
MAX School on Advanced Materials and Molecular Modelling
with **QUANTUM ESPRESSO**

QE-2021: Hands-on session – Day-2

(Convergence-tests calculations)

Topics of Day-2 hands-on session:

1. How to make basic convergence tests (`example1.Si`)
 2. How to deal with metals (`example2.Al`)
 3. How to deal with ultrasoft pseudopotentials and with spin polarization (`example1.Fe`)
- b To get the latest version of the exercises, move to `Day-2/` directory and execute:
- ```
$ git pull
```

# 1. Bulk system: Silicon

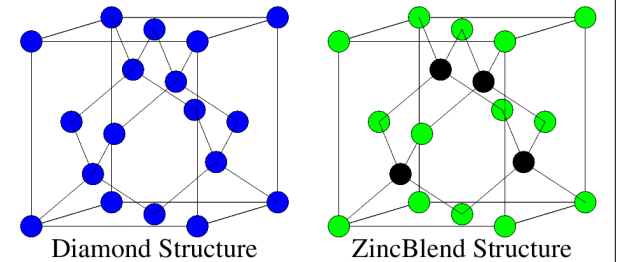
Self-consistent calculation (and a series of tests) for Silicon in the diamond structure:

- move to `Day-2/example1.Si` directory
- look at the input file `pw.si.scf.in`. It is composed of three “namelists” `&CONTROL` (note that `calculation = 'scf'` is the default value), `&SYSTEM`, `&ELECTRONS`, followed by three “cards” `ATOMIC_SPECIES`, `ATOMIC_POSITIONS`, `K_POINTS`
- in the `&CONTROL` namelist notice the following two variables (they are commented):
  - `outdir`: temporary directory for large files. Must be writable, will be created if not existent. You may set environment variable `ESPRESSO_TMPDIR` instead.
  - `pseudo_dir`: directory where pseudopotential (PP) files are kept. It must exist, be readable, and contain the required PP file (in this example, `Si.pz-vbc.UPF` for Silicon). You may set environment variable `ESPRESSO_PSEUDO` instead.

(note that for the hands-on exercises we rely on `ESPRESSO_TMPDIR` and `ESPRESSO_PSEUDO` environmental variables, hence we don't need to set `outdir` and `pseudo_dir` variables)

# Providing atomic structure in input

How is the crystal structure defined? This is a very simple case: the diamond lattice is an fcc (face-centered cubic) lattice with two atoms per unit cell. You need to specify:



- What is the Bravais lattice?  
`ibrav=2`, meaning fcc lattice
- How many and which parameters are needed to completely define Bravais lattice?  
just one: `cellldm(1)=10.2`, lattice parameter  $a$  in a.u.
- How many atoms there are in the unit cell?  
`nat=2`: two atoms
- How many different atomic species are present?  
`ntyp=1`: one species
- Which ones, described by which pseudopotential?  
See card `ATOMIC_SPECIES`
- Where the atoms are located in the unit cell?  
See card `ATOMIC_POSITIONS`: here, in Cartesian axes, in units of  $a$  (“`alat`”)

Notice that there are several alternative methods to specify an atomic structure!

## Brillouin zone (BZ) sampling

**k-points** are described in the **K\_POINTS** card. One has to choose

- Whether to provide a list of k-points or a uniform grid
- If a list is chosen: provide a list of k-points *in the Irreducible BZ* and corresponding symmetry weights; the latter do not need to add up to 1, they are normalized by the code

**Frequently Asked Question:** where do I find special k-points and their weights?

Answer: 1) in papers, 2) use an auxiliary code **kpoints.x**, 3) use uniform grids

- If a uniform grid is chosen: Monkhorst-Pack parameters (H.J. Monkhorst and J.D. Pack, *Phys. Rev. B* **13**, 5188 (1976)), and offsets along the three directions

## Running the pw.x code

For serial (single processor) execution you can use

```
$ pw.x -in pw.si.scf.in > pw.si.scf.out
```

(note: input redirection `pw.x < pw.si.scf.in` works but it is not recommended on parallel machines)  
Look at the directory specified by `outdir` (in our case `$ESPRESSO_TMPDIR`) and its content:

```
$ ls $ESPRESSO_TMPDIR
silicon.save silicon.xml
```

(to see only these files, you may need to use `ls $ESPRESSO_TMPDIR/silicon.*`)

The directory contains a data directory (`silicon.save`) with binary data files for further processing and an XML file (`silicon.xml`) with general information on the run. The name of the various files is determined by the value of the `prefix` variable and by their content.

*Do not run two instances of `pw.x` that access the same `outdir` with the same `prefix`!*  
Unpredictable behavior may follow (the directory is used for temporary files as well).  
In case of trouble, clean `outdir`.

## Running the pw.x code (II)

Examine output file `pw.si.scf.out`, look how self-consistency proceeds:

```
$ grep -e "total energy" -e estimated pw.si.scf.out
 total energy = -15.79103344 Ry
 estimated scf accuracy < 0.06376674 Ry
 total energy = -15.79409289 Ry
 estimated scf accuracy < 0.00230109 Ry
 total energy = -15.79447822 Ry
 estimated scf accuracy < 0.00006291 Ry
 total energy = -15.79449510 Ry
 estimated scf accuracy < 0.00000448 Ry
! total energy = -15.79449593 Ry
 estimated scf accuracy < 0.00000005 Ry
```

The total energy is the sum of the following terms:

Notice that there are 8 electrons in the cell: 2 (pseudo-)atoms/cell with 4 electrons. The system is a non-magnetic insulator, so just the lowest 4 ( $= 8/2$ ) valence bands (Kohn-Sham states) are computed.

# Convergence w.r.t. the kinetic energy cutoff



The kinetic energy cutoff `ecutwfc` (in Ry) determines the size of the Plane-Wave (PW) basis set used to expand wave-functions (i.e. Kohn-Sham orbitals)

(the default for the charge density is `ecutrho=4*ecutwfc`, which is OK for norm-conserving PPs)

- A manual test of convergence w.r.t. kinetic energy cutoff entails the following tasks (**BEWARE: we will not do it manually**)

1. change value of `ecutwfc` in `pw.si.scf.in` input to, e.g., 16, 20, 24, 28, 32 Ry
2. for each value of `ecutwfc`, run `pw.x` and collect the final energy
3. collect the data in a file, say `si.etot_vs_ecut` (i.e. each line should contain two values: `ecutwfc` and “total-energy”)
4. plot the energies collected in `si.etot_vs_ecut` using your preferred plotting program, for instance:

```
$ gnuplot
gnuplot> plot 'si.etot_vs_ecut' with lines
```

- because such a manual procedure is very cumbersome we use scripts instead



# Convergence w.r.t. kinetic energy cutoff (II)



To make convergence tests easier and faster, scripts are commonly used. To this end, Unix shell-scripts have been traditionally used, yet there are other more "fancy" alternatives, e.g., PWTk scripts.

