EPFL

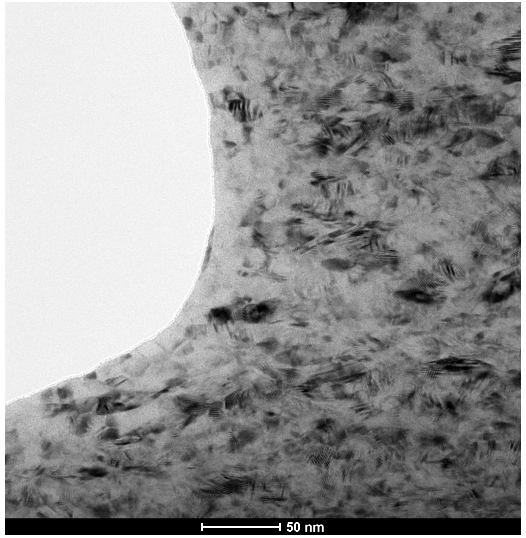
# Electron Microscopy: Advanced Methods (Week 0)

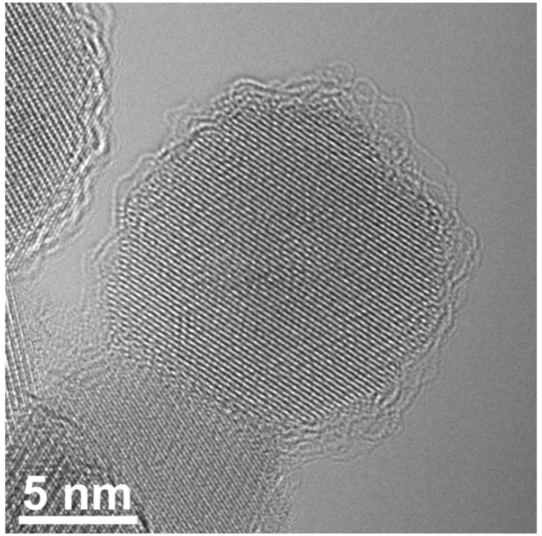
**Duncan Alexander**
EPFL-IPHYS-LSME

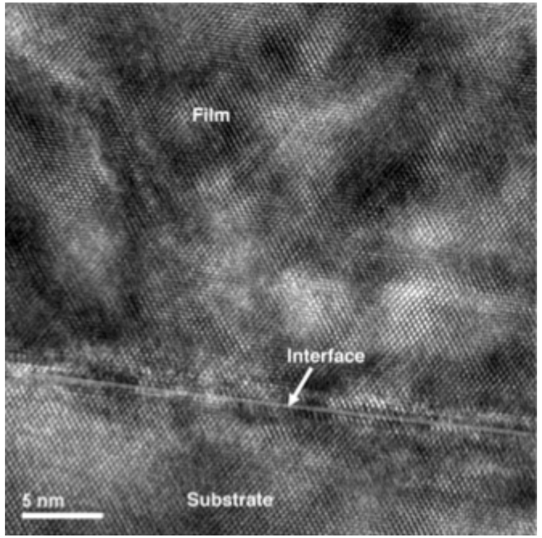
# Course objectives

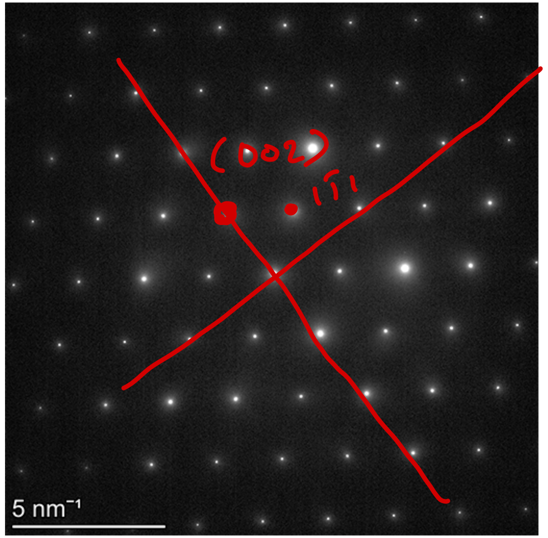
Give you a deep understanding of the most important modes of operation of a modern transmission electron microscope. We will focus on the instrument operation as well as on the essential electron–matter interactions that we exploit, in order to explain the results obtained using these techniques

Fcc [110]



# Organisation

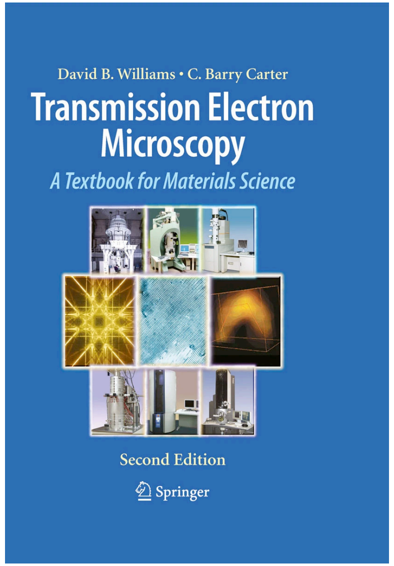
- Nominally: 2 hours lecture / 1 hour exercises and demos at the microscope
- 8/13 weeks in form of MOOCs. Follow course before the class-room “lecture”
- Class-room time will be used for Q&A, discussions, quizzes, and interactive sessions at the TEM
- Aim: interactive course. **Be participative!**
  *Use EdDiscussion for questions and discussions*
- Prerequisites:
  - Crystallography, solid state physics
  - SEM & TEM lecture at Bachelor level
  - Geometrical optics (convergent lenses)

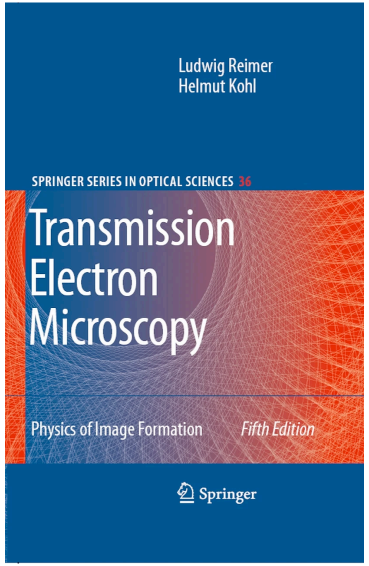
# Lecture material

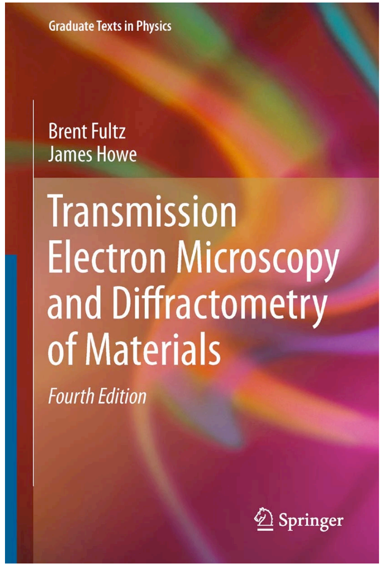
- Open on-line course – ~~Coursera~~ EPFL Platform – you will be emailed sign-up link for private session
- Lecture slides
- Books (Williams & Carter, Fultz & Howe, Reimer & Kohl…)

$|\vec{k}| = \frac{1}{\lambda}$

$\left(\frac{2\pi}{\lambda}\right)$



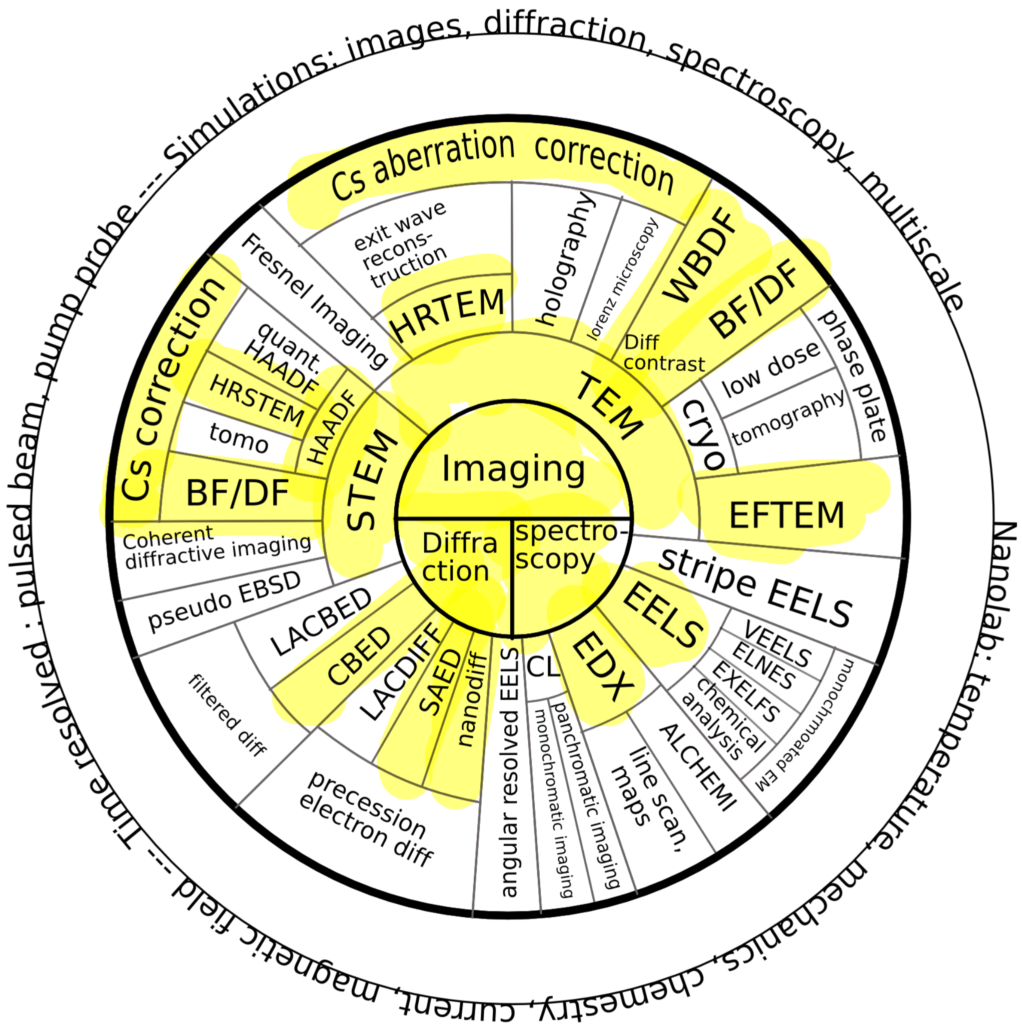
# Course layout

- Week 0: course introduction, “refresher” on crystallography and ray optics
- Weeks 1–2: introduction to TEM (Coursera)
- Weeks 3–7: TEM diffraction and imaging. 3–6 on Coursera (with in-class supplements), week 7 conventional lecture
- Weeks 8–9: phase contrast TEM (Coursera)
- Weeks 10–11: scanning TEM (STEM); conventional lectures
- Weeks 12–13: analytical TEM; conventional lectures

# Course evaluation

- Project-based evaluation with one individual report + oral evaluation during the exam period
- You will receive one (or max. 2) paper(s) with TEM images and data. You will be asked to write a short report explaining the techniques used for acquiring those images and data
- Each student will be given an individual interview based on their report. The questions will only be on the TEM-related techniques, but can encompass all parts of the course
- The grade will be 50% written report 50% oral exam

