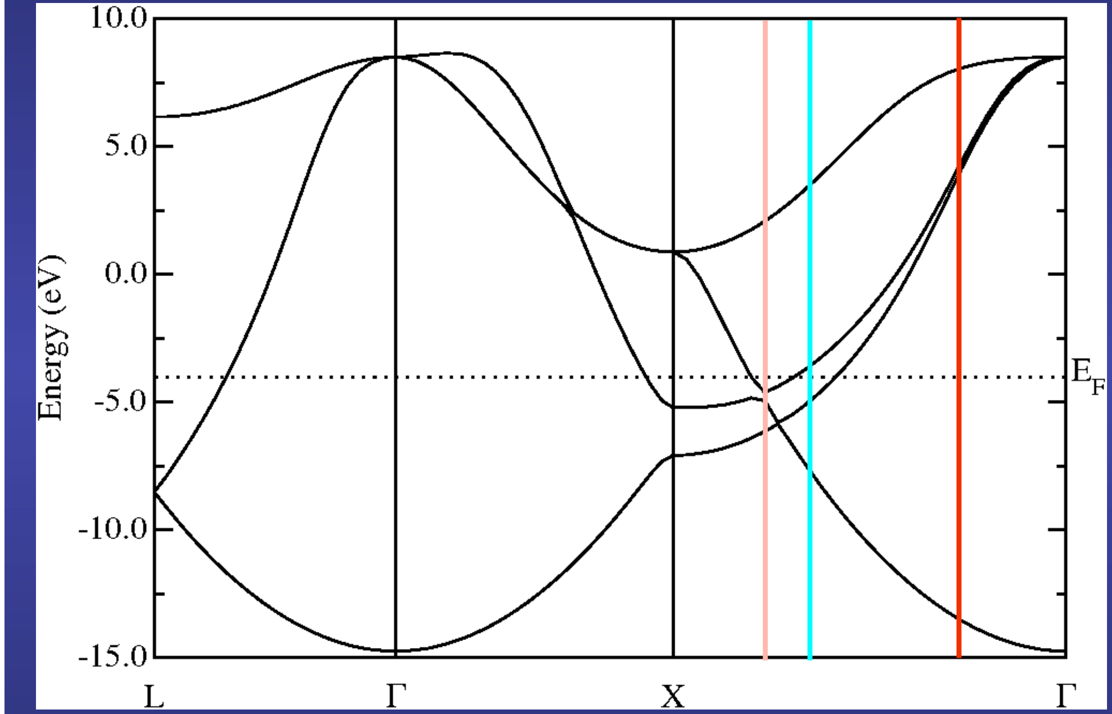
Large cells: Γ point

k = (0,0,0)