- A Unix shell-script is located in `ex1.ecutwfc.classic/` sub-directory (file: `ecutwfc.sh`)
- A PWTk script is located in `ex1.ecutwfc/` sub-directory (file: `ecutwfc.pwtk`)

**Unix shell-script**

```
#!/bin/sh

rm -f si.etot_vs_ecut.dat

for ecut in 12 16 20 24 28 32
do
 cat > pw.si.scf.$ecut.in << EOF
 &CONTROL
 prefix='silicon',
 /
 &SYSTEM
 ibrav = 2,
 celldm(1) = 10.2,
 nat = 2,
 ntyp = 1,
 ecutwfc = $ecut,
 /
 &ELECTRONS
 /
 ATOMIC_SPECIES
 Si 28.086 Si.pz-vbc.UPF
 ATOMIC_POSITIONS
 Si 0.00 0.00 0.00
 Si 0.25 0.25 0.25
 K_POINTS automatic
 4 4 4 1 1 1
 EOF

 pw.x -in pw.si.scf.$ecut.in > pw.si.scf.$ecut.out

 grep -e 'kinetic-energy cutoff' -e ! pw.si.scf.$ecut.out | \
 awk '/kinetic-energy/ {ecut=$(NF-1)}
 /!/{print ecut, $(NF-1)}' >> si.etot_vs_ecut.dat

done
```

**PWTk script**

```
load_fromPWI ../pw.si.scf.in

set fid [open si.etot_vs_ecut.dat w]

foreach ecut {12 16 20 24 28 32} {
 SYSTEM "ecutwfc = $ecut"
 runPW pw.Si.scf.$ecut.in

 puts $fid "$ecut [::pwtk::pwo::totene pw.Si.scf.$ecut.out]"
}

close $fid
```

# PWTK scripting: basics

The basic philosophy is to **keep the syntax close to original input syntax!**

pw.x input file

```
&CONTROL
 calculation = 'scf'
/
&SYSTEM
 ecutwfc = 25.0
 ecutrho = 200.0
 ...
/
ATOMIC_POSITIONS alat
 Si 0.00 0.00 0.00
 Si 0.25 0.25 0.25

K_POINTS automatic
 4 4 4 1 1 1
```

pw.Si.in

Run from terminal as:

```
pw.x -in pw.Si.in > pw.Si.out
```

pwtk script

```
CONTROL {
 calculation = 'scf'
}
SYSTEM {
 ecutwfc = 25.0
 ecutrho = 8*25.0
 ...
}
ATOMIC_POSITIONS alat {
 Si 0.0 0.0 0.0
 Si 1/4 1/4 1/4
}
K_POINTS automatic {
 4 4 4 1 1 1
}
```

```
runPW pw.Si.in
```

Si\_bulk.pwtk

Run from terminal as:

```
pwtk Si_bulk.pwtk
```

## PWTK scripting: basics

- PWTK scripts are basically Tcl-scripts, hence they use Tcl-syntax
- namelists and cards have the same names as in QE (with a few exceptions), but they are all written in **upper-case**. Their content is encapsulated in curly braces:

```
CONTROL { calculation = 'scf', outdir = '/tmp/pwscf/' }
ATOMIC_POSITIONS { ... }
```

- instead of curly braces, one can also use double-quotes ("..."), e.g.:

```
SYSTEM " celldm(1) = $a "
```

- the difference between curly braces {...} and double-quotes "..." is that inside double-quotes the variable `$a` is substituted by its value, whereas inside curly braces the `$a` is treated literally (i.e. no substitution)
- real numbers can be specified as mathematical expressions (e.g. `ecutrho = 8*25.0`)
- indices of `ntyp`-type array variables, such as `starting_magnetization(i)`, can be specified with atomic labels, e.g.:

```
SYSTEM { starting_magnetization(Fe) = -0.8 }
```

where `Fe` is one among atomic species defined in the `ATOMIC_SPECIES` card.

- PWTK script are case sensitive, i.e., `CONTROL { ... }` is OK, but `control { ... }` is not; namelist variables are also case sensitive!
- namelist **variables can be set on-the fly** (we will use this heavily)
- the order of namelists and cards is not important; PWTK knows how to construct proper input files
- namelists and cards can be called many times, but there is a big difference how multiple calls are handled for namelists and cards: **cards** are handled in **overwrite mode**, whereas **namelists** are handled in a *kind of* **append** mode. For example, the following is OK:

```
CONTROL { calculation = 'scf' }
CONTROL { outdir = '/tmp/qe' }
```

and is equivalent to:

```
CONTROL { calculation = 'scf' , outdir = '/tmp/qe' }
```

- to unset a namelist variable, set it to an empty-value; for example to unset the `outdir` variable, use:

```
CONTROL { outdir = }
```

- today we will use the following PWTK functions:
  - `load_fromPWI` – loads input data from an existing `pw.x` input file
  - `::pwtk::pwo::totene` – returns the converged total energy from `pw.x` output
  - `seq` – like the Unix `seq` command (returns a sequence of numbers)
  - `runPW` – constructs `pw.x` input file and runs a calculation
  - `runPP` – similar as `runPW` but for the `pp.x` program
  - `runDOS` – ... for the `dos.x` program
  - `runPROJWFC` – ... for the `projwfc.x` program
- PWTK web-site:  
<http://pwtk.ijs.si/> or <http://pwtk.quantum-espresso.org/>
- PWTK documentation is available at:  
[http://pwtk.ijs.si/toc\\_index.html](http://pwtk.ijs.si/toc_index.html)