# The TEM: a very versatile instrument



# Chapter 0: background prerequisites

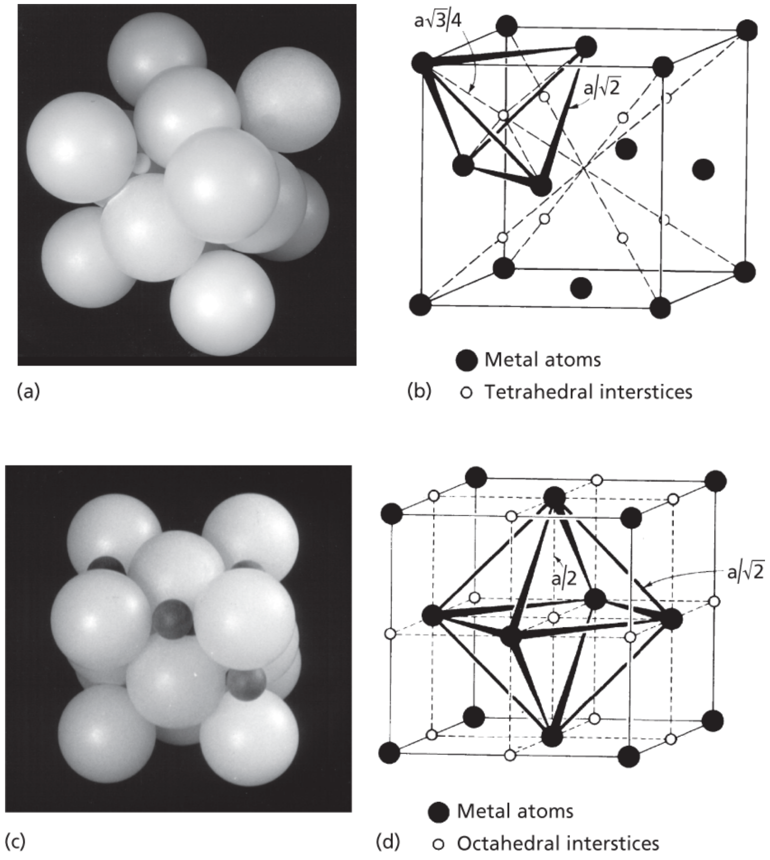
- Aim: provide short recap (or introduction?) of previous lecture courses you have taken

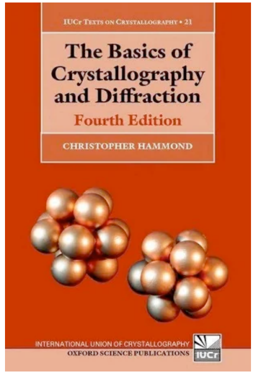
1. Crystallography: real and reciprocal space (week 0)
2. Geometrical optics: ray diagrams for converging lens (weeks 0–2)
3. TEM basics: weeks 1–2 (Coursera)

- Your duty: identify the domain(s) where your background is less solid and catch up during the next 2 weeks!

# The crystalline specimen

- A large part of the samples investigated by TEM are crystals (even sometimes in biology: e.g proteins can be crystallised!)
- Many imaging techniques make specific use of the interaction of the electron beam with the crystal: high resolution TEM, diffraction, dark-field imaging, weak-beam imaging, convergent beam electron diffraction, high resolution scanning TEM…
- Therefore we need to be familiar with the basics of crystallography to understand TEM

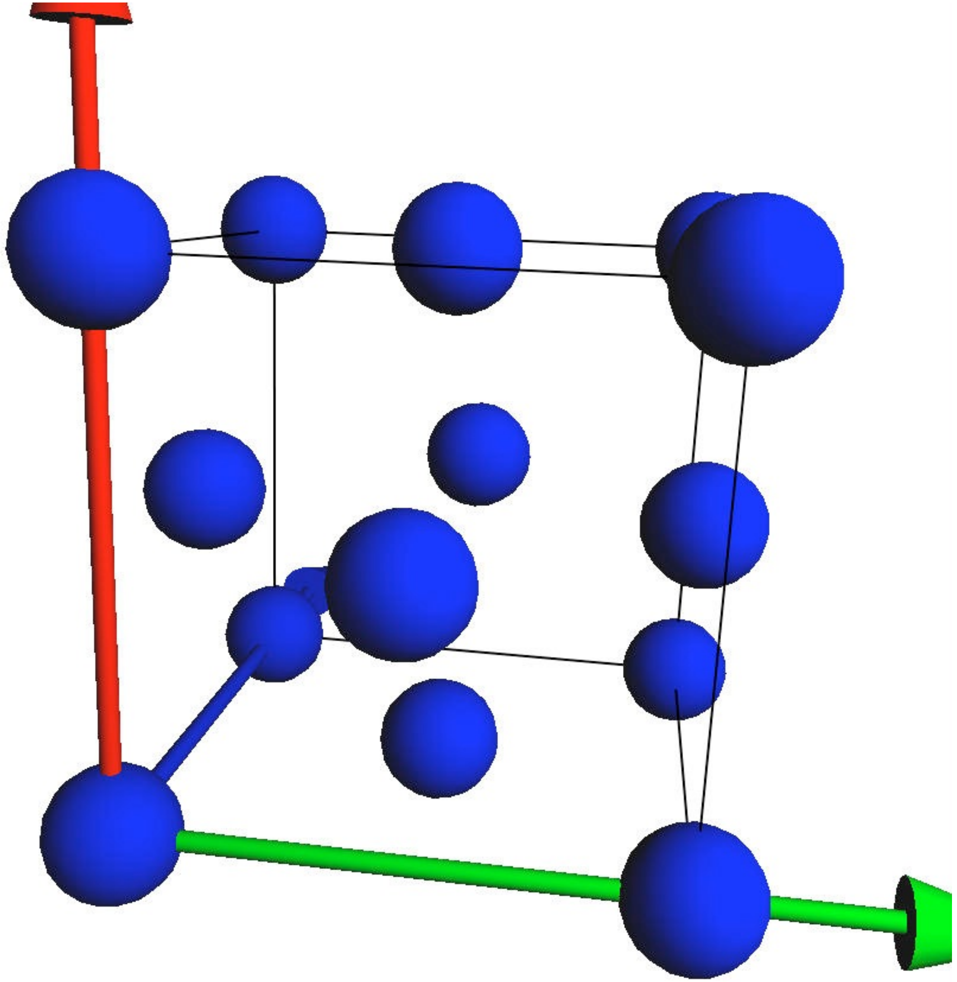



https://academic.oup.com/book/43705

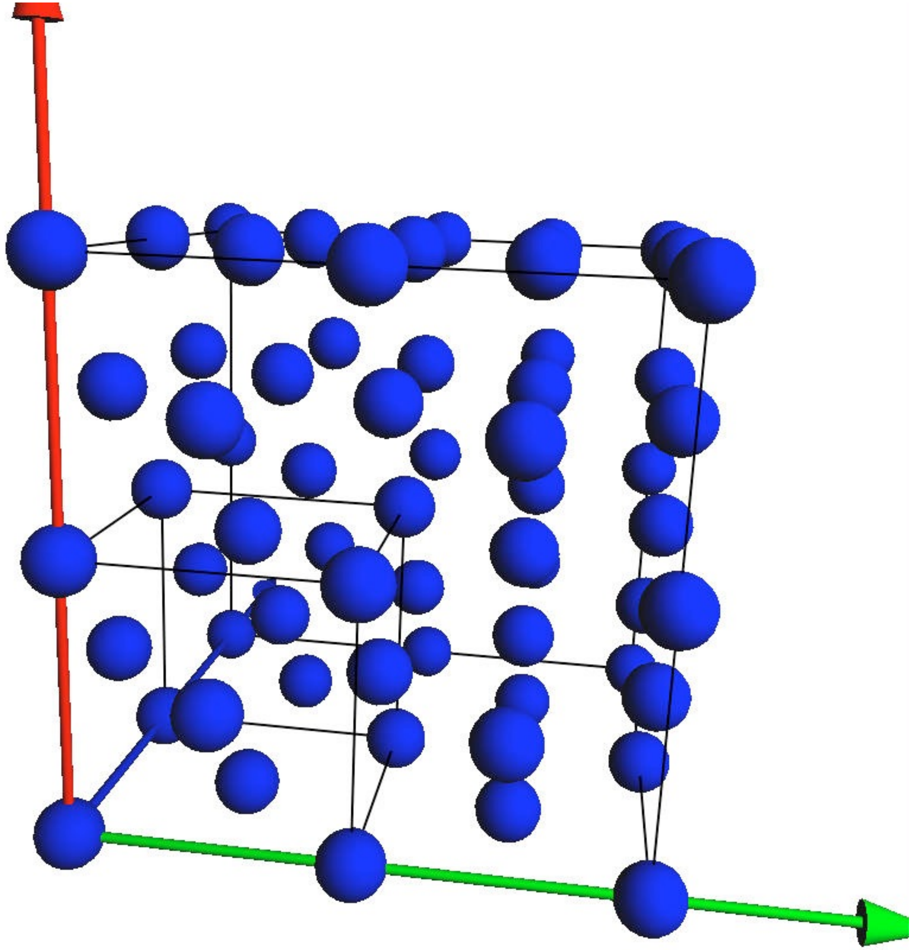
# Crystalline nature

- Crystals defined as atomic structures with translational periodicity & symmetry



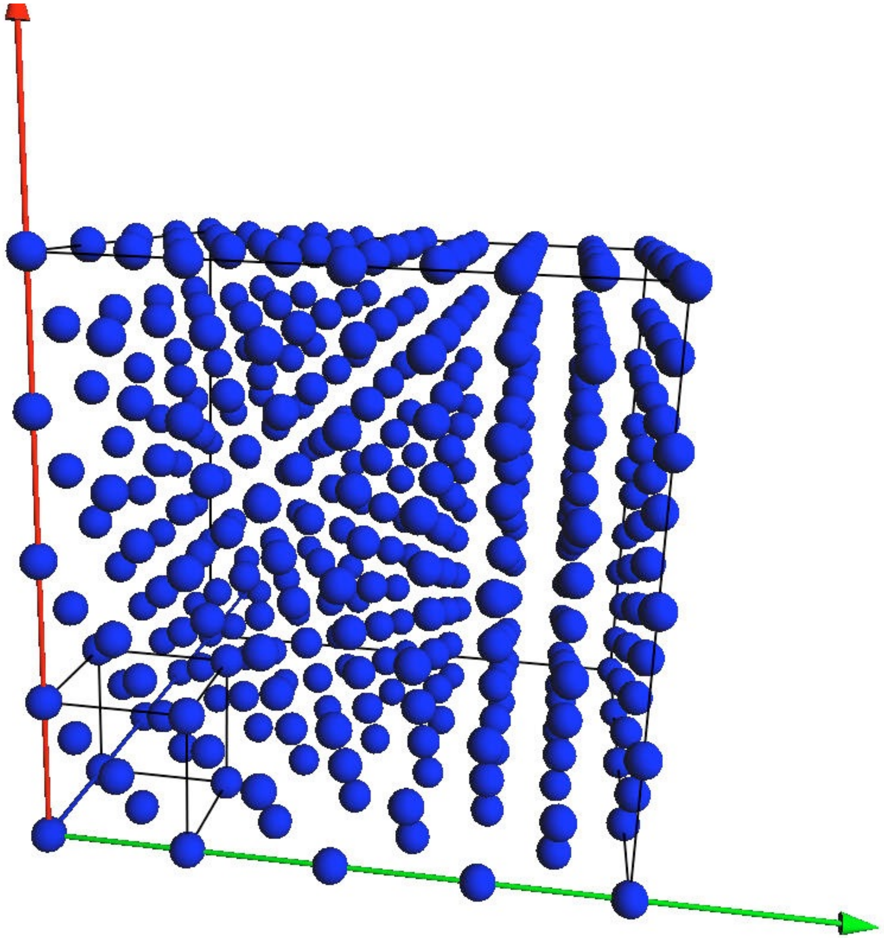
# Crystalline nature

- Crystals defined as atomic structures with translational periodicity & symmetry



