Hands-on
Density Functional Perturbation Theory:
calculation of phonons

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Quantum ESPRESSO Spring School
National University of Córdoba, Argentina
30 September 2015

Outline

1. Introduction

2. **Exercise 1:** Phonons at Gamma in non-polar materials

3. **Exercise 2:** Phonon dispersion in non-polar materials

4. **Exercise 3:** Phonons at Gamma in polar materials

5. **Exercise 4:** Phonon dispersion in polar materials

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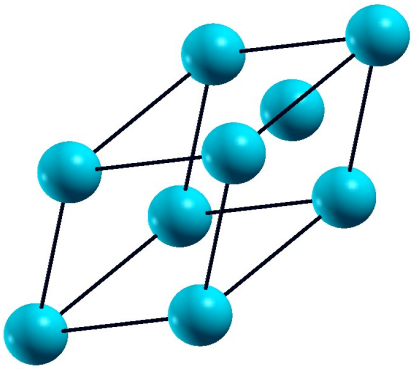
Basic concepts

Let us consider a unit cell with N_{at} atoms.



$s = 1 \ldots N_{at}$ index of an atom in the unit cell

$\alpha = x, y, z$ is the Cartesian index

$\mathbf{R}$ is the point in the Bravais-lattice, identifying the position of a given unit cell

$N_{\mathbf{R}}$ is the number of unit cells in the crystal

$\mathbf{u}_{s\alpha}(\mathbf{R})$ is the α -component of the displacement of **s**-th atom

$3 \times N_{at}$ variables

Interatomic Force Constants :

$$C_{s\alpha,s'\beta}(\mathbf{R},\mathbf{R}') = C_{s\alpha,s'\beta}(\mathbf{R}-\mathbf{R}') = \frac{\partial^2 E_{tot}}{\partial \mathbf{u}_{s\alpha}(\mathbf{R})\partial \mathbf{u}_{s'\beta}(\mathbf{R}')} \rightarrow N_{\mathbf{R}}^2$$

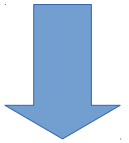
Basic concepts

Fourier transformation:

$$\tilde{\mathbf{u}}_{s\alpha}(\mathbf{q}) = \sum_{\mathbf{R}} \mathbf{u}_{s\alpha}(\mathbf{R})\, e^{-i\mathbf{q}\cdot\mathbf{R}}$$

Essence of the Bloch theorem:

$$\frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}^*_{s\alpha}(\mathbf{q}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}')} = \delta_{\mathbf{q},\mathbf{q}'} \frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}^*_{s\alpha}(\mathbf{q}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q})}$$



Important concept: We can perform calculations of Interatomic Force Constants for each **q** independently !!!

Basic concepts

Important concept: Instead of N_R^2 Interatomic Force Constants we need only N_R !!!

Sampling theorem

The number of **q** points is equal to the number of **R** points at which Interatomic Force Constants are computed.

Basic concepts

Normal mode frequencies, ω, and eigenvectors, $\mathbf{u}_{s\alpha}$ are determined by the secular equation:

$$\sum_{s',\beta} \tilde{D}_{s\alpha,s'\beta}(\mathbf{q})\,\tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}) = \omega_{\mathbf{q}}^2\,\tilde{\mathbf{u}}_{s\alpha}(\mathbf{q})$$

where

$$\tilde{D}_{s\alpha,s'\beta}(\mathbf{q}) = \frac{1}{\sqrt{M_s M_{s'}}} \sum_{\mathbf{R},\mathbf{R}'} \frac{\partial^2 E_{tot}}{\partial \mathbf{u}_{s\alpha}(\mathbf{R})\partial \mathbf{u}_{s'\beta}(\mathbf{R}')} e^{i\mathbf{q}(\mathbf{R}'-\mathbf{R})}$$

Interatomic Force Constants (IFC)

is the ***dynamical matrix***.

Diagonalization of the dynamical matrix gives phonon modes at **q**.

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Exercise 1: Phonons at Gamma in non-polar materials

Go to the directory with the input files:

```
cd  Hands-on_DFPT/exercise1
```

In this directory you will find:

- `README` – File describing how to do the exercise
- `Si.scf.in` – Input file for the SCF ground-state calculation
- `Si.ph.in` – Input file for the phonon calculation at Γ
- `Si.dynmat.in` – Input file to impose the acoustic sum rule
- `Si.vbc.UPF` – Pseudopotential of silicon
- `reference` – Directory with the reference results
- `out` – Directory for temporary files

Exercise 1: Phonons at Gamma in non-polar materials

Step 1. Perform a Self-Consistent Field ground-state calculation for silicon *at the equilibrium structure* using the **`pw.x`** program.

`Si.scf.in`

Input file for the SCF calculation

```
 &control
    calculation='scf'
    restart_mode='from_scratch',
    pseudo_dir='./'
    outdir='./out'
    prefix='Si',
 /
 &system
    ibrav = 2,
    celldm(1) = 10.20,
    nat = 2,
    ntyp = 1,
    ecutwfc = 16
 /
 &electrons
    diagonalization = 'davidson'
    mixing_mode = 'plain',
    conv_thr =  1.0d-8
    mixing_beta = 0.7
 /
ATOMIC_SPECIES
 Si  28.0855 Si.vbc.UPF
ATOMIC_POSITIONS
 Si 0.00 0.00 0.00
 Si 0.25 0.25 0.25
K_POINTS
   10
 0.1250000  0.1250000  0.1250000   1.00
 0.1250000  0.1250000  0.3750000   3.00
 0.1250000  0.1250000  0.6250000   3.00
 0.1250000  0.1250000  0.8750000   3.00
 0.1250000  0.3750000  0.3750000   3.00
 0.1250000  0.3750000  0.6250000   6.00
 0.1250000  0.3750000  0.8750000   6.00
 0.1250000  0.6250000  0.6250000   3.00
 0.3750000  0.3750000  0.3750000   1.00
 0.3750000  0.3750000  0.6250000   3.00
```

`pw.x < Si.scf.in > Si.scf.out`

Input Output

Exercise 1: Phonons at Gamma in non-polar materials

Step 2. Perform a phonon calculation at Γ using the **ph.x** program.

Si.ph.in

Input file for the phonon calculation

```
Phonons at Gamma
 &inputph
  prefix = 'Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  outdir = './out'
  fildyn = 'Si.dyn',
 /
 0.0  0.0  0.0
```

- The same prefix as in the SCF calculation
- Threshold for self-consistency
- Atomic mass
- Directory for temporary files
- File containing the dynamical matrix
- Coordinates of the **q** point in units of 2*pi/a in Cartesian framework

ph.x < Si.ph.in > Si.ph.out

Exercise 1: Phonons at Gamma in non-polar materials

Step 2. Perform a phonon calculation at Γ using the **ph.x** program.