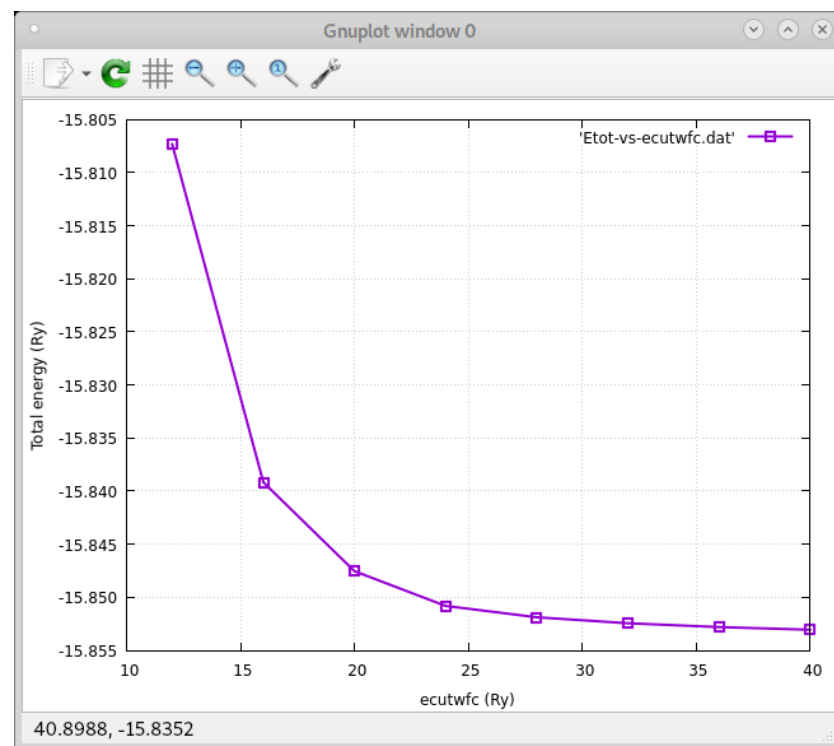
## Convergence w.r.t. the kinetic energy cutoff (III)

- To run the convergence test via the Unix shell-script move to `ex1.ecutwfc.classic` sub-directory (read the `README.md` file) and execute

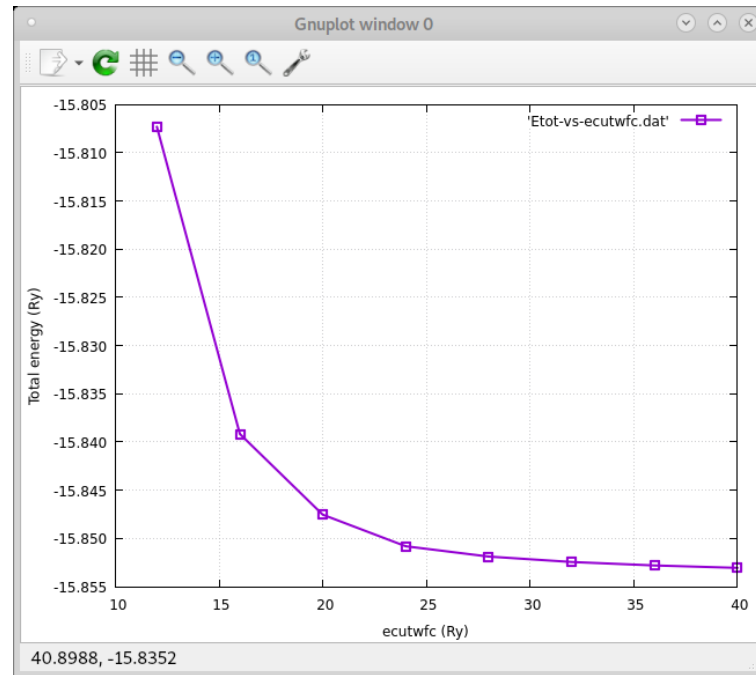
```
$./ecutwfc.sh
```

- To run the convergence test via the PWTK script move to `ex1.ecutwfc` sub-directory (read the `README.md` file) and execute

```
$ pwtk ecutwfc.pwtk
```



# Convergence w.r.t. the kinetic energy cutoff (IV)



## Notes:

- Convergence w.r.t the cutoff is a property of the *pseudopotential(s)* used.
- Convergence of the *absolute energy* is typically slower than convergence of *interesting physical properties*, e.g. structure.
- Absolute values of total energy do not have any physical meaning (and depend upon the specific PP): only energy *differences* do

## Convergence w.r.t. k-points

A sufficiently dense grid of k-points is needed in order to account for *periodicity*.

To test the convergence w.r.t. k-points, you need to edit the **K\_POINTS** card and request *automatic* Monkhorst-Pack grids:

```
K_POINTS automatic
nk1 nk2 nk3 k1 k2 k3
```

then step-wise increase **nk1=nk2=nk3** to, e.g., 2, 4, 6, 8 (keep **k1=k2=k3=1**) and run **pw.x** calculation for each value of **nk1=nk2=nk3**.

For example, with PWTK this can be achieved with the following snippet:

```
load_fromPWI pw.si.scf.in

foreach k {2 4 6 8} {
 K_POINTS automatic "$k $k $k 1 1 1"
 runPW pw.si.scf.$k.in
}
```



## Convergence w.r.t. k-points (II)

Description of the **K\_POINTS** card for *automatic* mode:

```
K_POINTS automatic
nk1 nk2 nk3 k1 k2 k3
```

The first three **nk1 nk2 nk3** numbers mean “*there are nk1,nk2,nk3 grid points along crystal axis 1,2,3*”; the second three **k1 k2 k3** numbers, either 0 or 1, mean “*grid starts from 0*” or “*displaced by half a step*” along crystal axis 1,2,3

Also note that:

- Convergence is not necessarily monotonic: there is no variational principle w.r.t. number of k-points
- The **2 2 2 1 1 1** Monkhorst-Pack grid is the same as the “two Chadi-Cohen points” (see: D.J. Chadi and M.L. Cohen, Phys. Rev. B **8**, 5747 (1973))