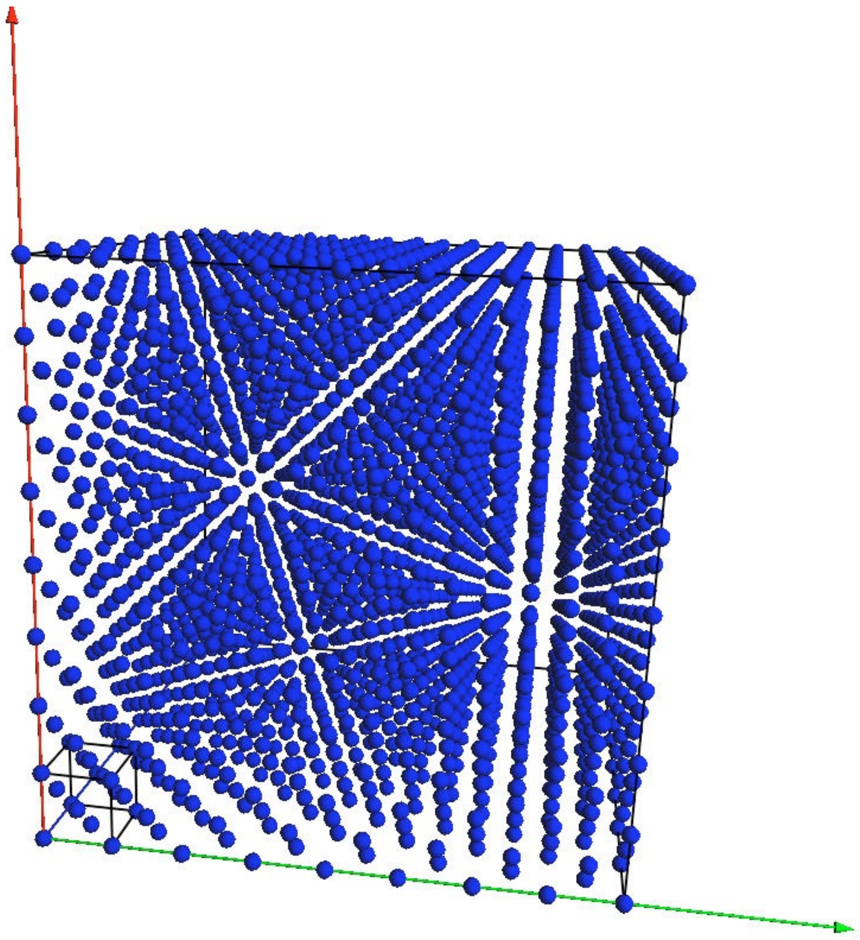
# Crystalline nature

- Crystals defined as atomic structures with translational periodicity & symmetry



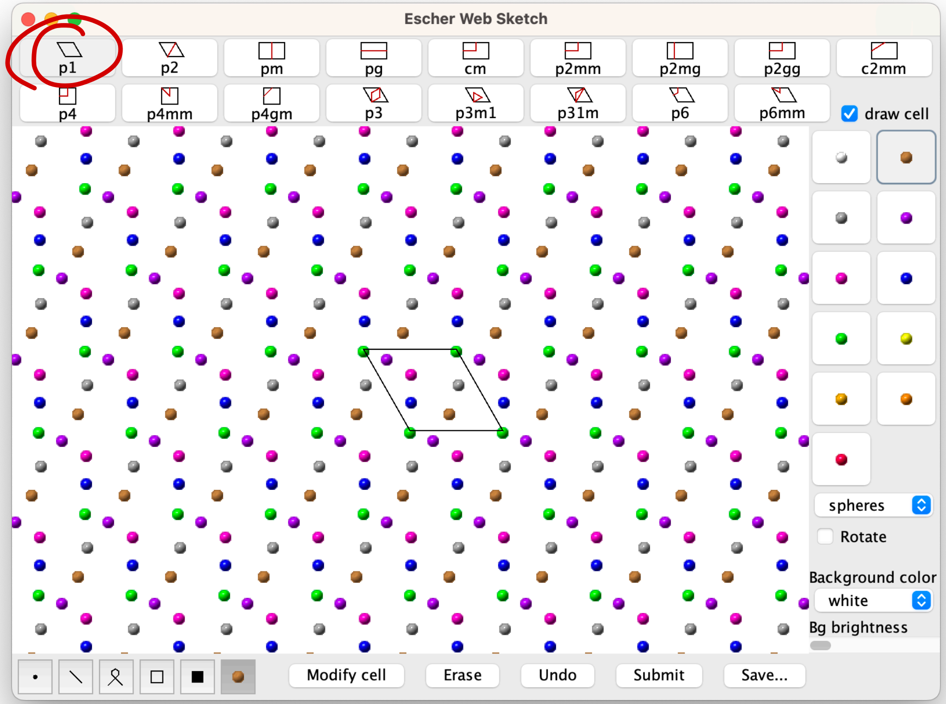
# Crystalline nature

- Crystals defined as atomic structures with translational periodicity & symmetry



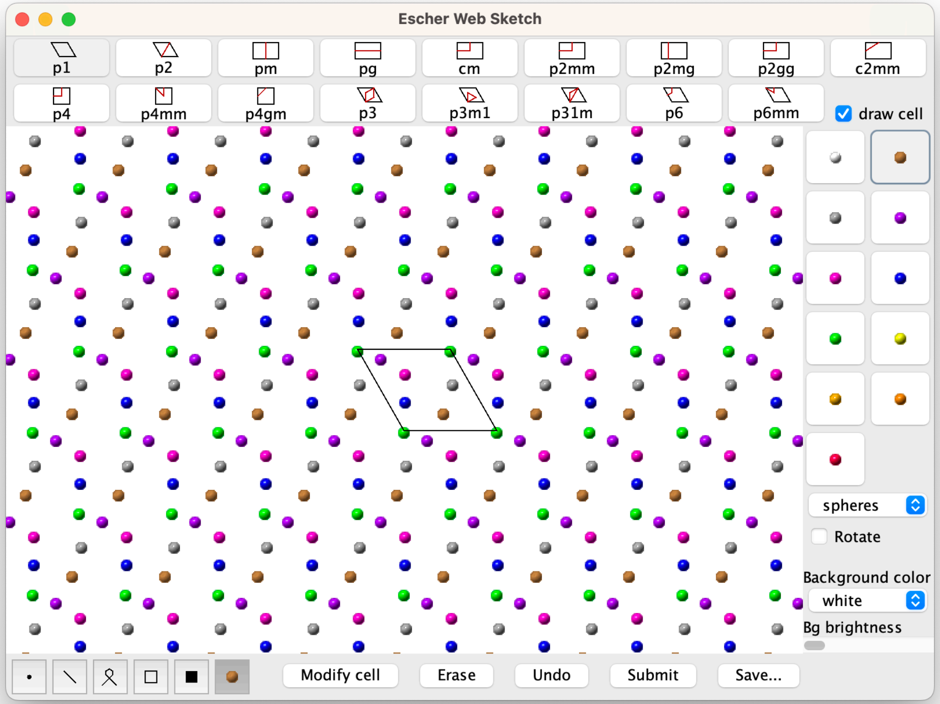
# Crystallography

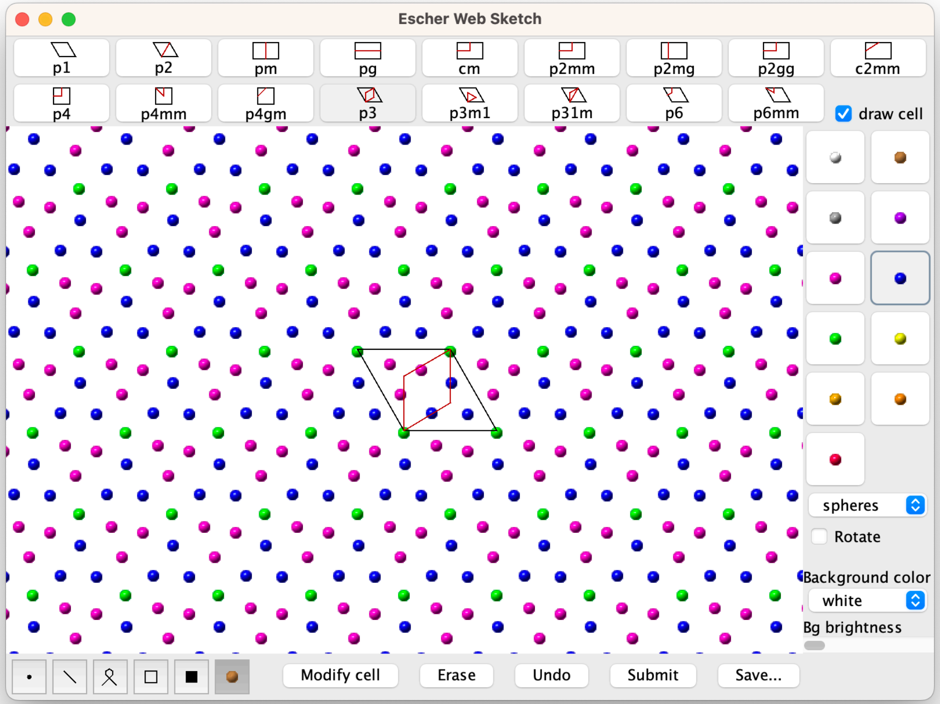
- Identify the (smallest) repeating pattern
- Determine the symmetries involved in repeating the pattern
- Java app for exploring symmetries in 2D: https://www.epfl.ch/schools/sb/research/iphys/teaching/crystallography/escher-web-sketch/



# Crystallography

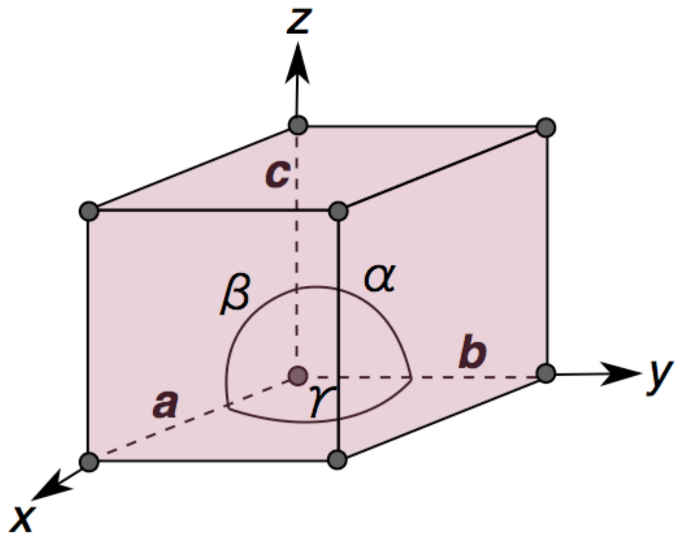
- Identify the (smallest) repeating pattern
- Determine the symmetries involved in repeating the pattern
- Java app for exploring symmetries in 2D: https://www.epfl.ch/schools/sb/research/iphys/teaching/crystallography/escher-web-sketch/



# Crystallography: the unit cell

- Unit cell is the (usually) smallest repeating unit of the crystal lattice
- Has a lattice point on each corner (and perhaps more elsewhere)
- Defined by:
  - lattice parameters $a, b, c$ along axes $x, y, z$
  - angles between crystallographic basis vectors: $\gamma = \mathbf{a} \angle \mathbf{b}$; $\alpha = \mathbf{b} \angle \mathbf{c}$; $\beta = \mathbf{a} \angle \mathbf{c}$




Cubic $a = b = c$

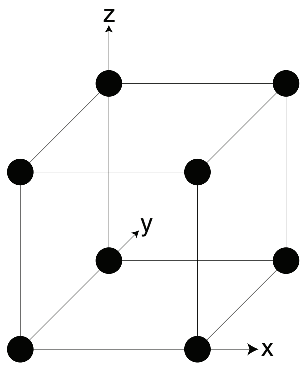
$\gamma = \alpha = \beta = 90^\circ$

Hexagonal : $a = b \neq c$ $\gamma = 120^\circ$

# Building a crystal structure

Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)