Fermi surface sampling for metallic systems

The determination of the Fermi level might be delicate for metallic systems

Band structure of bulk Al



For this k-point, three bands are occupied

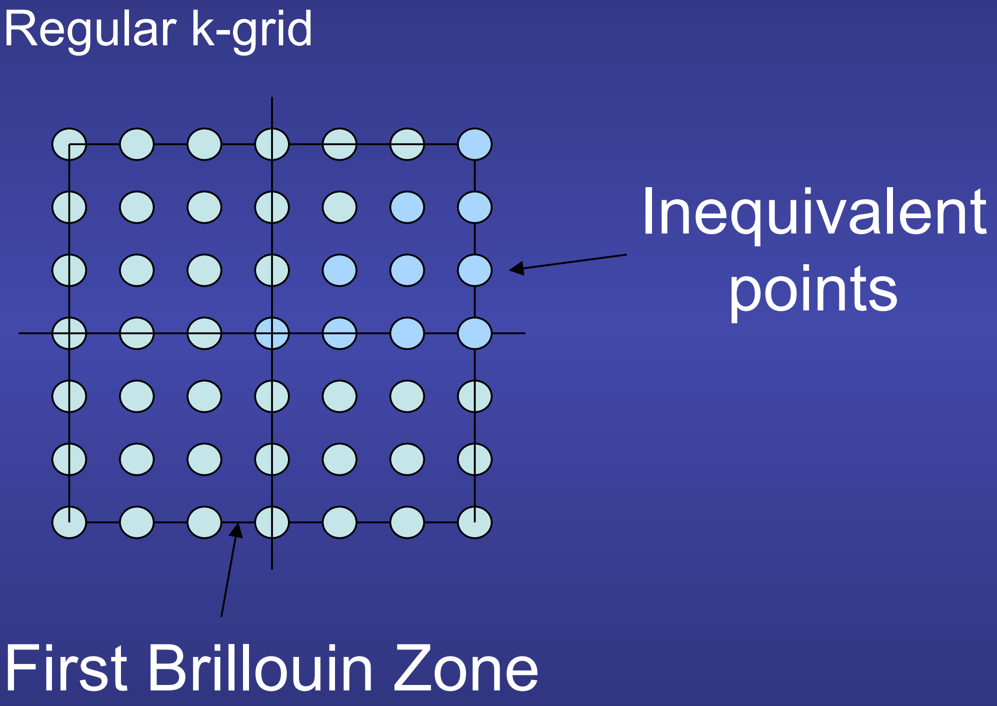
For this k-point, two bands are occupied

For this k-point, one band is occupied

Slightly different choices of k-points can lead to bands entering or exiting the sum, depending if a given eigenvalue is above or below the Fermi level.

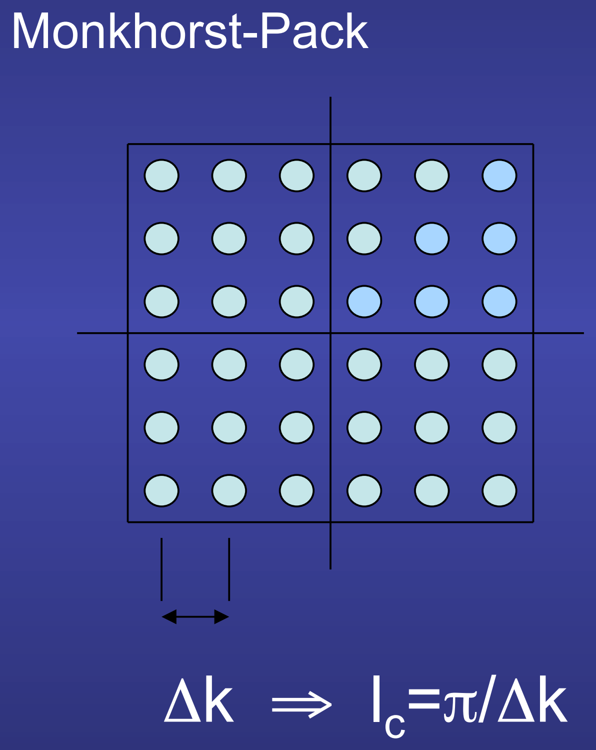
For a sufficiently dense Brillouin zone sampling, this should not be a problem

K-point sampling


Regular k-grid

Inequivalent points

First Brillouin Zone


Monkhorst-Pack

$\Delta k \Rightarrow l_c = \pi / \Delta k$

How to set up the k-point sampling in Siesta

Variables that control the fineness of the grid

kgrid_cutoff

```
kgrid_cutoff        10.0 Ang
```

A real-space radius that plays a role equivalent to the plane-wave cutoff in real space grids

(Moreno and Soler 92)

kgrid_Monkhorst_Pack

```
%block kgrid_Monkhorst_Pack
      4    0    0   0.5
      0    4    0   0.5
      0    0    4   0.5
%endblock kgrid_Monkhorst_Pack
```

The origin of the k-grid might be displaced to reduce the number of inequivalent k-points