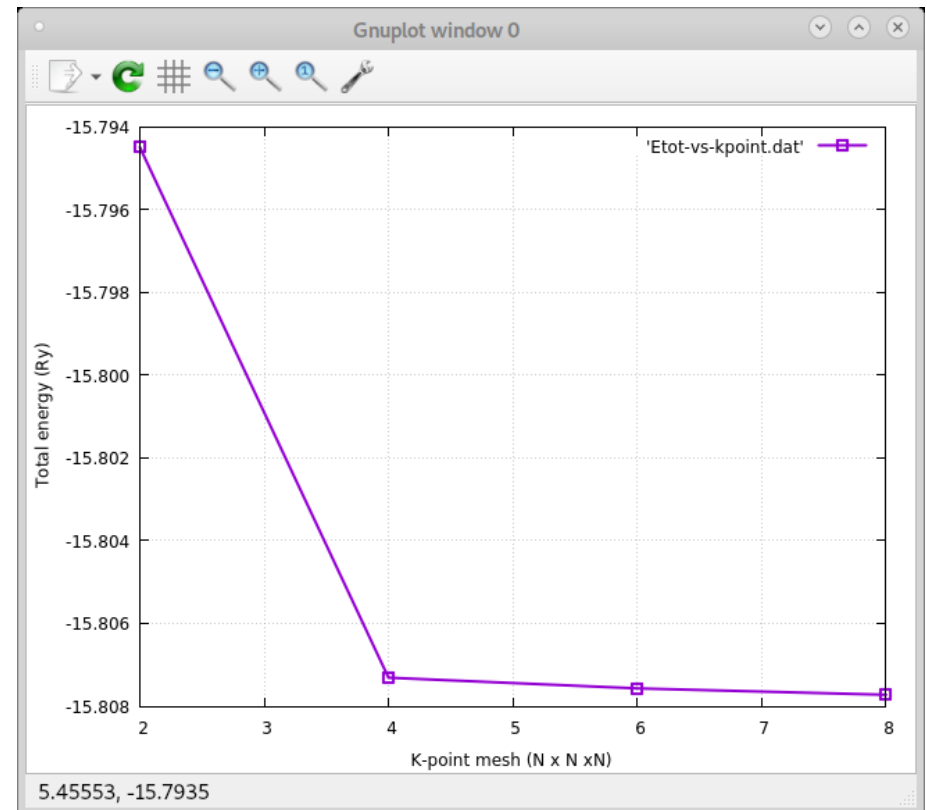
## Convergence w.r.t. k-points (III)

The PWTK script for testing the convergence with respect to k-points is located in `Day-2/example1.Si/ex2.kpoints` directory (see `README.md` for detailed instructions).

Within this directory execute:

```
$ pwtk kpoints.pwtk
```

You should get a plot like this one:



## Equation of State: silicon

Equilibrium in Si is determined by the minimum-energy lattice parameter alone: there are no forces on atoms, by symmetry (you can verify this by setting `tprnfor=.true.` in namelist `&CONTROL` and looking for forces reprinted at the end).

To find the lattice parameter:

- Choose suitable values for `ecutwfc` and the k-point grid (e.g. 30 Ry and 4 4 4 1 1 1)
- Run `pw.x` for values of `celldm(1)` ranging from 9.7 to 10.7 in steps of 0.1 a.u.

With PWTK this can be achieved with the following snippet:

```
load_fromPWI pw.si.scf.in

foreach alat [seq 9.7 0.1 10.7] {
 SYSTEM "celldm(1) = $alat"
 runPW pw.si.scf.$alat.in
}
```

## Equation of State: silicon (II)

The corresponding PWTK script is located in `Day-2/example1.Si/ex3.alat` directory (see `README.md` for detailed instructions).

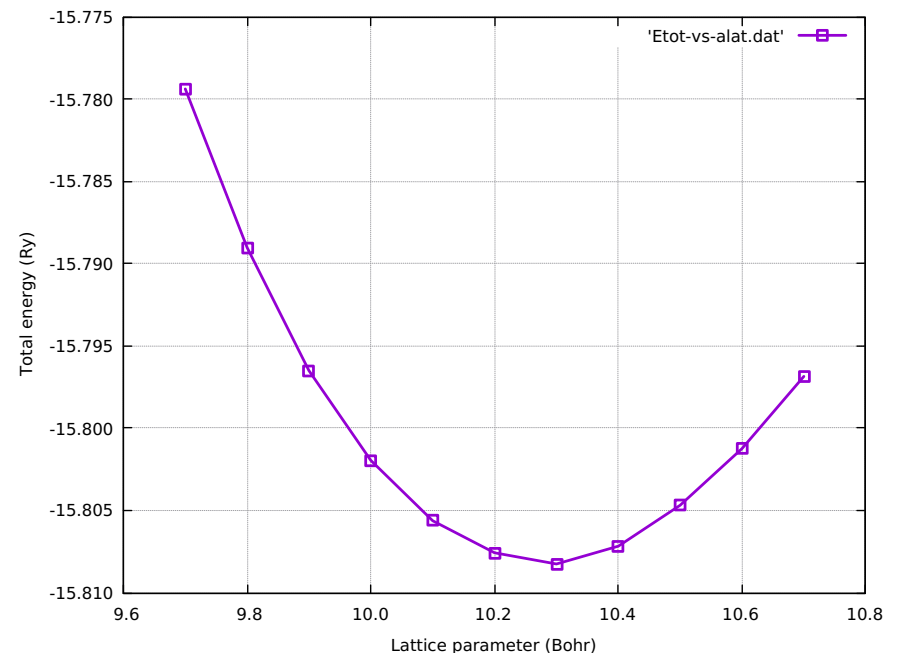
Within this directory execute:

```
$ pwtk alat.pwtk
```

The experimental lattice parameter for Si is 5.47 Å or 10.26 a.u.. This is a case where plain simple LDA yields remarkable results. You may experiment changing cutoff, k-points, pseudopotential, ...

You should find that:

- The energy vs lattice parameter  $E(a)$  curves are shifted down rather uniformly with increasing cutoff and are not strongly dependent on k-points.
- Structural properties and energy differences converge faster than total energies.



## Equation of State: silicon (III)

Use the code `ev.x` to fit your results to a phenomenological equation-of-state (EOS, e.g. Murnaghan) and to get accurate values for the lattice parameter and for the bulk modulus.

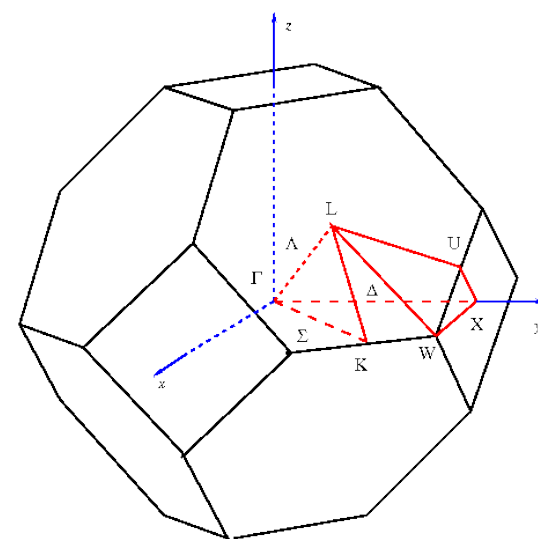
The `ev.x` code prompts for some data and reads a data-file like the one produced by the `alat.pwtk` script (the data-file is `Etot-vs-alat.dat`). For cubic systems a data-file should contain the following rows:

|       |          |
|-------|----------|
| $a_1$ | $E(a_1)$ |
| $a_2$ | $E(a_2)$ |
| $a_3$ | $E(a_3)$ |
| ...   |          |

# Band Structure of Silicon

The scheme to calculate the bands (spaghetti plot) is the following:

1. SCF `pw.x` calculation (`calculation = 'scf'`)
2. “bands”-type non-SCF `pw.x` calculation (fixed-potential) with:
  - `calculation = 'bands'`
  - the number of Kohn-Sham states explicitly set (variable `nbnd`)
  - a suitable path of k-points specified in `K_POINTS` (in this example we use the  $L - \Gamma - X - W - K - L$  path)
3. `bands.x` calculation, which, among others, produces data-files for the spaghetti plot



*Important:* `outdir` and `prefix` must be the same for “bands” and “scf” `pw.x` calculations and for the `bands.x` calculation

*Important:* the k-point path must be continuous in k-space

## Band Structure of Silicon (II)

The input for the `bands.x` program is the following:

```
&BANDS
 prefix='...', outdir='...', filband = 'Si.bands.dat', lsym=.true.
/
```

Two files are produced: `Si.bands.dat.gnu`, directly plottable with `gnuplot`, and `Si.bands.dat`, for further processing by the auxiliary command `plotband.x`.

If option `lsym=.true.`, `bands.x` performs a symmetry analysis. An additional file `Si.bands.dat.rep` is generated, containing information on symmetry labels of the various bands.

The snippet for running all three calculations manually is:

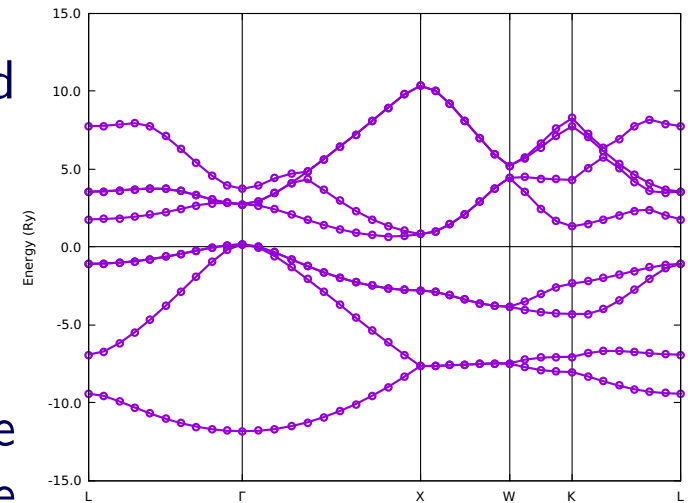
```
$ pw.x -in pw.Si.scf.in > pw.Si.scf.out
$ pw.x -in pw.Si.bands.in > pw.Si.bands.out
$ pw.x -in bands.Si.in > bands.Si.scf.out
```

**but** we will use a PWTK script instead.

# Band Structure of Silicon (III)

To execute the PWTK script that will perform all the needed calculations for plotting the bands, proceed as follows:

- move to directory `Day-2/example1.Si/ex4.bands` and read the `README.md` file
- set suitable values for `celldm(1)`, `ecutwfc`, and `K_POINTS`
- and execute: `pwtk bands.pwtk`
- you may set the `Efermi` value to the top of the occupied bands in the gnuplot file `plot.gp` (see the instructions in `README.md`); then re-plot spaghetti with: `gnuplot plot.gp`



*Remark:* in PWTK, once `outdir` and `prefix` are set, they are automatically inherited for subsequent calculations.



## Auxiliary program plotbands.x

plotband.x prompts for terminal input:

```
$ plotband.x
Input file > Si.bands.dat
Reading 8 bands at 39 k-points
Range: -5.6940 16.4680eV Emin, Emax > -5.6940 16.4680
high-symmetry point: -0.5000 0.5000 0.5000 x coordinate 0.0000
high-symmetry point: 0.0000 0.0000 0.0000 x coordinate 0.8660
high-symmetry point: 0.0000 0.0000 1.0000 x coordinate 1.8660
high-symmetry point: 0.0000 0.5000 1.0000 x coordinate 2.3660
high-symmetry point: 0.0000 0.7500 0.7500 x coordinate 2.7196
high-symmetry point: -0.5000 0.5000 0.5000 x coordinate 3.3320
output file (gnuplot/xmgr) > Si.bands.plot
bands in gnuplot/xmgr format written to file Si.bands.plot
output file (ps) > (press Return)
```

If symmetry analysis was performed in the previous step, the output is written to several plottable files `Si.bands.plot.N.M`, where  $N$  labels the high-symmetry lines,  $M$  labels irreducible representations.

## 2. A metallic example: Aluminum

Aluminum is even simpler than Silicon: one atom per unit cell in an fcc lattice.

**BUT:** it is a metal, only valence bands and a few k-points will not suffice.

- move to the `Day-2/example2.Al` directory
- read the `pw.x` input file `pw.al.scf.in`
- notice the presence of new variables: `occupations`, `smearing`, `degauss`;
- run `pw.x` as:  

```
$ pw.x -in pw.al.scf.in > pw.al.scf.out
```
- in the output file notice that
  - the number of bands (Kohn-Sham states) is automatically set to a value larger than the number of electrons divided by 2
  - the Fermi energy is computed.

# Convergence with respect to k-points, degauss, and smearing

This is a “*three-dimensional*” convergence test, where we will vary the number of k-points and values of **degauss** and **smearing** variables. In particular, we will vary:

- **smearing** variable, possible values: 'gauss' (or 'g'), 'marzari-vanderbilt' (or 'm-v'), 'methfessel-paxton' (or 'm-p')
- **degauss** variable, in range from 0.001 to 0.1
- k-points using the *automatic* grids of 4 4 4, 8 8 8, 12 12 12, and 16 16 16

With PWTK this can be achieved with the following snippet:

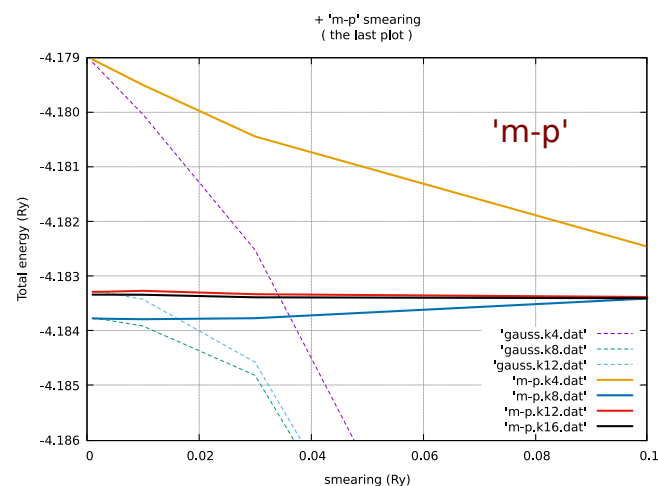
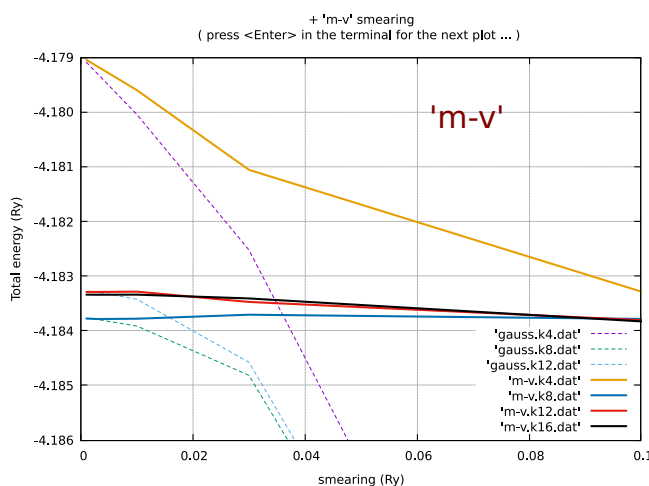
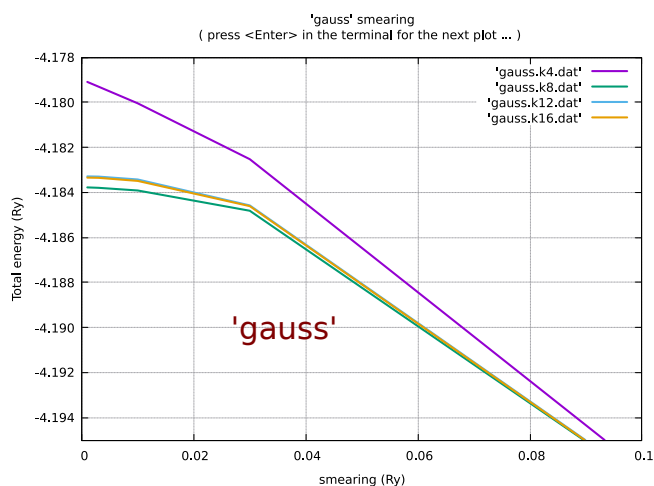
```
foreach nk {4 8 12 16} {
 foreach smear {'gauss' 'm-p' 'm-v'} {
 foreach degauss {0.001 0.003 0.01 0.03 0.1} {
 SYSTEM " smearing = $smear
 degauss = $degauss "
 K_POINTS automatic "$nk $nk $nk 1 1 1"
 runPW pw.Al.scf.$nk.$smear.$degauss.in
 }
 }
}
```

# Convergence with respect to k-points, degauss, and smearing (II)

- move to `Day-2/example2.Al/ex1.degauss` directory
- execute: `pwtch degauss.pwtch`

Notice how much slower the convergence is for metals than for insulators!

Both `m-v` and `m-p` depend much less upon `degauss` and allow for faster and safer convergence than simple gaussian broadening. For Al and `m-v` or `m-p` smearing, good convergence is achieved for a `12 12 12` k-point grid and `degauss`  $\sim 0.01$  to  $0.05$  Ry.



Beware that you cannot reduce the broadening too much: the energy levels must have some overlap, or else the advantage of broadening is lost!

## How to plot charge-density

Example `Day-2/example2.A1/ex2.chdens` shows how to calculate the valence and the all electron charge density (the latter requires a PAW potential and a very large cutoff energy)

- move to `Day-2/example2.A1/ex2.chdens` directory (*chdens* is an acronym for charge-density)
- execute: `pwtck 1-chdens.pwtck`  
this script calculates and “plots” the valence charge density; notice that the electron charge is located mainly in interstitial regions (due to the use of a pseudo-potential, there is *almost no* charge in close vicinity of nuclei; see next page);
- the scheme to calculate and plot the charge-density is:
  1. make an SCF `pw.x` calculation
  2. make a post-processing `pp.x` calculation (`plot_num=0` for charge density) and instruct the program to write charge density in a suitable format
  3. plot the charge density by `xcrysden` (let's plot density in contour/colorplane style; follow the instructions of tutor and select density range from `0.0` to `0.05`)

## How to plot charge-density (II)

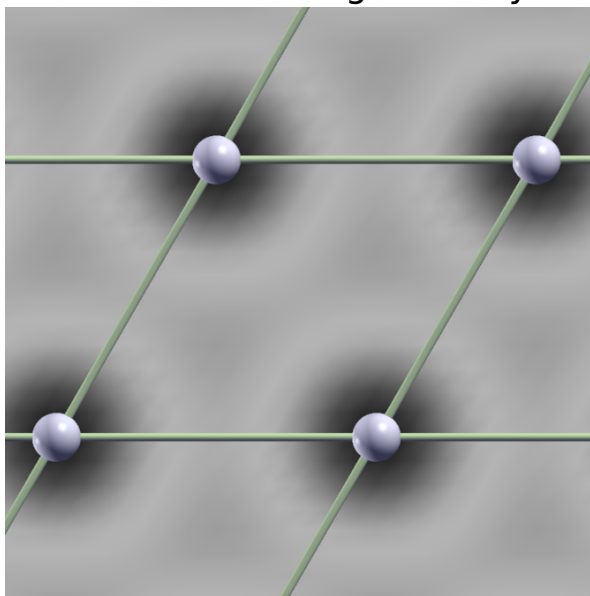
- to calculate all-electron **valence** and **total** charge densities, execute:

```
$ pwtk 2-chdens-paw.pwtk
```

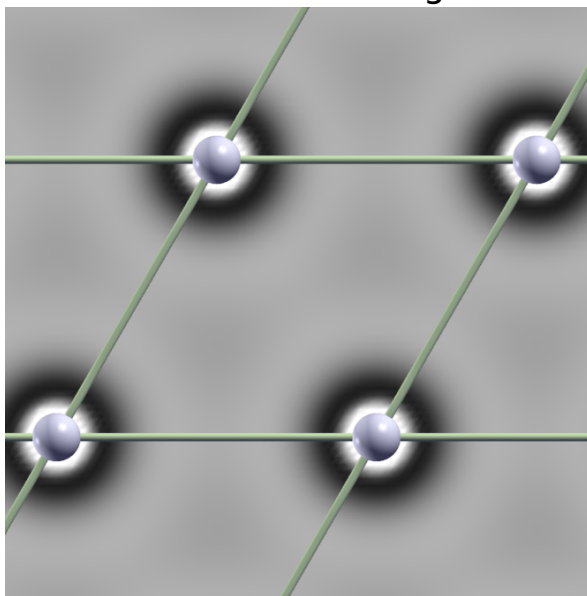
(note that `plot_num=17` for all-electron valence density and `plot_num=21` for all-electron total density)