# Building a crystal structure

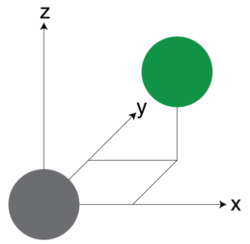
Use example of CuZn brass

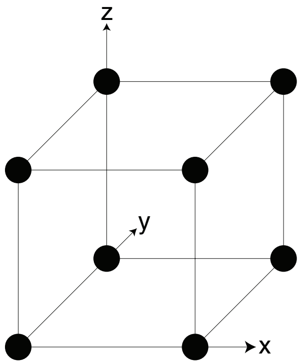
Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

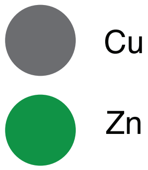
Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½ ← arrangement tied to each lattice point

× unit cell parameters

Motif:



# Building a crystal structure

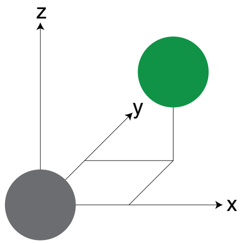
Use example of CuZn brass

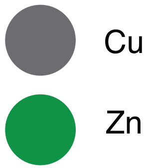
Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

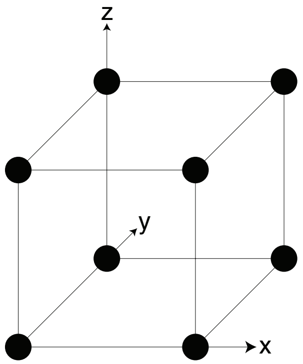
Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Motif:



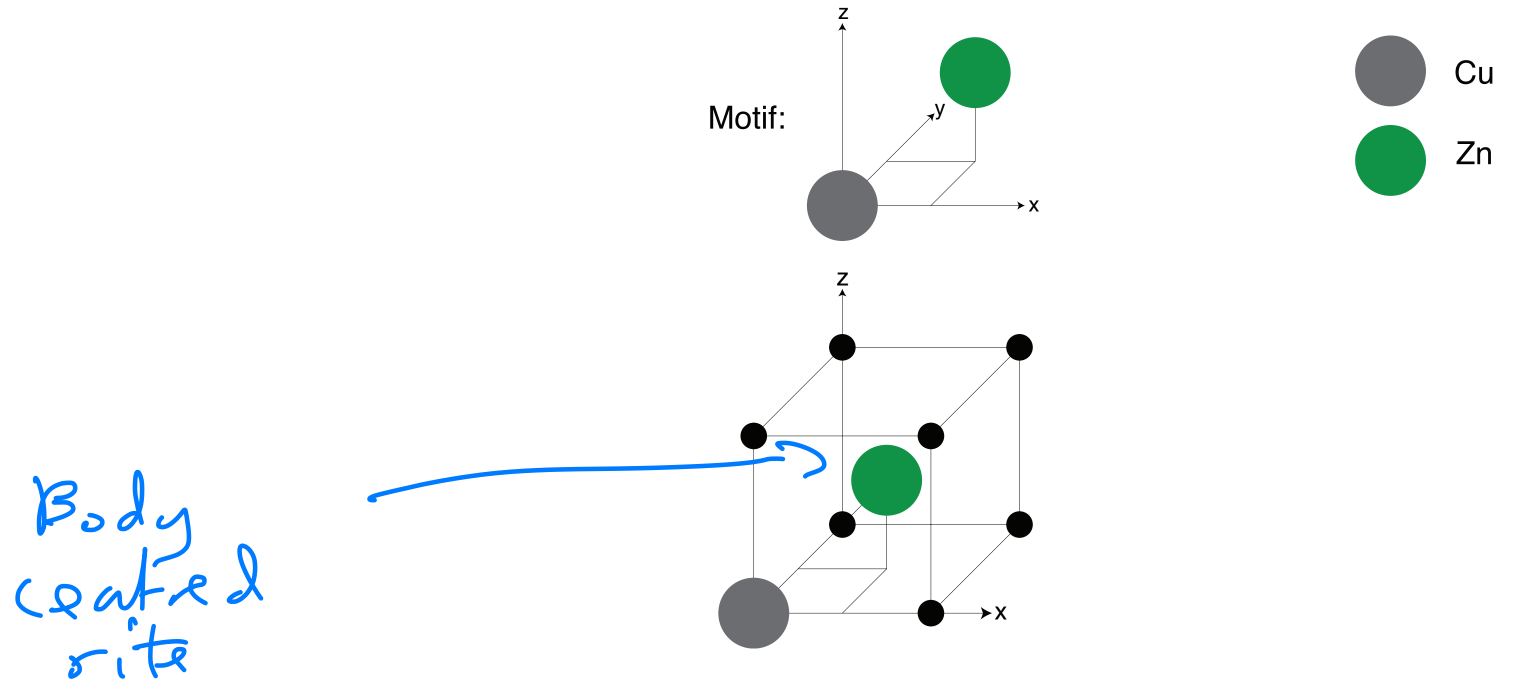
# Building a crystal structure

Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point



# Building a crystal structure

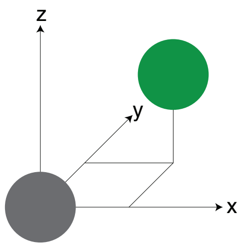
Use example of CuZn brass

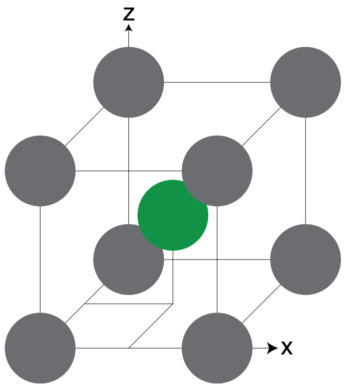
Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

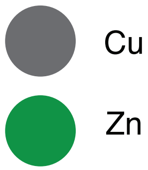
Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Motif:



# Building a crystal structure

Use example of CuZn brass

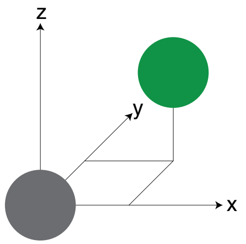
Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

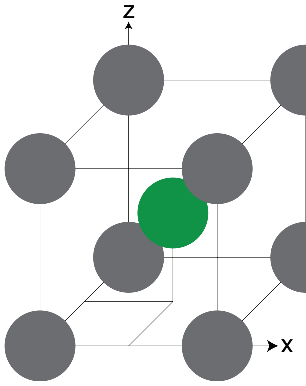
Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

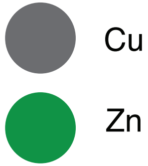
Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space

Motif:



# Building a crystal structure

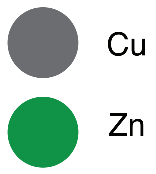
Use example of CuZn brass

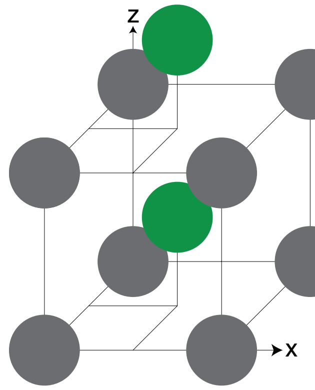
Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space



# Building a crystal structure

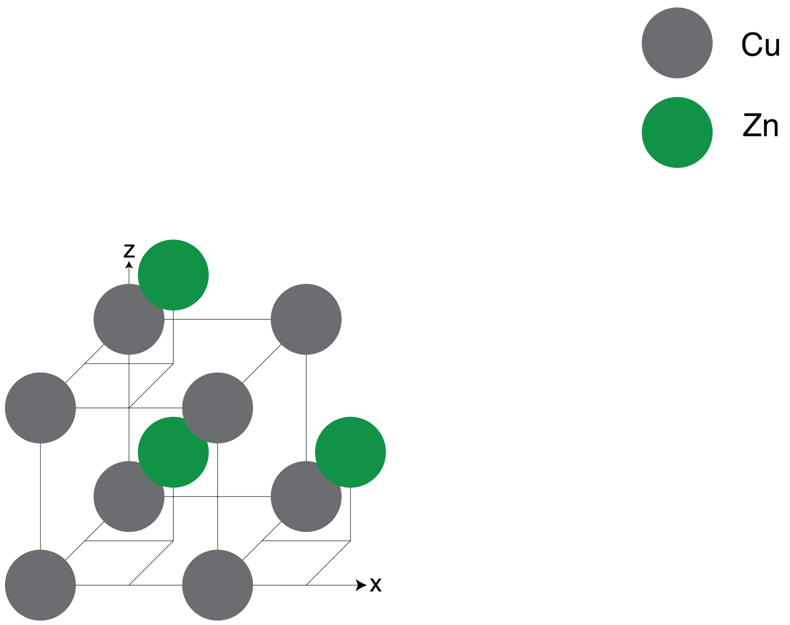
Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space



# Building a crystal structure

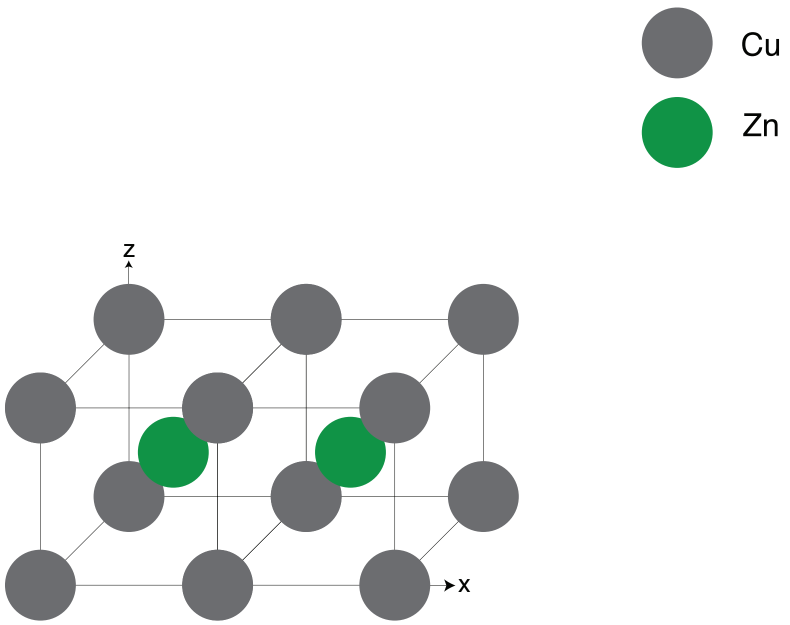
Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space



# Building a crystal structure

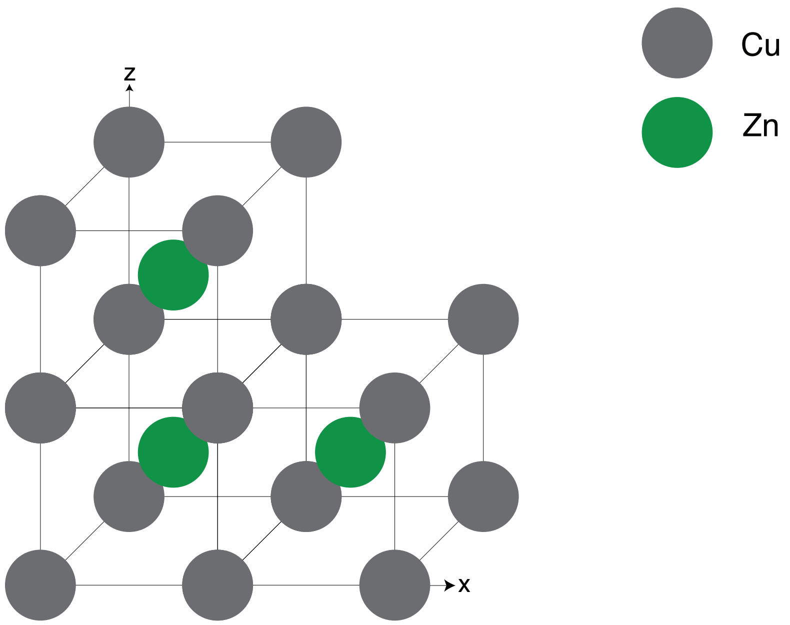
Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space