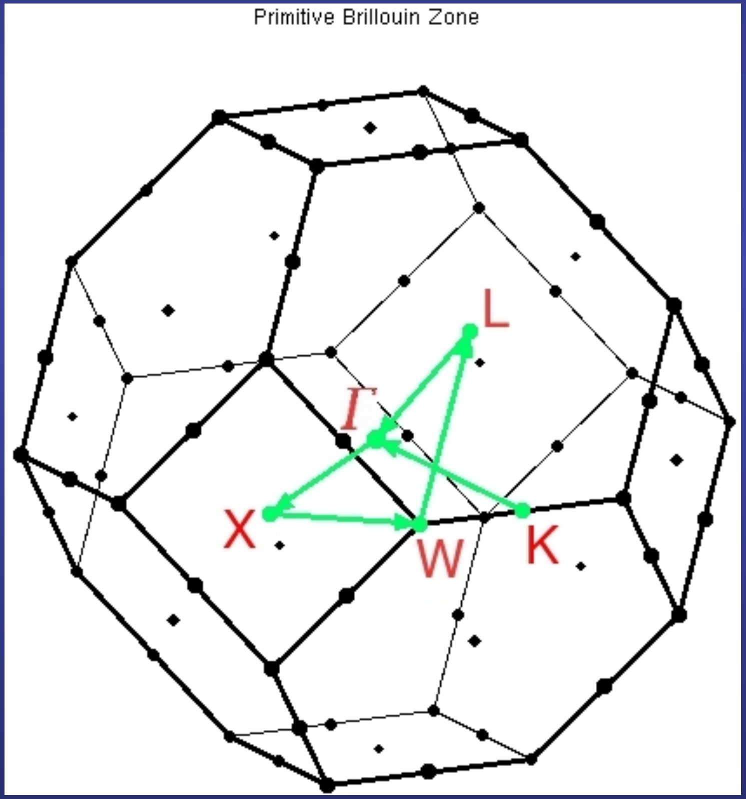
Comparing energies of structures having different symmetries: take care of BZ samplings

The BZ sampling of all the structures must be sampled with the same accuracy

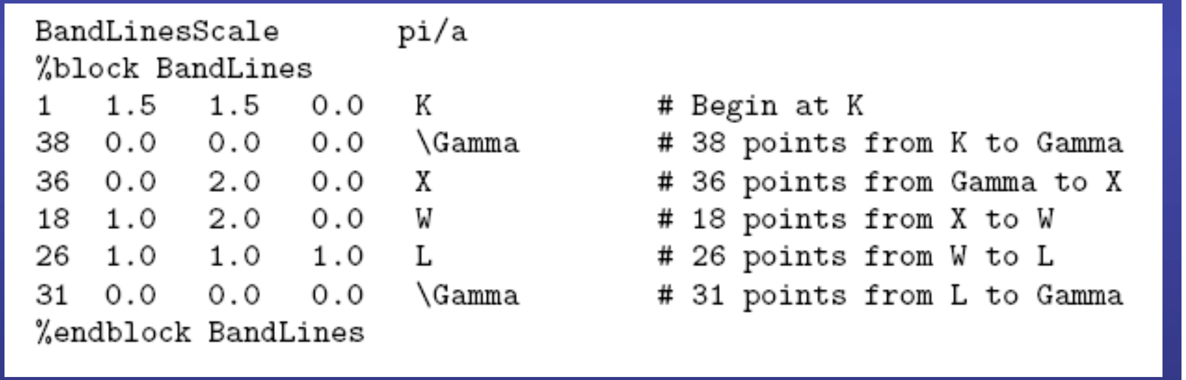
Since for unit cells of different shapes it is not possible to choose exactly
the same k-point sampling, a usual strategy is to try and maintain the
same density of k-points

Once SCF has been achieved, we compute the bands along the high symmetry points in the First-Brillouin zone