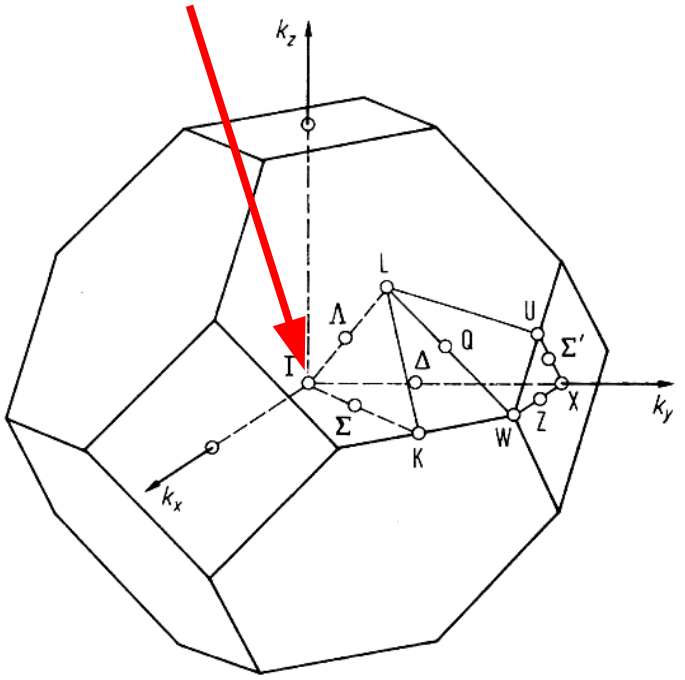
Si.ph.in

Input file for the phonon calculation

```
Phonons at Gamma
 &inputph
  prefix = 'Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  outdir = './out'
  fildyn = 'Si.dyn',
 /
 0.0  0.0  0.0
```

We consider only the Γ point:

q = 2*pi/a (0.0, 0.0, 0.0)



Brillouin zone

Exercise 1: Phonons at Gamma in non-polar materials

Dynamical matrix file **`Si.dyn :`**

```
**************************************************************************
     freq (    1) =       0.074375 [THz] =       2.480880 [cm-1]
(  0.509124  0.000000 -0.476699  0.000000 -0.116409  0.000000 )
(  0.509124  0.000000 -0.476699  0.000000 -0.116409  0.000000 )
     freq (    2) =       0.074375 [THz] =       2.480880 [cm-1]
(  0.047843  0.000000 -0.118723  0.000000  0.695425  0.000000 )
(  0.047843  0.000000 -0.118723  0.000000  0.695425  0.000000 )
     freq (    3) =       0.074375 [THz] =       2.480880 [cm-1]
(  0.488369  0.000000  0.508589  0.000000  0.053228  0.000000 )
(  0.488369  0.000000  0.508589  0.000000  0.053228  0.000000 )
     freq (    4) =      15.474507 [THz] =     516.174002 [cm-1]
( -0.366708  0.000000 -0.101088  0.000000  0.596076  0.000000 )
(  0.366708  0.000000  0.101088  0.000000 -0.596076  0.000000 )
     freq (    5) =      15.474507 [THz] =     516.174002 [cm-1]
(  0.264492  0.000000 -0.653724  0.000000  0.051853  0.000000 )
( -0.264492  0.000000  0.653724  0.000000 -0.051853  0.000000 )
     freq (    6) =      15.474507 [THz] =     516.174002 [cm-1]
(  0.543663  0.000000  0.249852  0.000000  0.376835  0.000000 )
( -0.543663  0.000000 -0.249852  0.000000 -0.376835  0.000000 )
**************************************************************************
```

Acoustic modes

Optical modes

Exercise 1: Phonons at Gamma in non-polar materials

Acoustic sum rule at Γ

Because of the numerical inaccuracies the interatomic force constants do not strictly satisfy the acoustic sum rule (ASR) => acoustic frequencies are not exactly zero.

However, the ASR can be imposed using the **dynmat.x** program.

The input file is **Si.dynmat.in** :

```
&input
 fildyn = 'Si.dyn',
 asr = 'simple'
/
```

File containing the dynamical matrix

A way to impose the acoustic sum rule (simple, crystal, one-dim, zero-dim)

dynmat.x < Si.dynmat.in > Si.dynmat.out

Exercise 1: Phonons at Gamma in non-polar materials

The program **dynmat.x** produces the file **dynmat.out** which contains the new acoustic frequencies, which are *exactly* equal to zero.

```
     diagonalizing the dynamical matrix ...

q =       0.0000      0.0000      0.0000
**********************************************************************
     freq (    1) =       0.000000 [THz] =       0.000000 [cm-1]
(  0.000000   0.000000    -0.707107   0.000000     0.000000   0.000000   )
(  0.000000   0.000000    -0.707107   0.000000     0.000000   0.000000   )
     freq (    2) =       0.000000 [THz] =       0.000000 [cm-1]
( -0.707107   0.000000     0.000000   0.000000     0.000000   0.000000   )
( -0.707107   0.000000     0.000000   0.000000     0.000000   0.000000   )
     freq (    3) =       0.000000 [THz] =       0.000000 [cm-1]
(  0.000000   0.000000     0.000000   0.000000    -0.707107   0.000000   )
(  0.000000   0.000000     0.000000   0.000000    -0.707107   0.000000   )
     freq (    4) =      15.474329 [THz] =     516.168042 [cm-1]
(  0.000000   0.000000     0.707107   0.000000     0.000000   0.000000   )
(  0.000000   0.000000    -0.707107   0.000000     0.000000   0.000000   )
     freq (    5) =      15.474329 [THz] =     516.168042 [cm-1]
(  0.000000   0.000000     0.000000   0.000000    -0.707107   0.000000   )
(  0.000000   0.000000     0.000000   0.000000     0.707107   0.000000   )
     freq (    6) =      15.474329 [THz] =     516.168042 [cm-1]
( -0.707107   0.000000     0.000000   0.000000     0.000000   0.000000   )
(  0.707107   0.000000     0.000000   0.000000     0.000000   0.000000   )
**********************************************************************
```

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5. **Exercise 4:** Phonon dispersion in polar materials

Exercise 2: Phonon dispersion in non-polar materials

Go to the directory with the input files:

```
cd  Hands-on_DFPT/exercise2
```

In this directory you will find:

- `README` – File describing how to do the exercise
- `Si.scf.in` – Input file for the SCF ground-state calculation
- `Si.ph.in` – Input file for the phonon calculation on a uniform **q**-grid
- `Si.q2r.in` – Input file for calculation of Interatomic Force Constants
- `Si.matdyn.in` – Input file for Fourier Interpolation for various **q** points
- `Si.plotband.in` – Input file for plotting a phonon dispersion
- `Si.vbc.UPF` – Pseudopotential of silicon
- `reference` – Directory with the reference results
- `out` – Directory for temporary files

Exercise 2: Phonon dispersion in non-polar materials

Step 1. Perform a SCF calculation for silicon *at the equilibrium structure* using the **pw.x** program.

```
pw.x < Si.scf.in > Si.scf.out
```

Step 2. Perform a phonon calculation on a uniform grid of **q** points using the **ph.x** program.

```
Phonons on a uniform q-grid
 &inputph
  prefix='Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  ldisp = .true.,
  nq1 = 4,
  nq2 = 4,
  nq3 = 4,
  outdir='./out'
  fildyn='Si.dyn',
 /
```