# Building a crystal structure

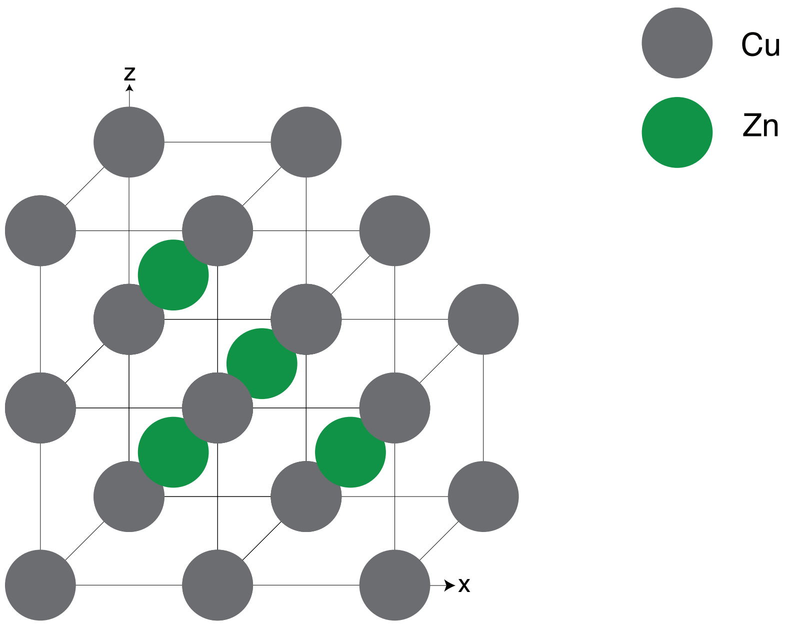
Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

Extend lattice further in to space



# Building a crystal structure

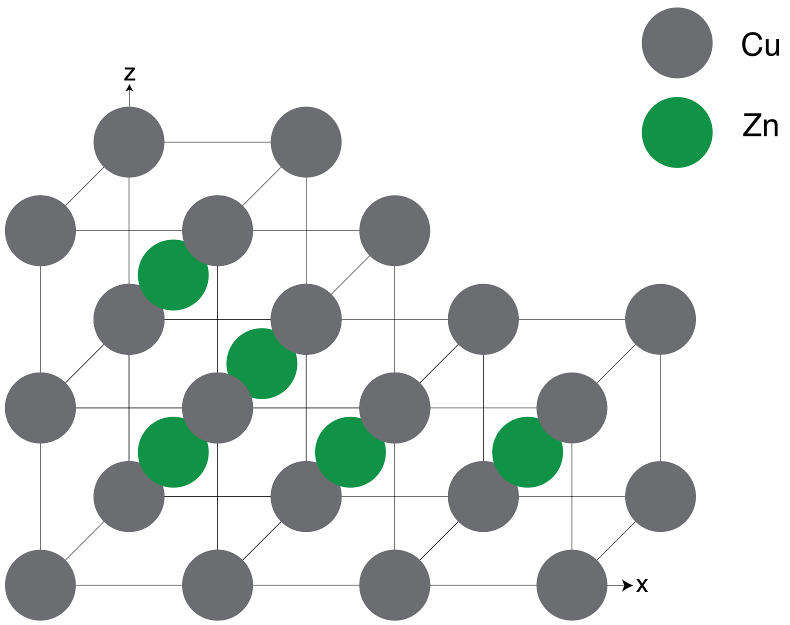
Use example of CuZn brass

Choose the unit cell - for CuZn: primitive cubic (lattice point on each corner)

Choose the motif – Cu: 0, 0, 0; Zn: ½,½,½

Structure = lattice +motif ⇒ Start applying motif to each lattice point

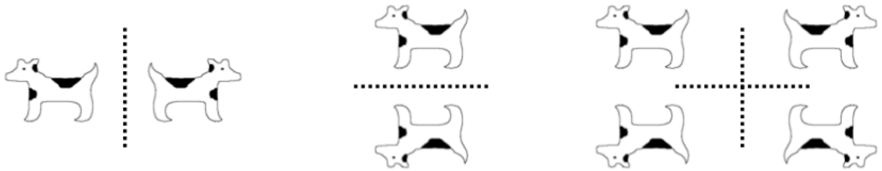
Extend lattice further in to space



# Symmetry elements

- As well as having translational symmetry, nearly all crystals obey other symmetries – i.e. can reflect or rotate structure without changing atom positions

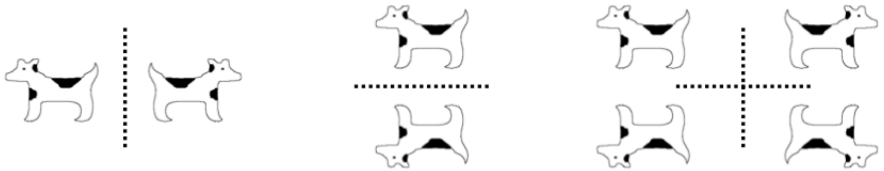
Mirror planes:



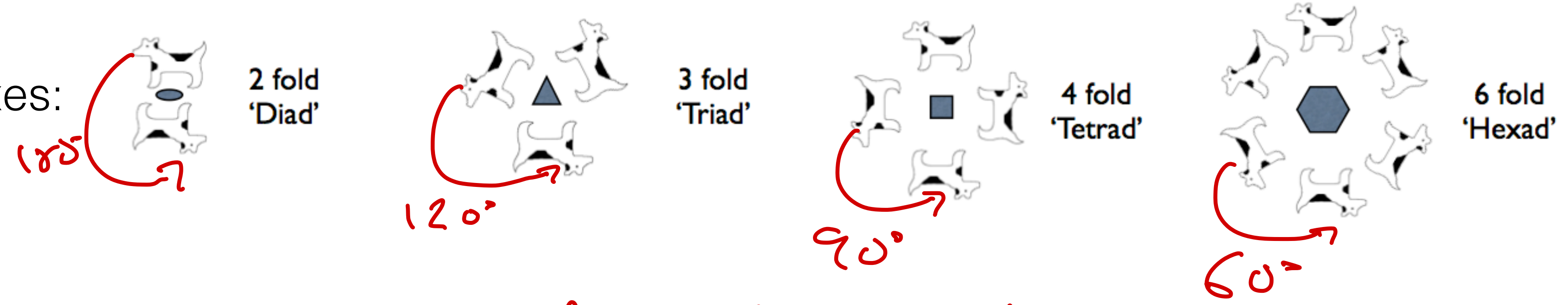
# Symmetry elements

- As well as having translational symmetry, nearly all crystals obey other symmetries – i.e. can reflect or rotate structure without changing atom positions

Mirror planes:



Rotation axes:



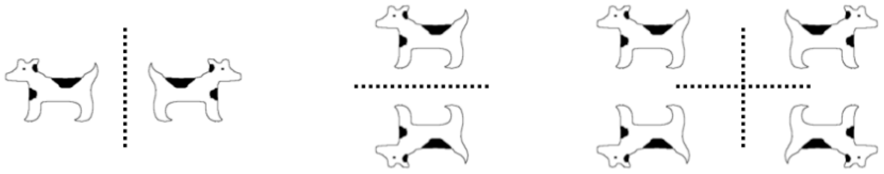

No 5-fold: no translational symmetry

↳ "Quasi crystals"

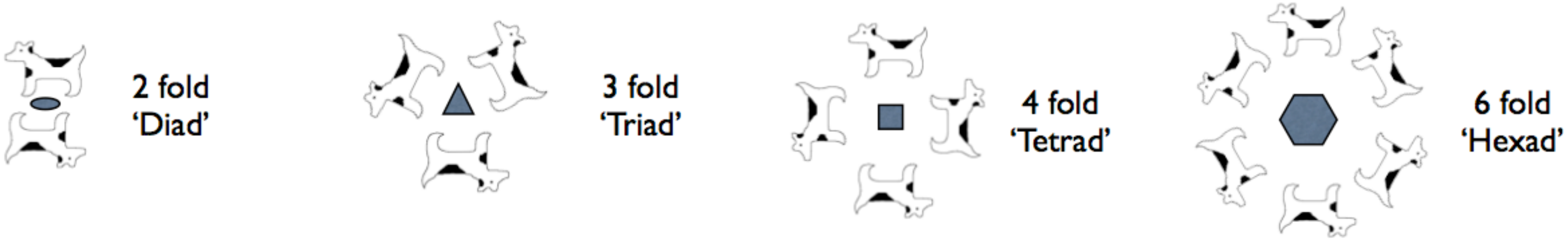
# Symmetry elements

- As well as having translational symmetry, nearly all crystals obey other symmetries – i.e. can reflect or rotate structure without changing atom positions

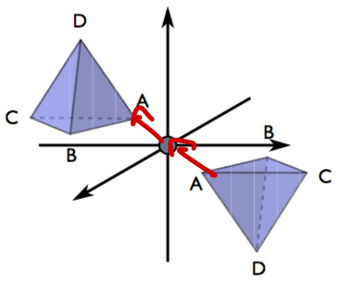
Mirror planes:



Rotation axes:




Centre of symmetry or inversion centre:

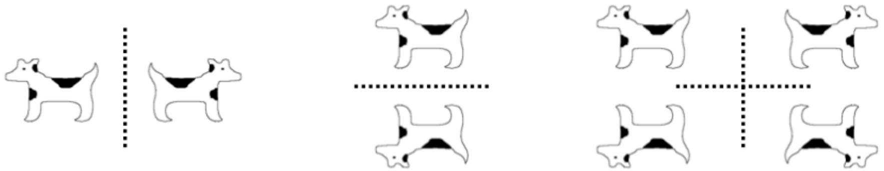



Invert through point

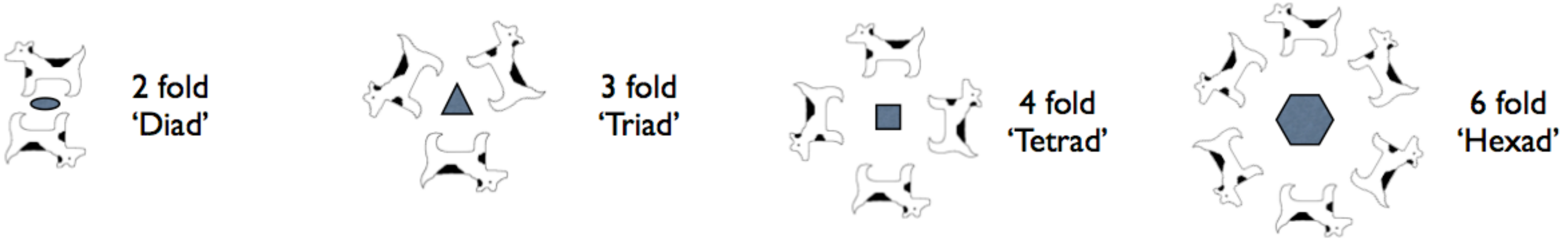
# Symmetry elements

- As well as having translational symmetry, nearly all crystals obey other symmetries – i.e. can reflect or rotate structure without changing atom positions

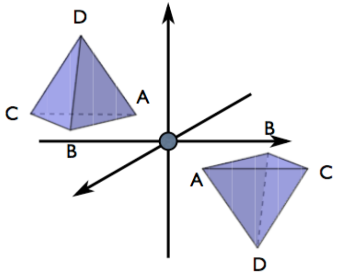
Mirror planes:



Rotation axes:




Centre of symmetry or inversion centre:

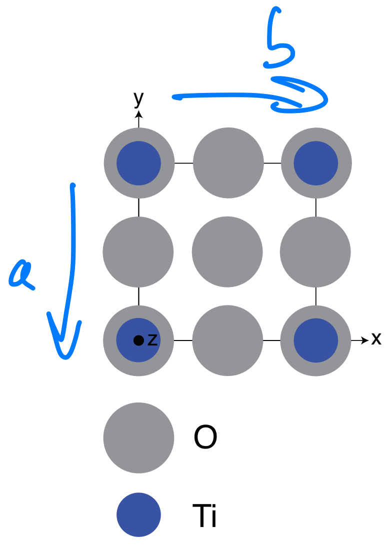



Inversion axes: combination of rotation axis with centre of symmetry

# Symmetry elements

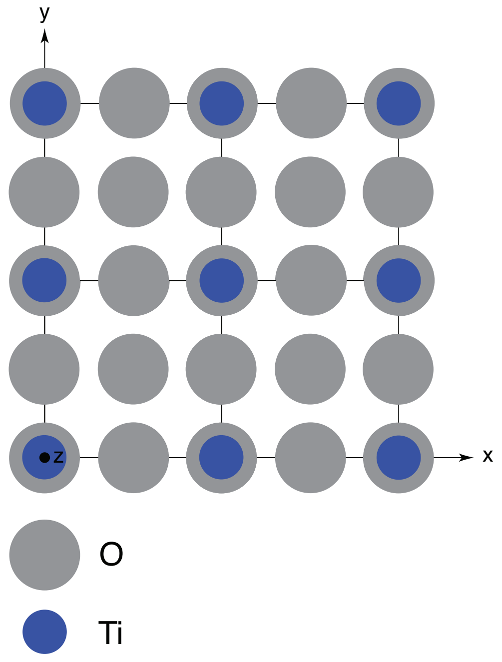
- Example – tetragonal lattice:
  $a = b \neq c$; $\alpha = \beta = \gamma = 90°$

- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):



# Symmetry elements

- Example – tetragonal lattice:
  $a = b \neq c; \alpha = \beta = \gamma = 90°$
- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):



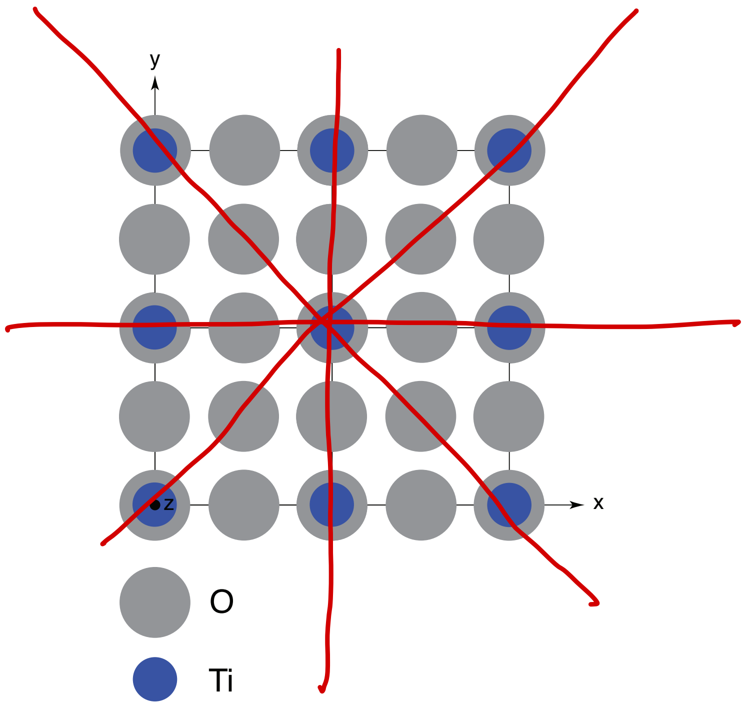
# Symmetry elements

- Example – tetragonal lattice:
  $a = b \neq c$; $\alpha = \beta = \gamma = 90°$

- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):

Identify mirror planes

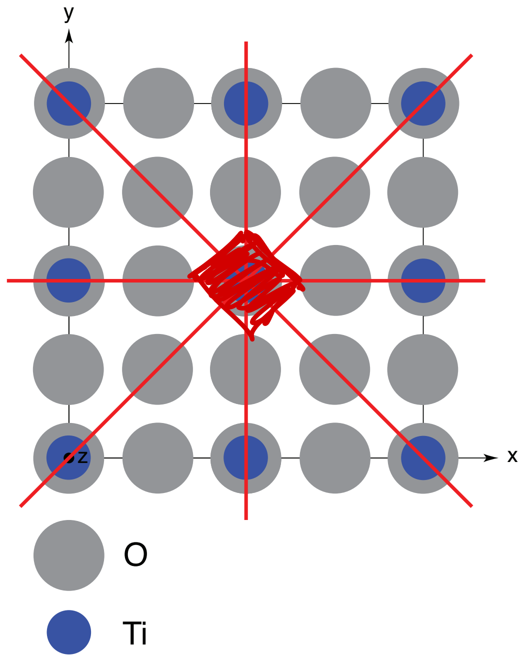
Identify rotation axis



# Symmetry elements

- Example – tetragonal lattice:
  $a = b \neq c;\ \alpha = \beta = \gamma = 90^\circ$

- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):

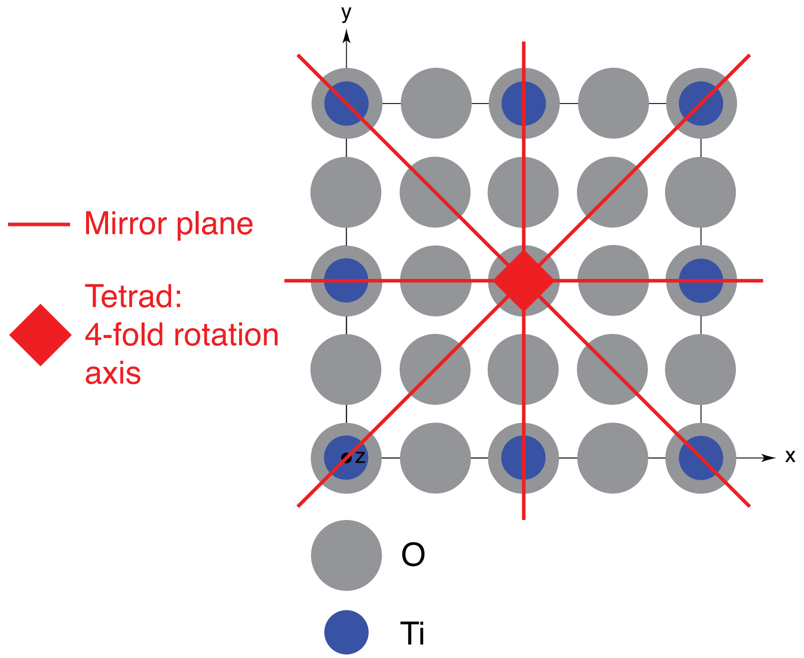



Identify mirror planes

Identify rotation axis 4-fold "tetrad"

# Symmetry elements

- Example – tetragonal lattice:
  $a = b \neq c; \alpha = \beta = \gamma = 90°$
- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):

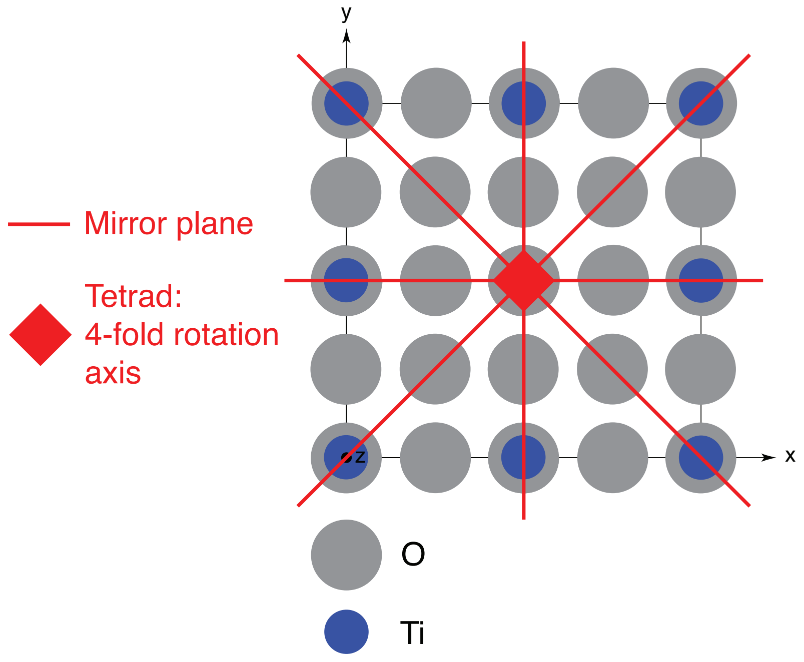



Identify mirror planes

Identify rotation axis

# Symmetry elements

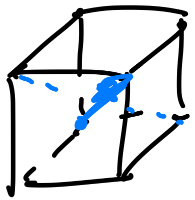
- Example – tetragonal lattice:
  $a = b \neq c;\ \alpha = \beta = \gamma = 90°$
- Anatase $TiO_2$ (body-centred lattice) view down [0 0 1] ($z$-axis):



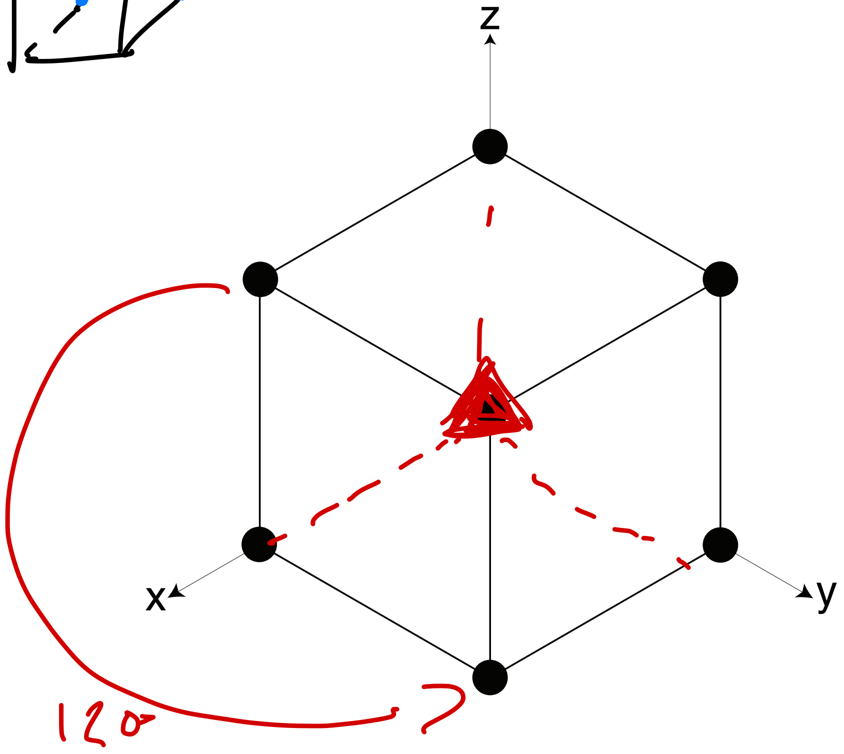

Identify mirror planes

Identify rotation axis: 4-fold = defining symmetry of tetragonal lattice!