First-Brillouin zone of a FCC ,
with the high symmetry points



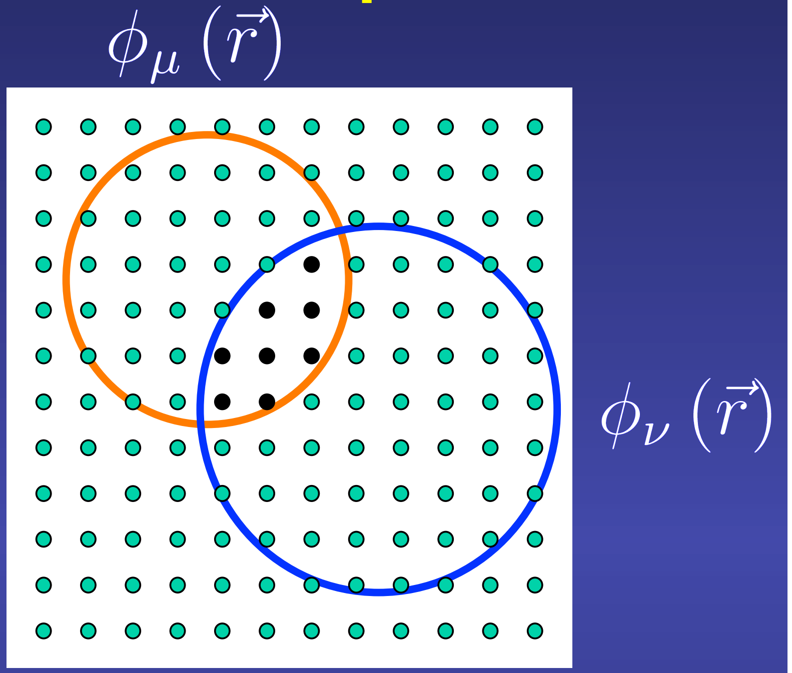
New variables to plot the band structure



```
BandLinesScale       pi/a
%block BandLines
1    1.5    1.5    0.0    K              # Begin at K
38   0.0    0.0    0.0    \Gamma         # 38 points from K to Gamma
36   0.0    2.0    0.0    X              # 36 points from Gamma to X
18   1.0    2.0    0.0    W              # 18 points from X to W
26   1.0    1.0    1.0    L              # 26 points from W to L
31   0.0    0.0    0.0    \Gamma         # 31 points from L to Gamma
%endblock BandLines
```

Three dimensional grid to compute Hartree, exchange correlation and neutral atom potentials

$$\rho\left(\vec{r}\right) = \sum_{\mu\nu} \rho_{\mu\nu}\phi_{\nu}^{*}\left(\vec{r}\right)\phi_{\mu}\left(\vec{r}\right)$$



Find all the atomic orbitals that do not vanish at a given grid point

(in practice, interpolate the radial part from numerical tables)

Once the density is known, we compute the potentials

EVERYTHING O(N)

$$\rho\left(\vec{r}\right) \to V^{xc}\left(\vec{r}\right)$$

$$\delta\rho\left(\vec{r}\right) = \rho\left(\vec{r}\right) - \rho_{atoms}\left(\vec{r}\right)$$

$$\delta\rho\left(\vec{r}\right) \xrightarrow{FFT} \delta V^{H}\left(\vec{r}\right)$$

Once the hamiltonian and the overlap matrices are build, we have to solve the Schrodinger equation

$$\underset{N\times N}{\begin{pmatrix} & & \\ & H & \\ & & \end{pmatrix}} \underset{N\times 1}{\begin{pmatrix} \\ C \\ \\ \end{pmatrix}} = E_{n\vec{k}} \underset{N\times N}{\begin{pmatrix} & & \\ & S & \\ & & \end{pmatrix}} \underset{N\times 1}{\begin{pmatrix} \\ C \\ \\ \end{pmatrix}}$$

Order-N

Minimization of an energy functional

Not valid for metals or “dirty” gap systems

Order-N^3

Standard diagonalization techniques

Both eigenvectors and eigenvalues available