Option for the calculation on a grid

Uniform grid of **q** points

$$\mathbf{q}_{ijk} = \frac{i-1}{\mathrm{nq1}}\mathbf{G}_1 + \frac{j-1}{\mathrm{nq2}}\mathbf{G}_2 + \frac{k-1}{\mathrm{nq3}}\mathbf{G}_3$$

```
ph.x < Si.ph.in > Si.ph.out
```

Exercise 2: Phonon dispersion in non-polar materials

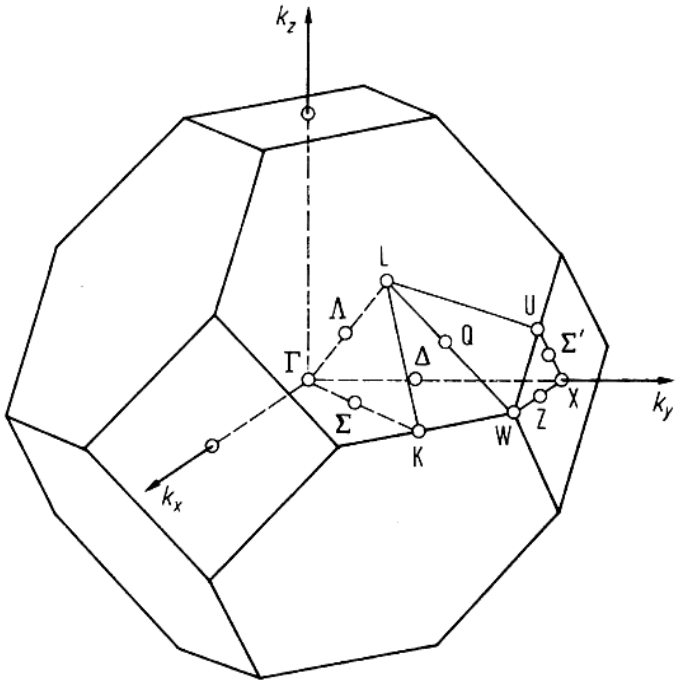
Step 1. Perform a SCF calculation for silicon *at the equilibrium structure* using the **`pw.x`** program.

```
pw.x < Si.scf.in > Si.scf.out
```

Step 2. Perform a phonon calculation.

```
Phonons on a uniform q-grid
 &inputph
  prefix='Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  ldisp = .true.,
  nq1 = 4,
  nq2 = 4,
  nq3 = 4,
  outdir='./out'
  fildyn='Si.dyn',
 /
```

We sample the Brillouin zone with a uniform grid 4x4x4 of **q** points.



Exercise 2: Phonon dispersion in non-polar materials

- 4x4x4 = 64 q-points => Use of symmetry => 8 non-equivalent **q** points

  The file **`Si.dyn0`** contains a list of the non-equivalent **q** points (8, in this case).

```
      4   4   4    (q-grid)
      8             (number of non-equivalent q-points)
q1 =  0.0000000000000000E+00   0.0000000000000000E+00   0.0000000000000000E+00
q2 = -0.2500000000000000E+00   0.2500000000000000E+00  -0.2500000000000000E+00
q3 =  0.5000000000000000E+00  -0.5000000000000000E+00   0.5000000000000000E+00
q4 =  0.0000000000000000E+00   0.5000000000000000E+00   0.0000000000000000E+00
q5 =  0.7500000000000000E+00  -0.2500000000000000E+00   0.7500000000000000E+00
q6 =  0.5000000000000000E+00   0.0000000000000000E+00   0.5000000000000000E+00
q7 =  0.0000000000000000E+00  -0.1000000000000000E+01   0.0000000000000000E+00
q8 = -0.5000000000000000E+00  -0.1000000000000000E+01   0.0000000000000000E+00
```

- The phonon program **ph.x** generates files for every non-equivalent **q** point **`Si.dyn1`**, **`Si.dyn2`**, **…**, **`Si.dyn8`**, which contain information about dynamical matrices, phonon frequencies and displacements.

Exercise 2: Phonon dispersion in non-polar materials

Step 3. Calculation of the Interatomic Force Constants (IFC) using the **`q2r.x`** program.

Fourier transforms of IFC's :

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) = \frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}^*_{s\alpha}(\mathbf{q}_{ijk}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}_{ijk})}$$

α, β are Cartesian components, and s, s' are atomic indices.

$$C_{s\alpha,s'\beta}(\mathbf{R}_{lmn}) = \frac{1}{N_{\mathbf{q}}} \sum_{i,j,k} \tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) e^{i\mathbf{q}_{ijk}\cdot\mathbf{R}_{lmn}}$$

$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) \longrightarrow C_{s\alpha,s'\beta}(\mathbf{R}_{lmn})$

Fourier transforms of IFC's on a grid of **q** points nq1 x nq2 x nq3 in reciprocal space

IFC's in a supercell nq1 x nq2 x nq3 in real space

Exercise 2: Phonon dispersion in non-polar materials

Input file **`Si.q2r.in`** :

```
&input
  fildyn='Si.dyn',
  zasr='simple',
  flfrc='Si444.fc'
/
```

← Dynamical matrices from the phonon calculation

← A way to impose the acoustic sum rule

← Output file of the interatomic force constants

The denser the grid of **q** points, the larger the vectors **R** for which the Interatomic Force Constants are calculated!

To perform the calculation:

```
q2r.x < Si.q2r.in > Si.q2r.out
```

Exercise 2: Phonon dispersion in non-polar materials

Step 4. Calculate phonons at generic **q'** points using IFC by means of the code **`matdyn.x`**

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}') = \sum_{l,m,n} C_{s\alpha,s'\beta}(\mathbf{R}_{lmn}) e^{-i\mathbf{q}'\cdot\mathbf{R}_{lmn}}$$

$C_{s\alpha,s'\beta}(\mathbf{R}_{lmn})$ → **Fourier interpolation** → $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}')$

IFC's on a grid in real space

Fourier transforms of IFC's at generic **q'** points in reciprocal space

Input file **`Si.matdyn.in`** :

```
 &input
    asr='simple',
    amass(1)=28.0855,
    flfrc='Si444.fc',
    flfrq='Si.freq'
 /
396
    0.000000    0.000000    0.000000    0.000000
    0.012658    0.000000    0.000000    0.012658
    ...         ...         ...         ...
```