- comparison between PP valence-density vs. all-electron densities (valence and total):

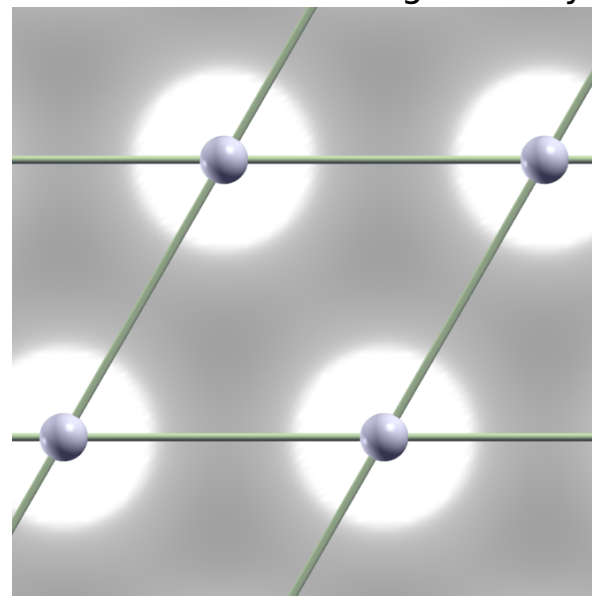
PP valence charge density



all-electron valence charge density



all-electron total charge density



### 3. A magnetic example: Iron

Iron has two remarkable features: it is magnetic and it requires an Ultrasoft PP (USPP) since its localized 3d atomic states are very hard.

- move to the `Day-2/example3.Fe` directory and read the `pw.x` input file `pw.fe_fm.scf.in`
- the structure is bcc (`ibrav=3`) with one atom per unit cell
- notice the presence of variables `nspin` and of `starting_magnetization`, indicating LSDA (`nspin=2`) with unconstrained total magnetization and initial symmetry broken; plus, variables for *metallic* calculations
- notice that this calculation uses GGA (PBE): it is specified inside the PP file (can be guessed from the PP file name), reprinted on output as "Exchange-correlation"
- also notice that with USPP, it is typically needed to set `ecutrho`  $> 4 \times \text{ecutwfc}$  (it should be at least 8 to 12 times larger)

# Magnetic structures

Run `pw.x` in the usual way (`pw.x -in pw.fe_fm.scf.in > pw.fe_fm.scf.out`).  
In the output, notice:

- the number of k-points is doubled w.r.t the non-magnetic case: the first set of k-points contains spin-up states, the second set spin-down states  
(use `verbosity='high'` in namelist `&CONTROL` if there are more than 100 k-points)
- in the output notice such lines:

```
total magnetization = 2.41 Bohr mag/cell
absolute magnetization = 2.60 Bohr mag/cell
```

Since there is a single (magnetic) atom per unit cell, the only possible magnetic structure is ferromagnetic.



## Magnetic structures: going antiferromagnetic

- in order to reach antiferromagnetic states, you need to:
  - introduce a **supercell** with two sublattices of different species of atoms (even if they are the same, it is important that they are labeled as different)
  - start with opposite initial magnetization for the two sublattices
- Can you write input data for an AFM structure?  
**hint:** split bcc into two simple cubic sublattices, **ibrav=1**, with two atoms at  $(0,0,0)$  and  $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$ .

As a convenience, an antiferromagnetic file is provided (**pw.fe\_afm.scf.in**)

You can compare the ferromagnetic and antiferromagnetic files by:

```
$ diff pw.fe_fm.scf.in pw.fe_afm.scf.in
```

## Convergence check for USPP

For computational efficiency, it is convenient to keep `ecutwfc` as low as possible, while `ecutrho` is less critical (look at the CPU time report at the end of an output: there are very many `fft`, depending upon `ecutwfc`, while a much smaller number of `fft` depends upon `ecutrho`)

Set the `ecutrho/ecutwfc` ratio (*dual*) to 4, 8, 12 and compute the energy vs `ecutwfc` curve. For *dual* = 4 it will look funny: energy *increases* with increasing cutoff (see next page), but for a higher *dual* (i.e. better description of augmentation charge) the normal behavior is observed.

The corresponding PWTk snippet is:

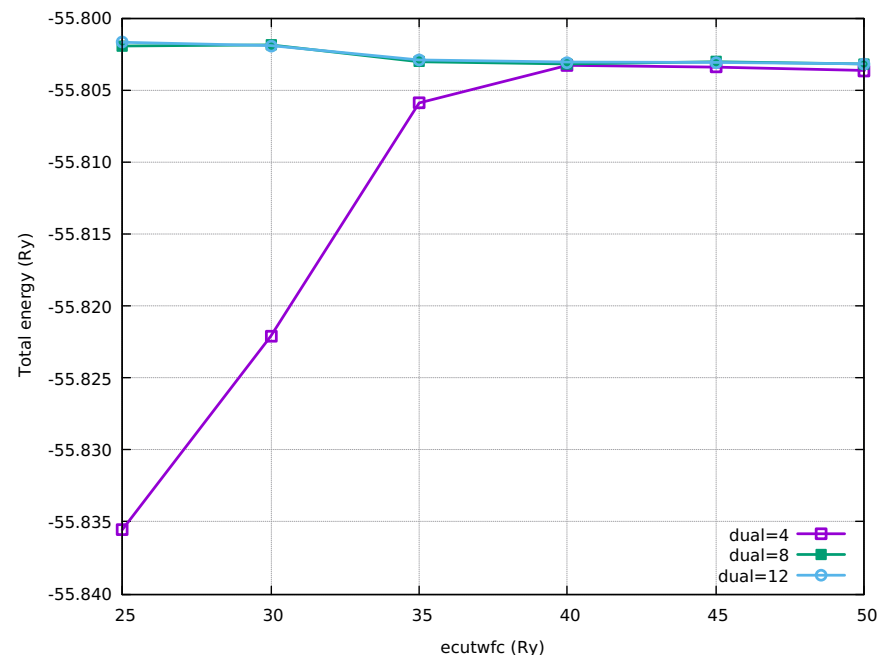
```
load_fromPWI pw.fe_fm.scf.in

foreach dual {4 8 12} {
 foreach ecut {25 30 35 40 45 50} {
 SYSTEM "ecutwfc = $ecut
 ecutrho = $ecut*$dual "
 runPW pw.fe_fm.scf.$dual.$ecut.in
 }
}
```