# More defining symmetry elements



- Cubic crystal system:
  $a = b = c$; $\alpha = \beta = \gamma = 90°$
- View down body diagonal (i.e. [1 1 1] axis)
- Choose Primitive cell
  (lattice point on each corner)



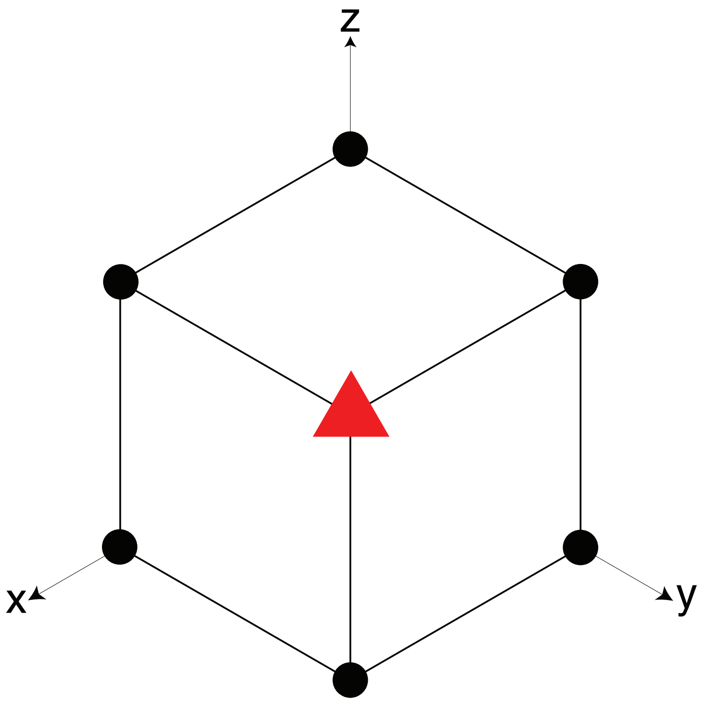

Identify rotation axis:

3-fold axis
(Triad)

# More defining symmetry elements

- Cubic crystal system:
  $a = b = c; \alpha = \beta = \gamma = 90°$
- View down body diagonal (i.e. [1 1 1] axis)
- Choose Primitive cell
  (lattice point on each corner)

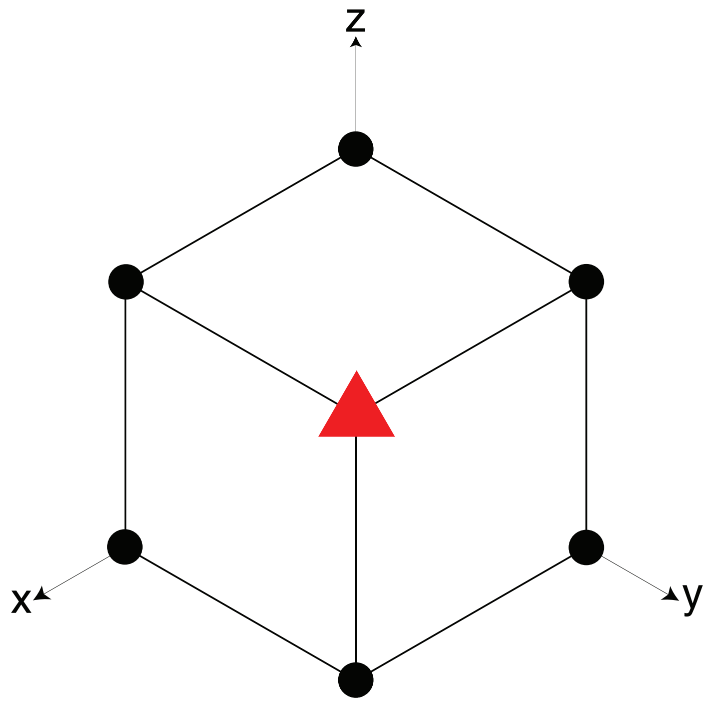
Identify rotation axis:



# More defining symmetry elements

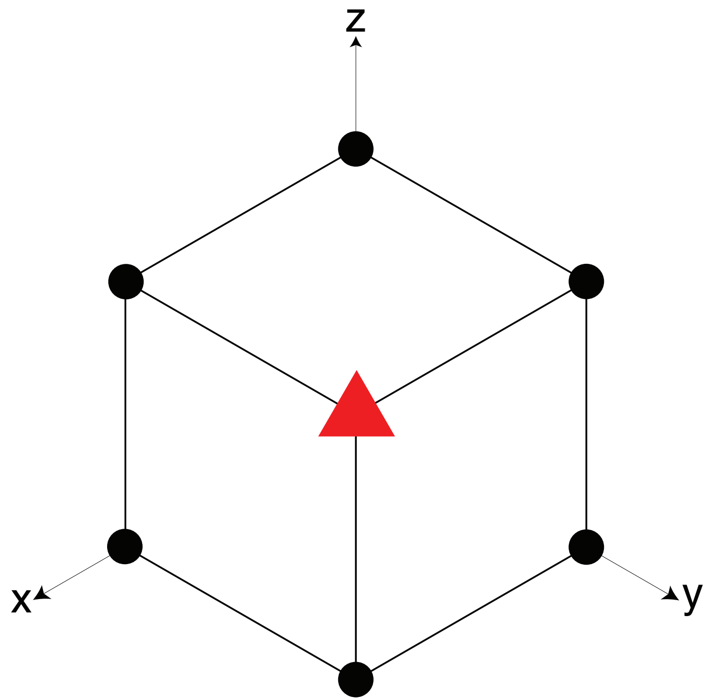
- Cubic crystal system:
  $a = b = c;\ \alpha = \beta = \gamma = 90°$
- View down body diagonal (i.e. [1 1 1] axis)
- Choose Primitive cell
  (lattice point on each corner)

Identify rotation axis: 3-fold (triad)



# More defining symmetry elements

- Cubic crystal system:
  $a = b = c; \alpha = \beta = \gamma = 90°$
- View down body diagonal (i.e. [1 1 1] axis)
- Choose Primitive cell
  (lattice point on each corner)

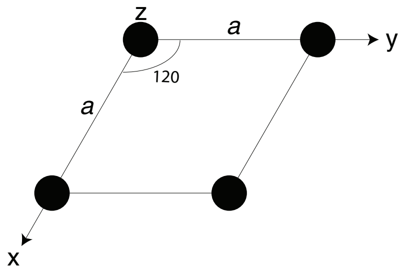



Identify rotation axis: 3-fold (triad)

Defining symmetry of cube: four 3-fold rotation axes (not 4-fold rotation axes!)

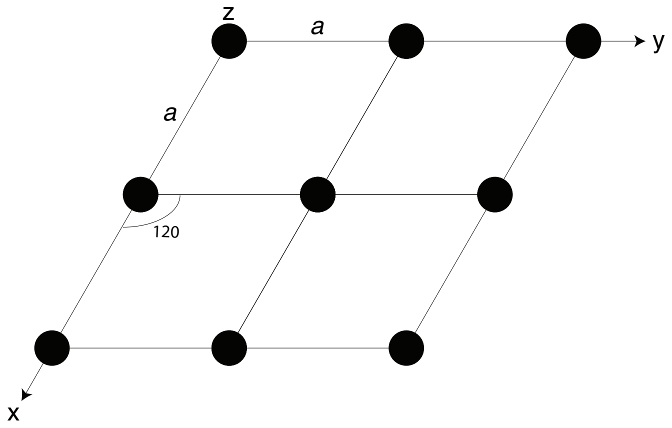
# More defining symmetry elements

- Hexagonal crystal system:
  $a = b \neq c$;
  $\alpha = \beta = 90°, \gamma = 120°$
- Primitive cell, lattice points on each corner; view down $z$-axis – i.e. [0 0 1]



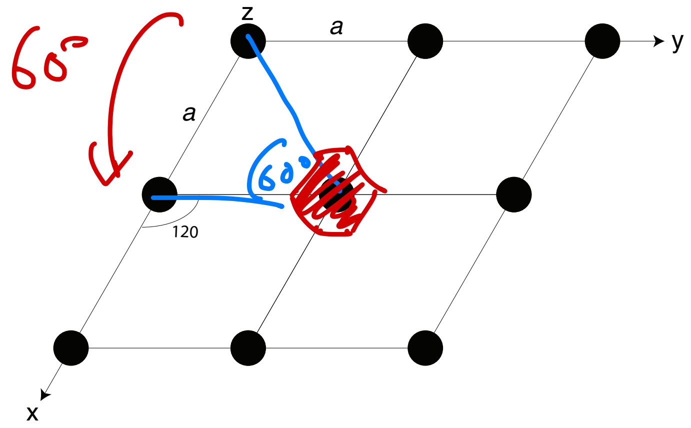
# More defining symmetry elements

- Hexagonal crystal system:
  $a = b \neq c$;
  $\alpha = \beta = 90°, \gamma = 120°$
- Primitive cell, lattice points on each corner; view down $z$-axis – i.e. [0 0 1]
- Draw 2 x 2 unit cells



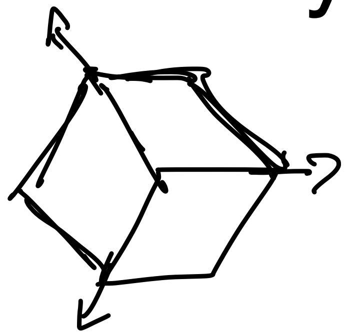
# More defining symmetry elements

- Hexagonal crystal system:
  $a = b \neq c$;
  $\alpha = \beta = 90°, \gamma = 120°$
- Primitive cell, lattice points on each corner; view down $z$-axis – i.e. [0 0 1]
- Draw 2 x 2 unit cells

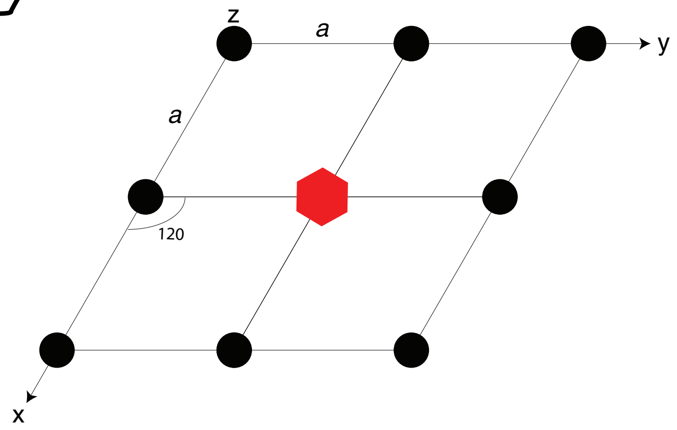



Identify rotation axis: 6-fold (Hexad)

# More defining symmetry elements



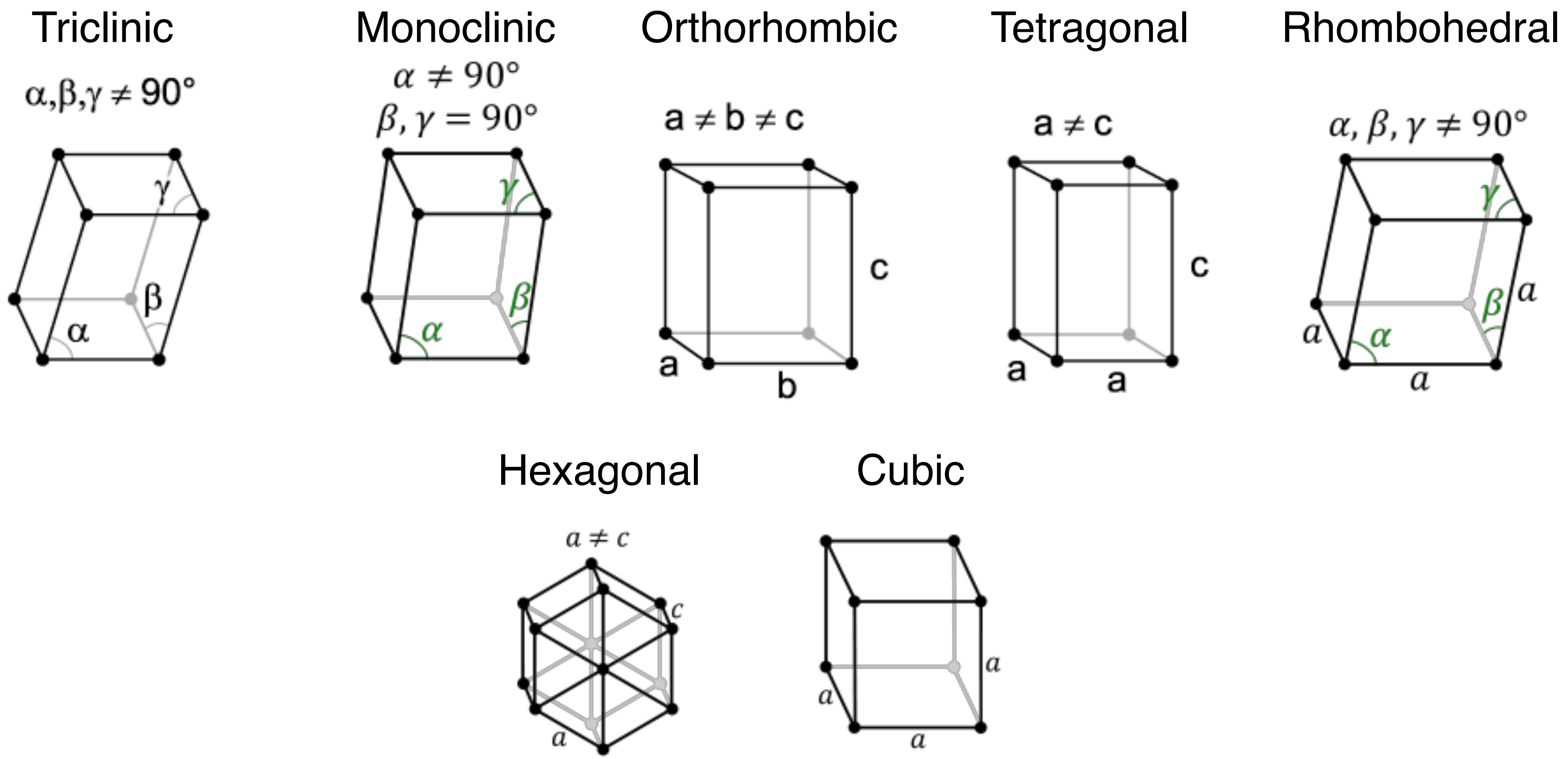
- Hexagonal crystal system:
  $a = b \neq c$;
  $\alpha = \beta = 90°, \gamma = 120°$
- Primitive cell, lattice points on each corner; view down $z$-axis – i.e. [0 0 1]
- Draw 2 x 2 unit cells