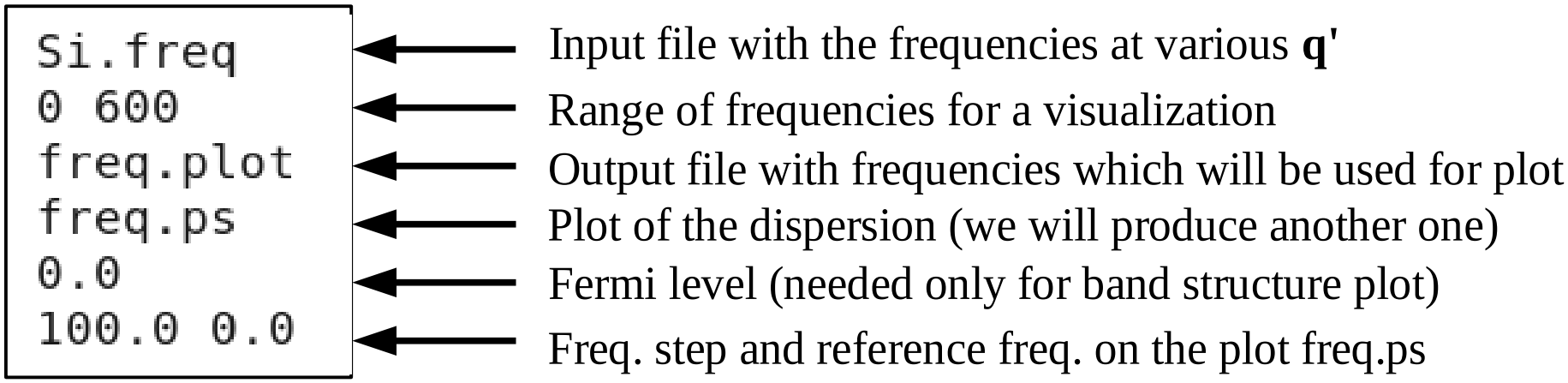
- `asr='simple'` — Acoustic sum rule
- `amass(1)=28.0855` — Atomic mass
- `flfrc='Si444.fc'` — File with IFC's
- `flfrq='Si.freq'` — Output file with the frequencies
- `396` — Number of **q** points
- coordinates — Coordinates of **q** points

`matdyn.x < Si.matdyn.in > Si.matdyn.out`

Exercise 2: Phonon dispersion in non-polar materials

Step 5. Plot the phonon dispersion using the **plotband.x** program and **gnuplot**.

Input file **Si.plotband.in** :



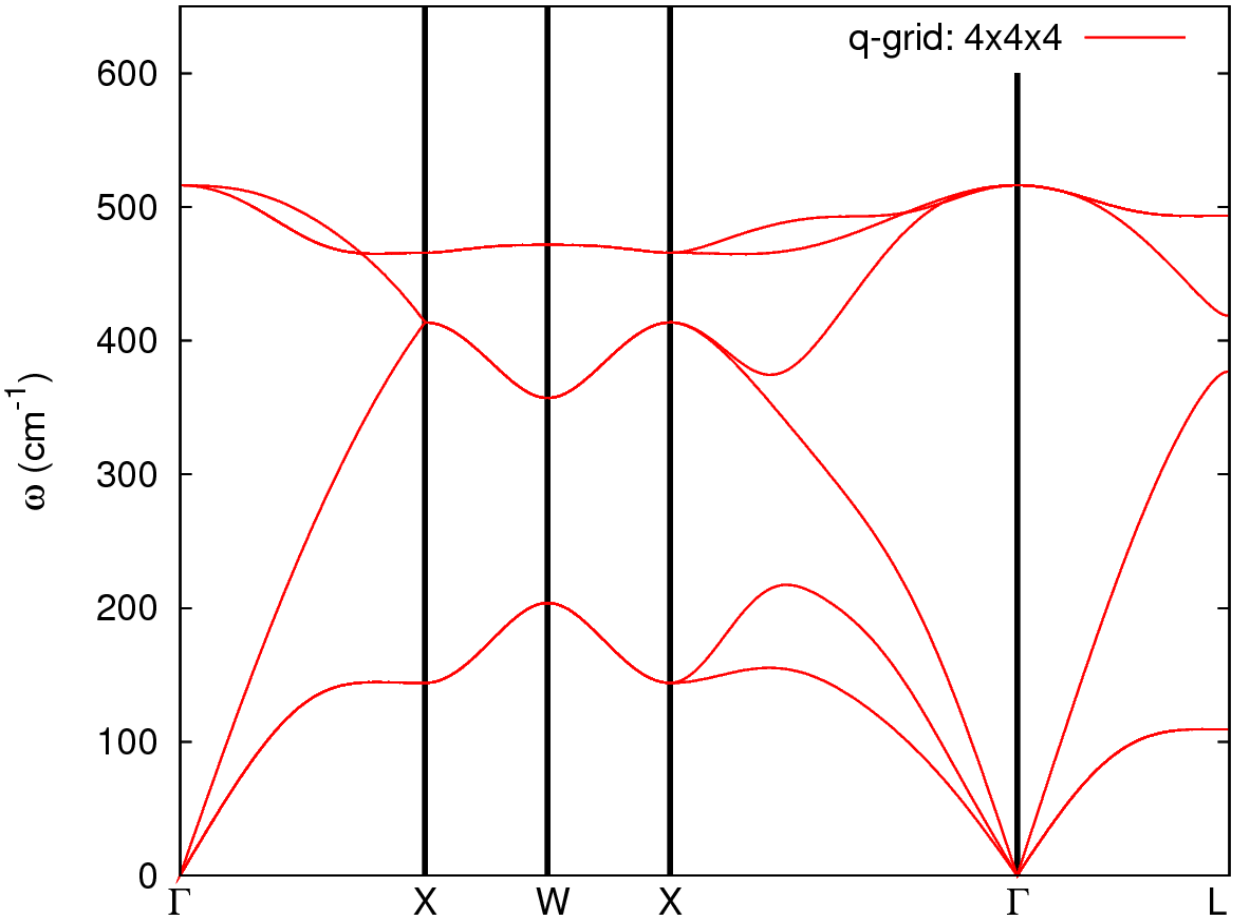

```
plotband.x < Si.plotband.in > Si.plotband.out
```

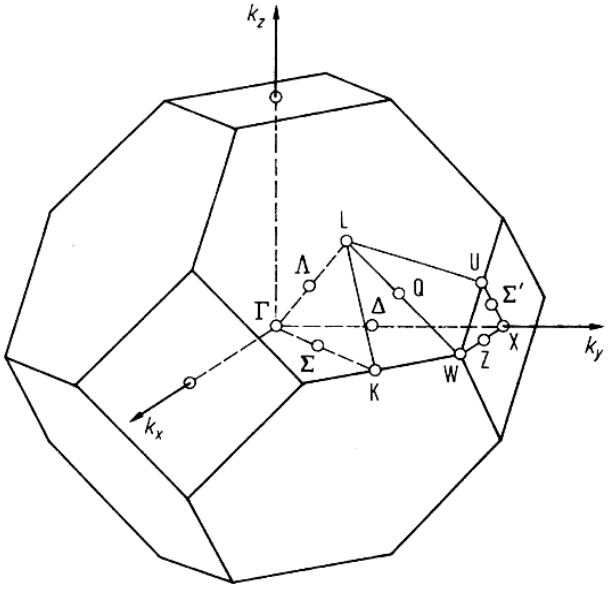
Use **gnuplot** and the file **plot_dispersion.gnu** in order to plot the phonon dispersion of silicon (**experimental_data.dat**).

You will obtain a postscript file **phonon_dispersion.eps** which you can visualize.