## Convergence check for USPP (II)

A PWTK script to make convergence check for USPP is provided, i.e.:

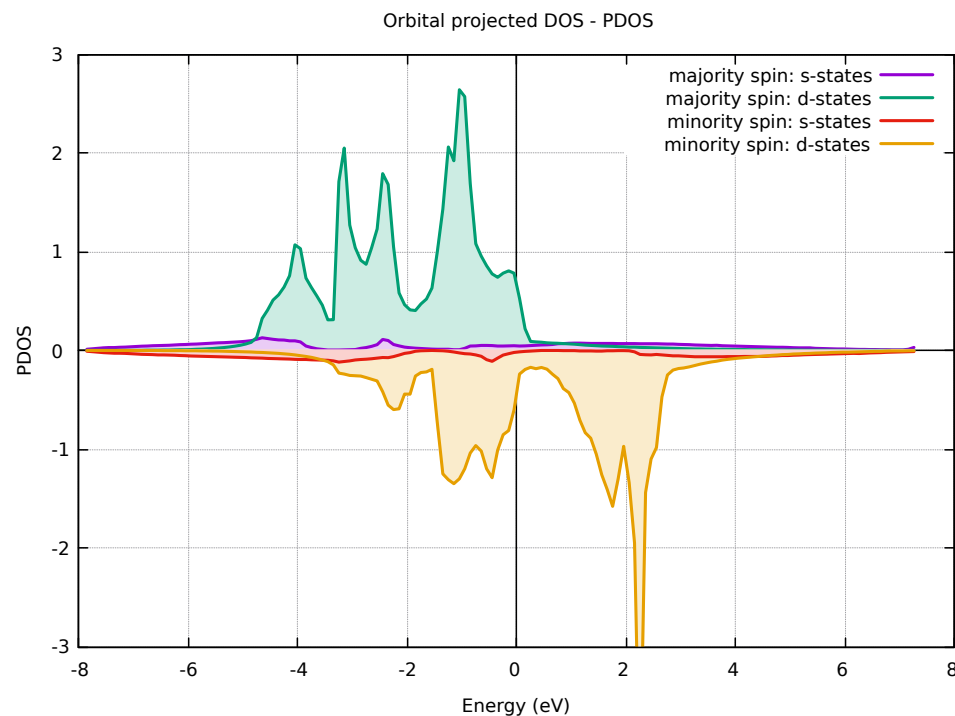
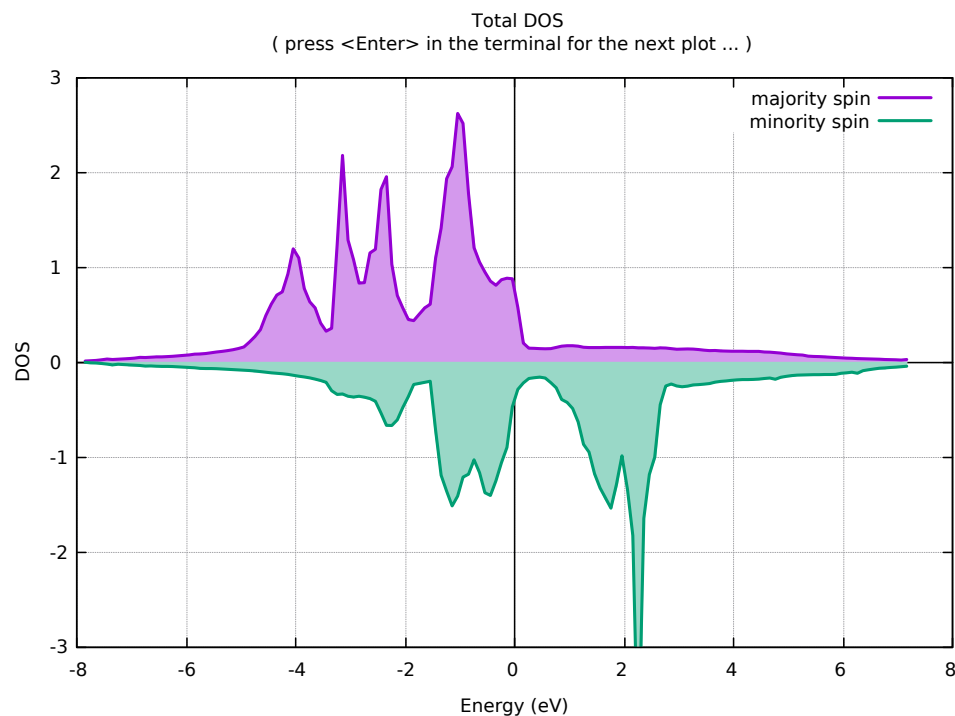
- move to directory:  
`Day-2/example3.Fe/ex1.ecut`
- execute: `pwtk ecut.pwtk`
- you should obtain such a plot  
(notice that curves for  $dual = 8$  and  $12$  almost coincide)



**Homework:** for converged values of both cutoffs and k-points, you may compare the stability of iron in the bcc, fcc, hcp phases (the latter being a slightly more complicated structure)

# Density of States (DOS) and Projected DOS (PDOS)

1. move to `Day-2/example3.Fe/ex2.dos` directory and
2. edit the `dos.pwtk` script and set `ecutwfc` and `ecutrho` to appropriate values
3. execute: `pwtk dos.pwtk`  
(this script calculates both total DOS and DOS projected (PDOS) to atomic orbitals)



# Density of States (DOS) and Projected DOS (PDOS)

The scheme to calculate DOS and PDOS consists of:

1. an SCF `pw.x` calculation (`calculation='scf'`)
2. a non-SCF `pw.x` calculation (`calculation='nscf'`), where:
  - the same `prefix` and `outdir` are used as in the preceding SCF calculation
  - a denser k-point mesh is specified
  - in this example the *linear tetrahedron method* is used  
(variable `occupations='tetrahedra'`)
3. a `dos.x` calculation to calculate DOS (DOS is written to a file as specified by the `fildos` variable in the `dos.x` input; also here the values of `prefix` and `outdir` are the same as for SCF `pw.x` calculation)
4. a `projwfc.x` calculation to calculate PDOS projected to atomic states (this calculation is analogous to `dos.x` one, inputs are also very similar; you can compare them as:

```
$ diff dos.Fe.in projwfc.Fe.in
```

the difference is that `dos.x` uses the `fildos` whereas `projwfc.x` uses the `filpdos` variable)

Explore the content of `fildos` and `filpdos` files!