Exercise 2: Phonon dispersion in non-polar materials

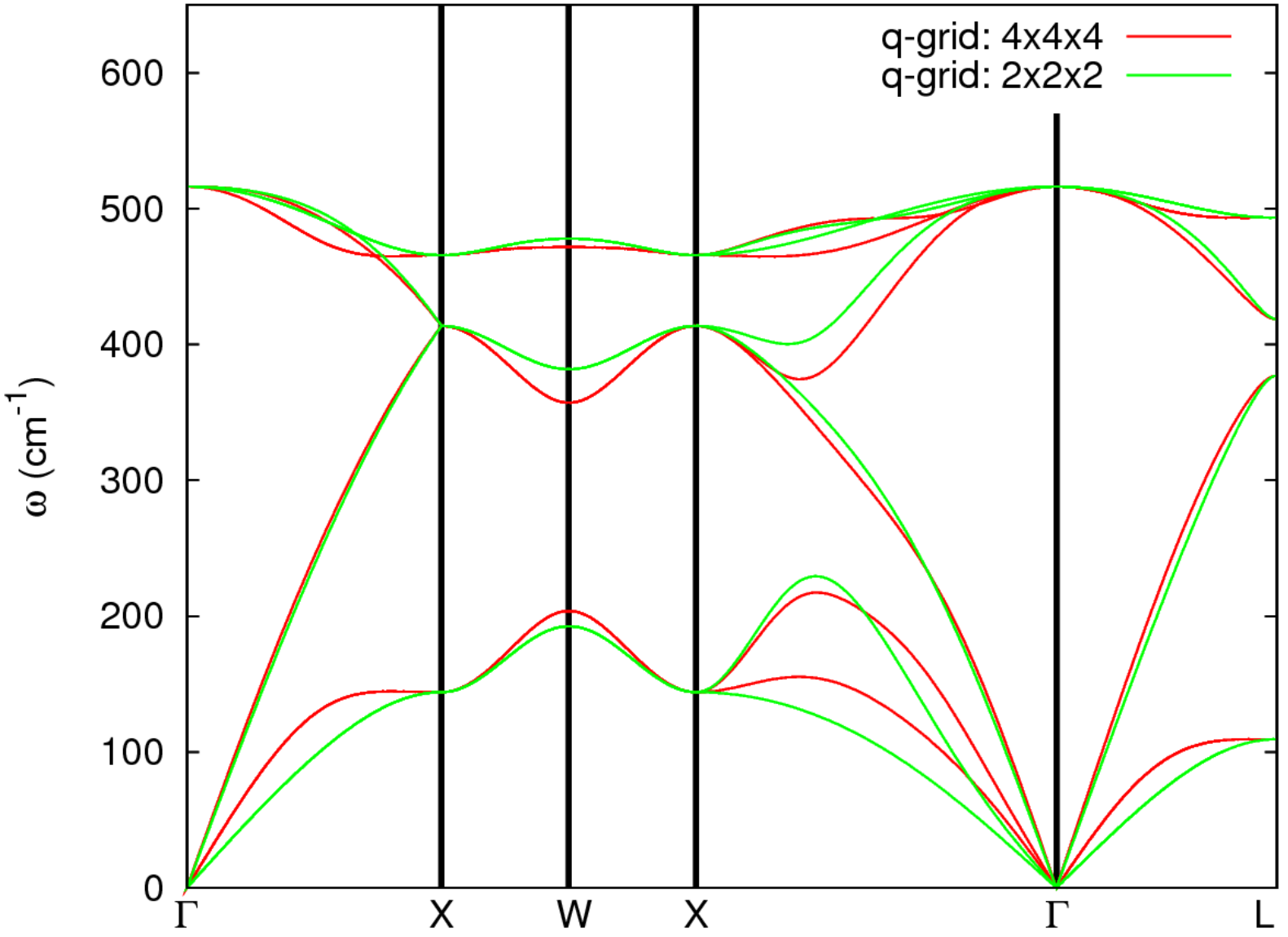
Phonon dispersion of silicon along some high-symmetry directions in the Brillouin zone (file **`phonon_dispersion.eps`**):





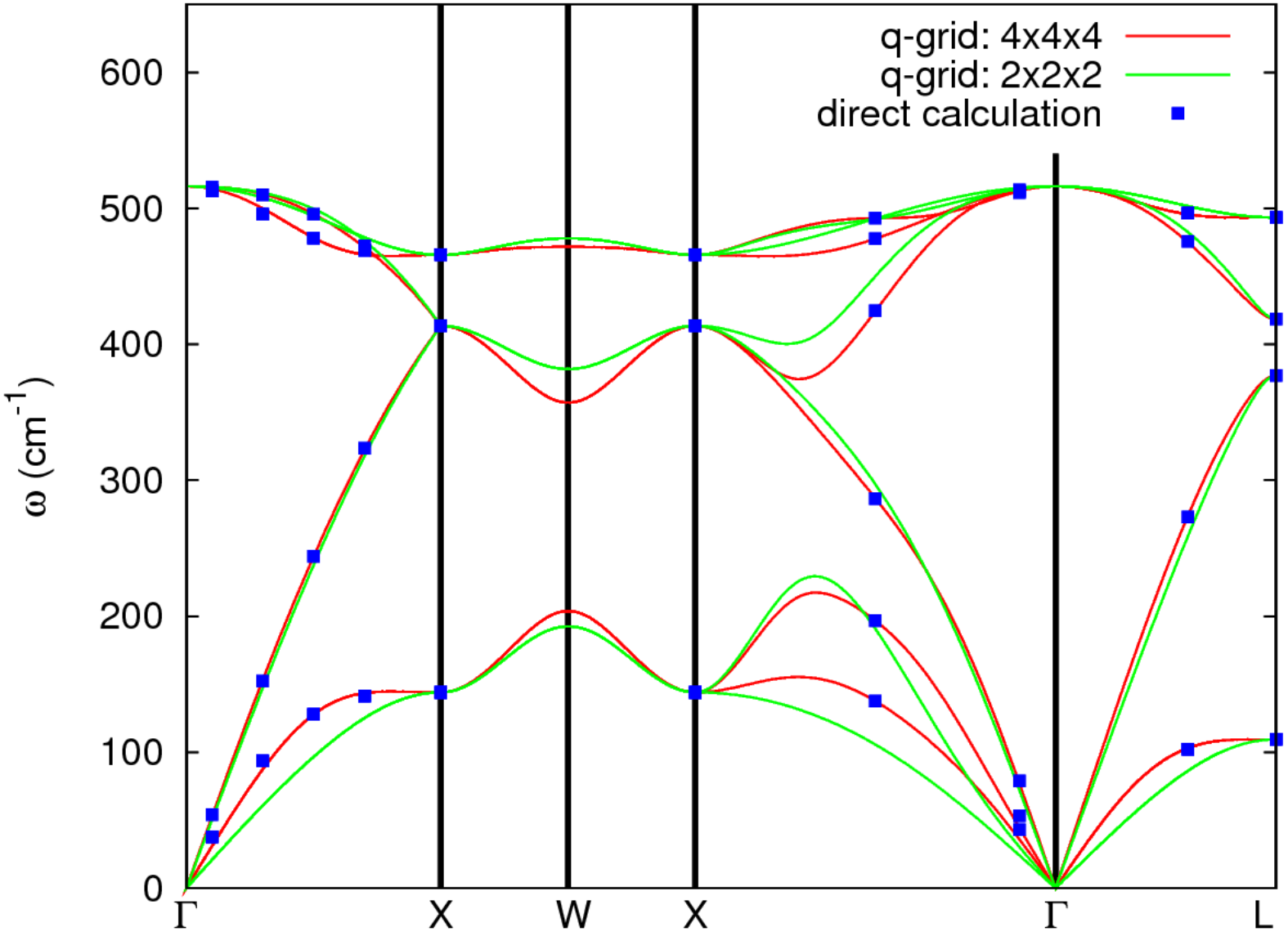
Exercise 2: Phonon dispersion in non-polar materials

How to determine whether the quality of the Fourier interpolation is satisfactory? → Compare with the direct calculation (no interpolation)!



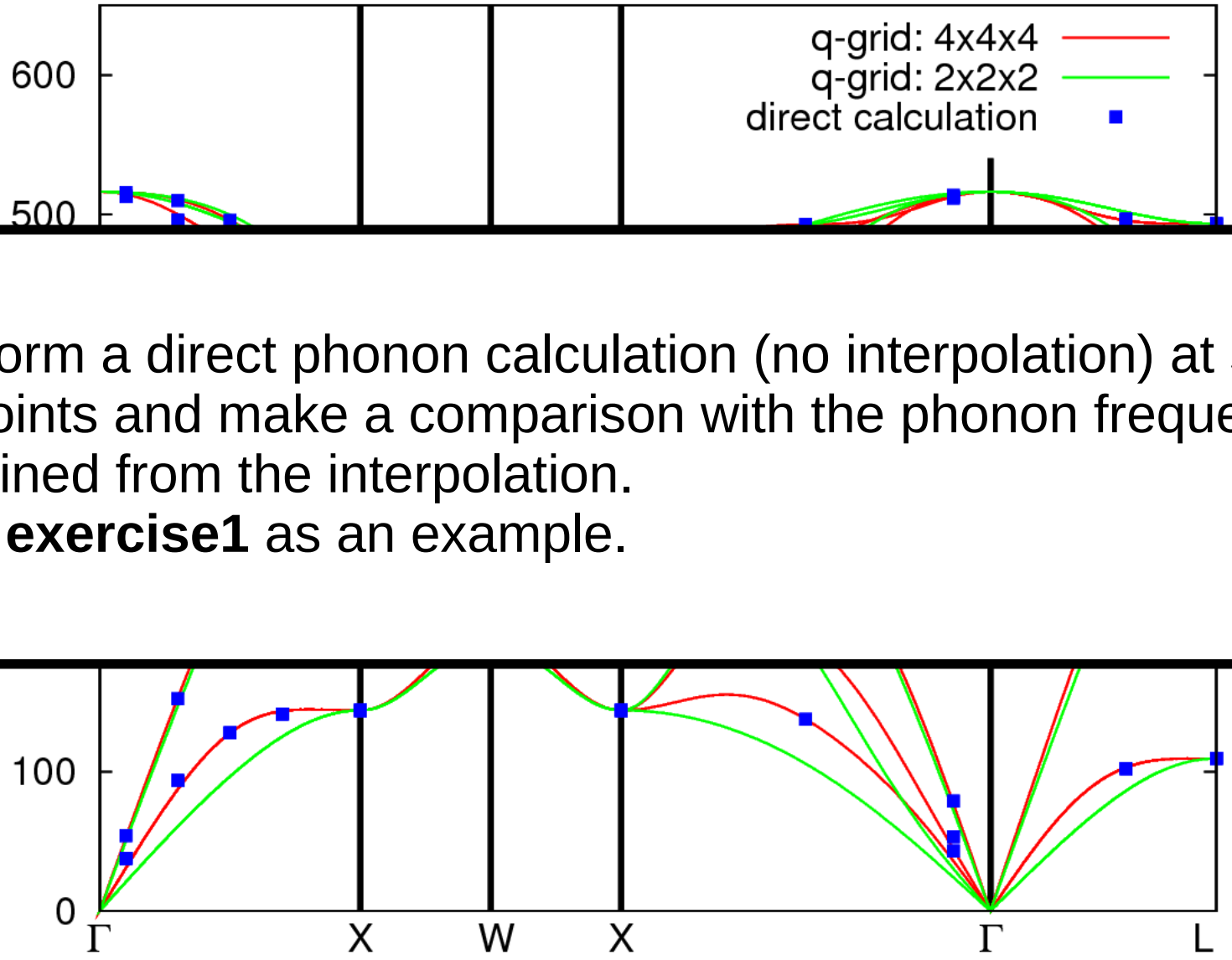
Exercise 2: Phonon dispersion in non-polar materials

Comparison of the phonon dispersion computed using the Fourier interpolation with the direct calculation at several **q** points. The **q**-grid 4x4x4 is very satisfactory for the Fourier interpolation for silicon!



Exercise 2: Phonon dispersion in non-polar materials

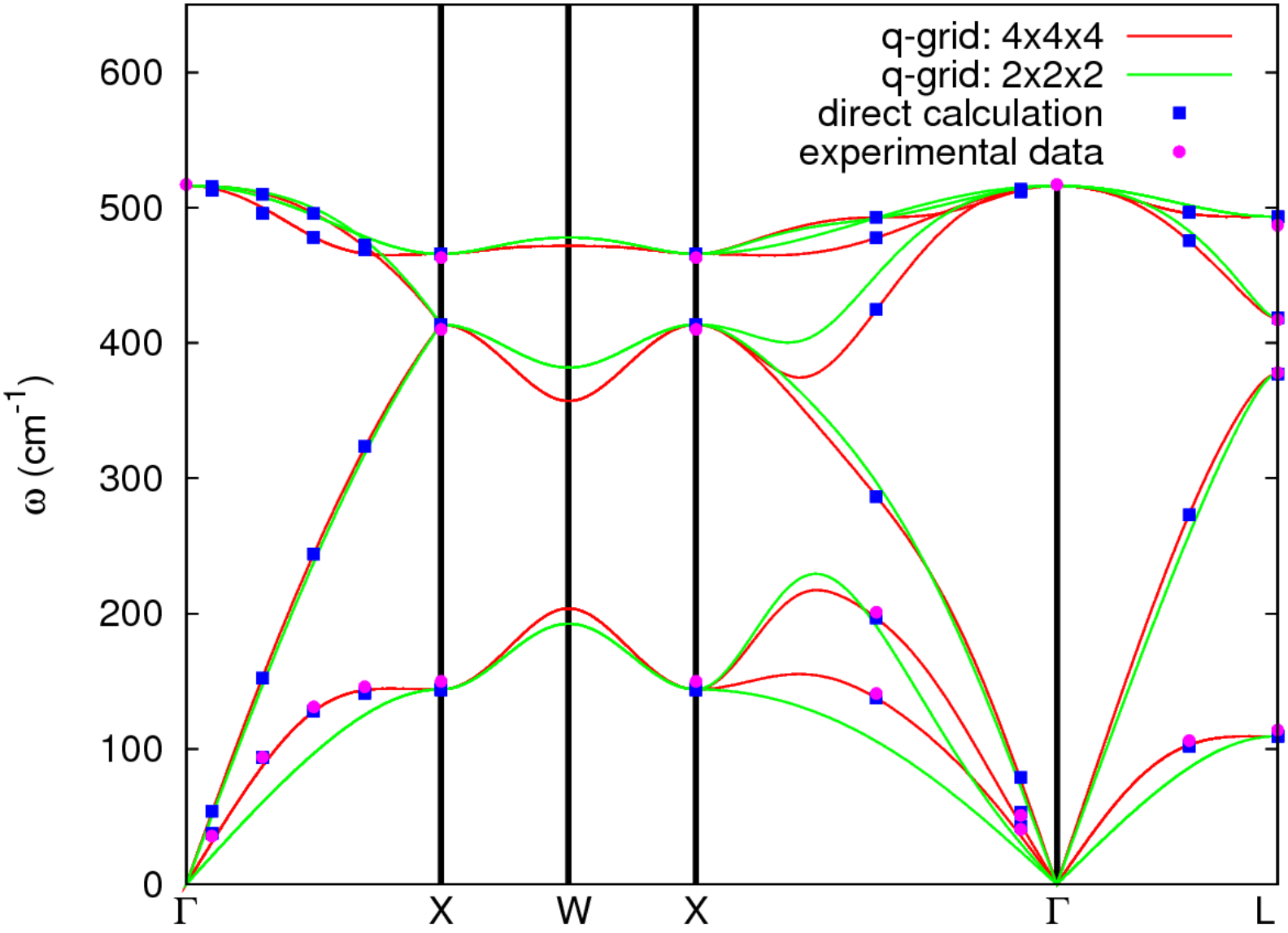
Comparison of the phonon dispersion computed using the Fourier interpolation with the direct calculation at several **q** points. The **q**-grid 4x4x4 is very satisfactory for the Fourier interpolation for silicon!



Perform a direct phonon calculation (no interpolation) at several **q'** points and make a comparison with the phonon frequencies obtained from the interpolation.
Use **exercise1** as an example.

Exercise 2: Phonon dispersion in non-polar materials

The agreement of *ab initio* calculation of the phonon dispersion using the Fourier interpolation on a **q**-grid 4x4x4 is excellent with the experimental data!



Exercise 2: Phonon dispersion in non-polar materials

The Fourier interpolation works well if the Interatomic Force Constants (IFC's) are known on a sufficiently large supercell, i.e. on a large enough grid of **q** points in the phonon calculation.

There are cases when the IFC's are long range and the Fourier interpolation does not work properly:

- When there are Kohn anomalies in metals. In this case the dynamical matrices are not a smooth function of **q** and the IFC's are long range.
- In polar insulators where the atomic displacements generate long range electrostatic interactions and the dynamical matrix is not analitical for $q \rightarrow 0$. However, this case can be dealt with by calculating the Born effective charges and the dielectric tensor of the material.

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Exercise 3: Phonons at Gamma in polar materials

Polar materials in the **q** = **0** limit: a macroscopic electric field appears as a consequence of the long-range character of the Coulomb interaction (incompatible with Periodic Boundary Conditions).

A non-analytic term must be added to Interatomic Force Constants at **q** = **0**:

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}) = \tilde{C}^{\text{analytic}}_{s\alpha,s'\beta}(\mathbf{q}) + \frac{4\pi}{\Omega}\frac{(\mathbf{q}\cdot\boldsymbol{Z}^{\star}_{s})_{\alpha}(\mathbf{q}\cdot\boldsymbol{Z}^{\star}_{s'})_{\beta}}{\mathbf{q}\cdot\epsilon_{\infty}\cdot\mathbf{q}}$$

Effective charges $\boldsymbol{Z}^{\star}_{s}$ are related to polarization **P** induced by a lattice distortion:

$$Z^{\star}_{s,\alpha\beta} = \Omega\frac{\partial \mathrm{P}_{\alpha}}{\partial u_{s\beta}}$$

Dielectric tensor $\epsilon^{\alpha\beta}_{\infty}$ is related to polarization **P** induced by an electric field **E** :

$$\epsilon^{\alpha\beta}_{\infty} = \delta_{\alpha\beta} + 4\pi\left.\frac{\partial \mathrm{P}_{\alpha}}{\partial \mathrm{E}_{\beta}}\right|_{u_s(q=0)=0}$$

All of the above can be calculated from (mixed) second order derivatives of the total energy.

Exercise 3: Phonons at Gamma in polar materials

Go to the directory with the input files:

```
cd  Hands-on_DFPT/exercise3
```

Step 1. Perform a Self-Consistent Field ground-state calculation for a polar semiconductor AlAs.

Step 2. Perform a phonon calculation at Gamma for AlAs.

```
Phonons at Gamma
 &inputph
  prefix='AlAs',
  tr2_ph = 1.0d-14,
  amass(1) = 26.98,
  amass(2) = 74.92,
  outdir='./out'
  fildyn='AlAs.dyn',
  epsil = .true.
 /
 0.0  0.0   0.0
```

If .true. will calculate and store the dielectric tensor and effective charges

Exercise 3: Phonons at Gamma in polar materials

In the file **`AlAs.ph.out`** you will find an information about the dielectric tensor and effective charges:

```
     Dielectric constant in cartesian axis

     (      13.744319556      -0.000000000      -0.000000000 )
     (      -0.000000000      13.744319556       0.000000000 )
     (      -0.000000000      -0.000000000      13.744319556 )

     Effective charges (d Force / dE) in cartesian axis

          atom      1   Al
       Ex  (        1.88263        0.00000       -0.00000 )
       Ey  (        0.00000        1.88263        0.00000 )
       Ez  (       -0.00000        0.00000        1.88263 )
          atom      2   As
       Ex  (       -3.23388       -0.00000       -0.00000 )
       Ey  (       -0.00000       -3.23388        0.00000 )
       Ez  (       -0.00000        0.00000       -3.23388 )

    Diagonalizing the dynamical matrix

    q = (    0.000000000   0.000000000   0.000000000 )

**************************************************************************
    freq (    1) =       0.136062 [THz] =       4.538540 [cm-1]
    freq (    2) =       0.136062 [THz] =       4.538540 [cm-1]
    freq (    3) =       0.136062 [THz] =       4.538540 [cm-1]
    freq (    4) =      11.258409 [THz] =     375.540116 [cm-1]
    freq (    5) =      11.258409 [THz] =     375.540116 [cm-1]
    freq (    6) =      11.258409 [THz] =     375.540116 [cm-1]
**************************************************************************
```

No LO-TO splitting

Exercise 3: Phonons at Gamma in polar materials

Step 3. Impose Acoustic Sum Rule and add the non-analitic LO-TO splitting using the **dynmat.x** program.

Input file **AlAs.dynmat.in** :

```
&input
   fildyn = 'AlAs.dyn',
   asr='simple',
   amass(1)=26.98,
   amass(2)=74.92
   q(1) = 1.0,
   q(2) = 0.0,
   q(3) = 0.0
/
```

Direction for the LO-TO splitting

Output file **dynmat.out** :

```
**********************************************
     freq (    1) =       -0.000000 [THz] =
(   0.538473   0.000000     -0.458309   0.000000
(   0.538473   0.000000     -0.458309   0.000000
     freq (    2) =       -0.000000 [THz] =
(   0.000000   0.000000      0.000000   0.000000
(   0.000000   0.000000      0.000000   0.000000
     freq (    3) =        0.000000 [THz] =
(  -0.458309   0.000000     -0.538473   0.000000
(  -0.458309   0.000000     -0.538473   0.000000
     freq (    4) =       11.257454 [THz] =
(   0.000000   0.000000      0.940852   0.000000
(  -0.000000   0.000000     -0.338817   0.000000
     freq (    5) =       11.257454 [THz] =
(   0.000000   0.000000      0.000000   0.000000
(   0.000000   0.000000      0.000000   0.000000
     freq (    6) =       12.307908 [THz] =
(   0.940852   0.000000     -0.000000   0.000000
(  -0.338817   0.000000      0.000000   0.000000
**********************************************
```

LO-TO splitting

dynmat.x < AlAs.dynmat.in > AlAs.dynmat.out

Outline

1. Introduction

2. **Exercise 1:** Phonons at Gamma in non-polar materials

3. **Exercise 2:** Phonon dispersion in non-polar materials

4. **Exercise 3:** Phonons at Gamma in polar materials

5. **Exercise 4:** Phonon dispersion in polar materials

Exercise 4: Phonon dispersion in polar materials

Go to the directory with the input files:

```
cd  Hands-on_DFPT/exercise4
```

- Calculate phonon dispersion in AlAs following the same steps as in **exercise2**.

- Where necessary put missing information in the input files.

Exercise 4: Phonon dispersion in polar materials

Step 1. Perform a SCF ground-state calculation for AlAs using **`pw.x`**

Step 2. Perform a phonon calculation on a 4x4x4 **q**-grid using **`ph.x`**
(dielectric tensor and effective charges will be calculated)

Step 3. Perform Fourier Transformations (FT) of $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q})$ in order to obtain Interatomic Force Constants in real space $C_{s\alpha,s'\beta}(\mathbf{R})$ using **`q2r.x`**.

A term having the same behaviour for **q** -> **0** as the non-analytic term is subtracted from $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q})$ before the FT and re-added to $C_{s\alpha,s'\beta}(\mathbf{R})$, so that no problem related to non-analytic behaviour and related long-rangeness arises in the FT.

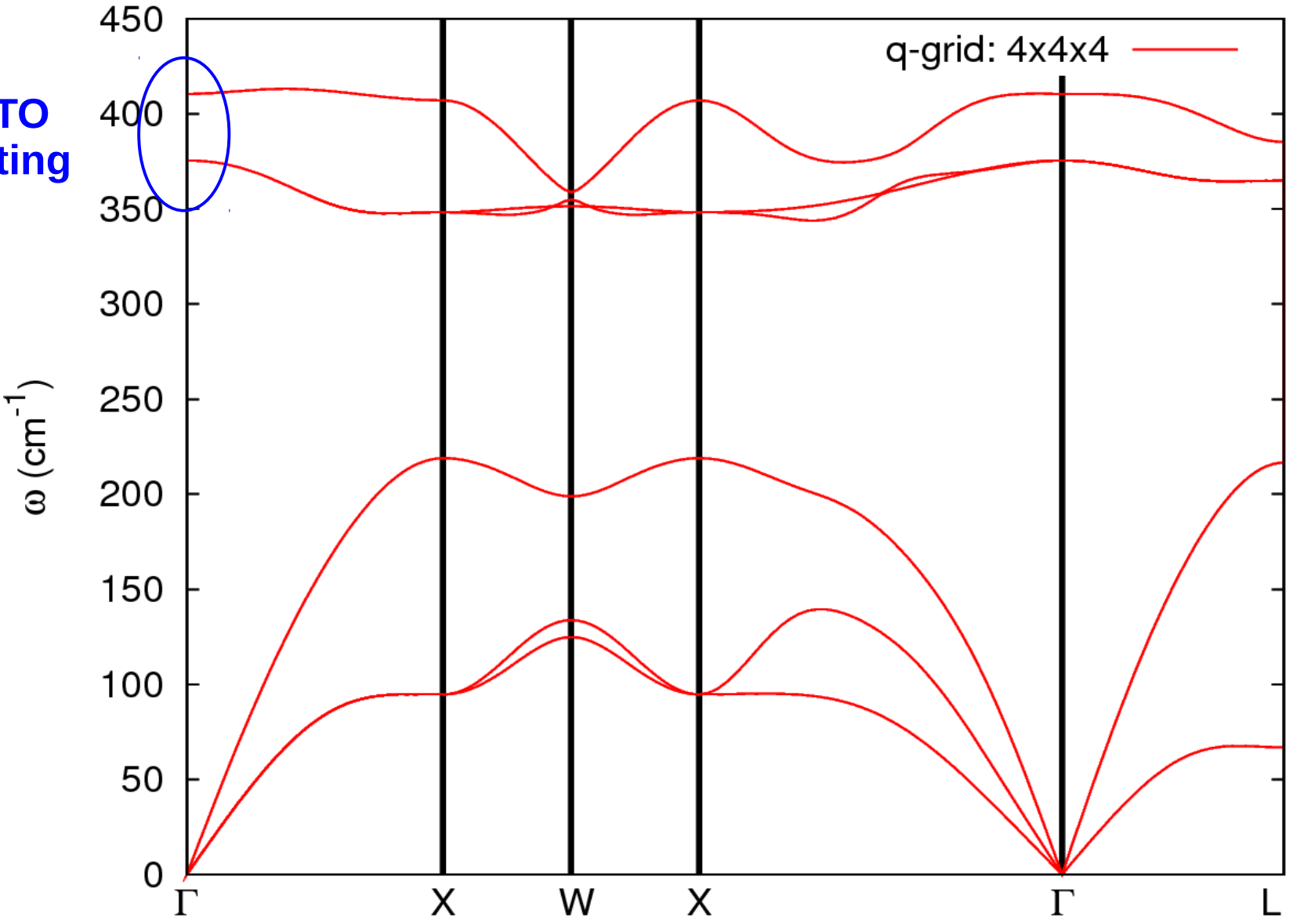
Step 4. Calculate phonons at generic **q'** points using Interatomic Force Constants (including the non-analytic term) using the code **`matdyn.x`**

Step 5. Plot the phonon dispersion of AlAs using **`plotband.x`** and **`gnuplot`**.

Exercise 4: Phonon dispersion in polar materials

The phonon dispersion of AlAs:

LO-TO splitting



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