Identify rotation axis: 6-fold (hexad) – defining symmetry of hexagonal lattice

# The seven crystal systems

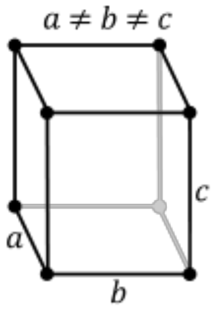
- 7 possible unit cell shapes with different symmetries that can be repeated by translation in 3 dimensions
  ⇒ 7 crystal systems each defined by symmetry



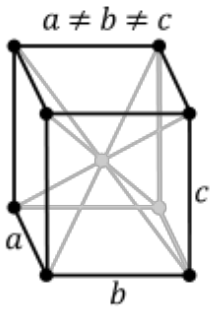

Diagrams from www.Wikipedia.org

# Four possible lattice centerings

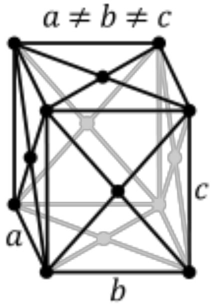
P: Primitive - lattice points on cell corners



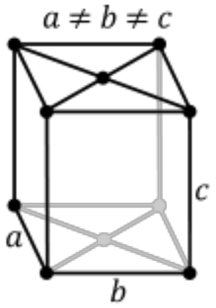

I: Body-centred - additional lattice point at cell centre




F: Face-centred - one additional lattice point at centre of each face



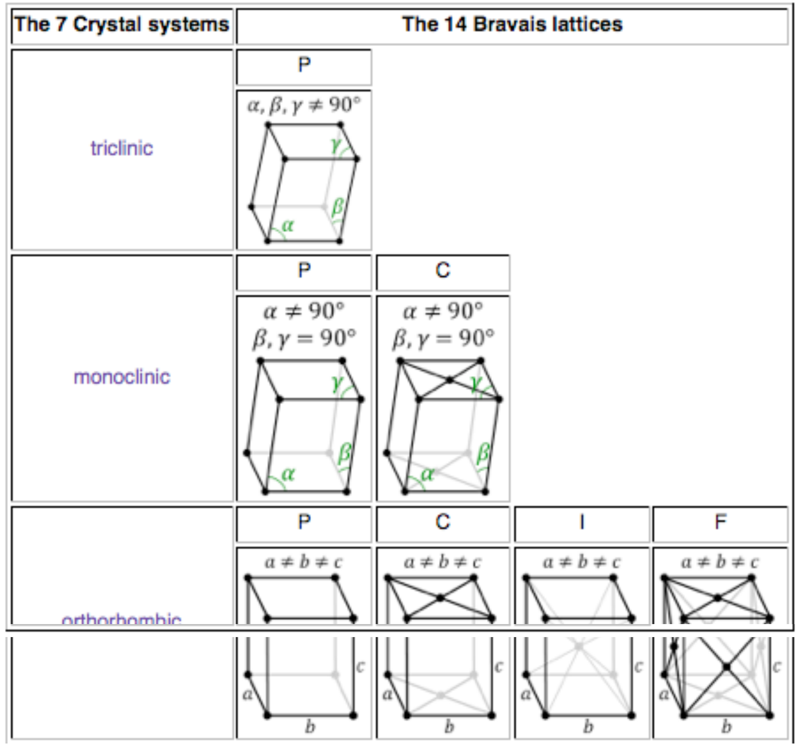

A/B/C: Centred on a single face - one additional lattice point centred on A, B or C face

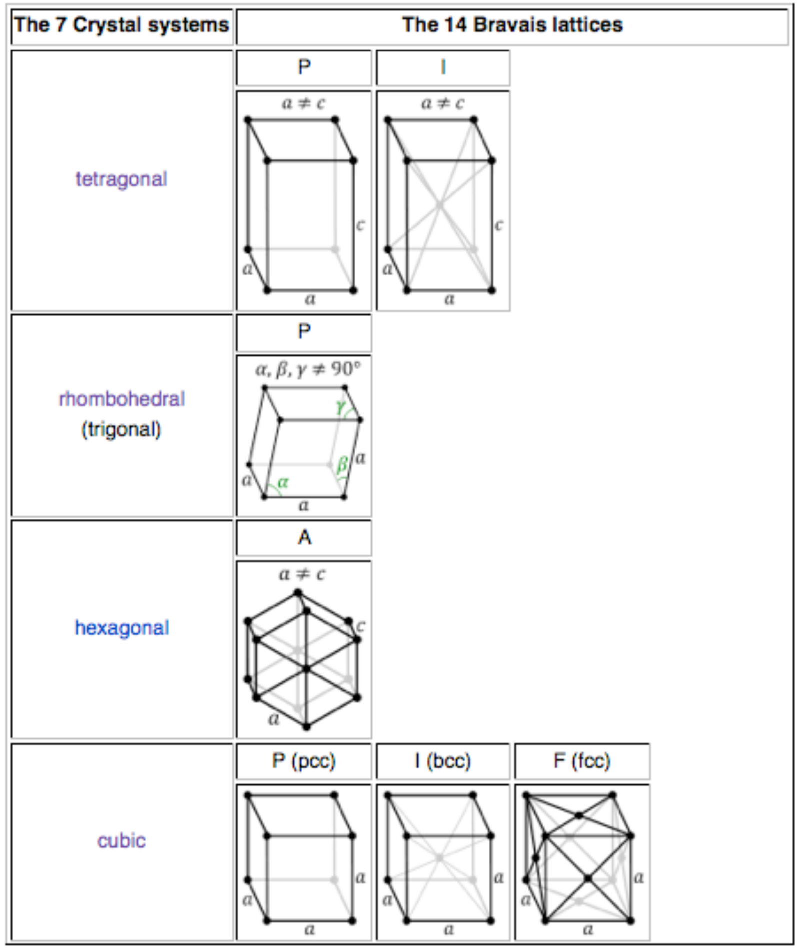



Diagrams from www.Wikipedia.org

# 14 Bravais lattices

- Combinations of crystal systems and lattice point centering that describe all possible crystals – equivalent system/centring combinations eliminated ⇒ 14 (not 7 x 4 = 28)




Tetragonal body centered = face centered

Diagrams from www.Wikipedia.org

# 14 Bravais lattices

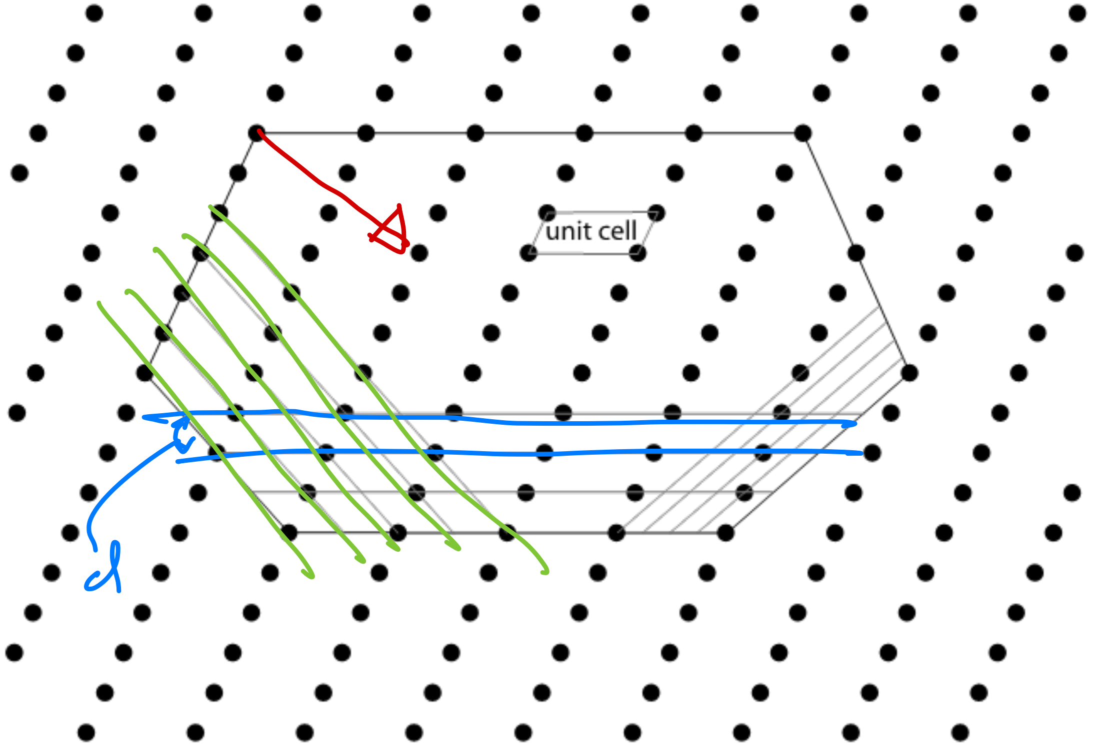
I: body-centered
F: face-centered

| Crystal System | Defining Symmetry (rotation or inversion) | Conventional Unit Cell | Conventional Lattice Types |
|---|---|---|---|
| Cubic | 4 triads | $a = b = c$<br>$\alpha = \beta = \gamma = 90^\circ$ | P, I, F |
| Hexagonal | 1 hexad | $a = b \neq c$<br>$\alpha = \beta = 90^\circ, \gamma = 120^\circ$ | P |
| Trigonal | 1 triad | $a = b \neq c$<br>$\alpha = \beta = 90^\circ, \gamma = 120^\circ$ | P, R |
| Tetragonal | 1 tetrad | $a = b \neq c$<br>$\alpha = \beta = \gamma = 90^\circ$ | P, I |
| Orthorhombic | 3 diads | $a \neq b \neq c$<br>$\alpha = \beta = \gamma = 90^\circ$ | P, C, I, F |
| Monoclinic | 1 diad | $a \neq b \neq c$<br>$\alpha = \gamma = 90^\circ, \beta \geq 90^\circ$ | P, C |
| Triclinic | - | $a \neq b \neq c$<br>$\alpha \neq \beta \neq \gamma$ | P |

- Combine crystal systems and lattice types with different compatible symmetry element combinations ⇒ 230 space groups

# Crystal lattice planes and vectors

- In 2D, we can draw families of lines parallel to each other, containing the same linear arrangement of atoms
- In 3D these are called **lattice planes**
- Lattice planes are defined using **Miller indices**
- We can also define vectorial directions – how do we label these?

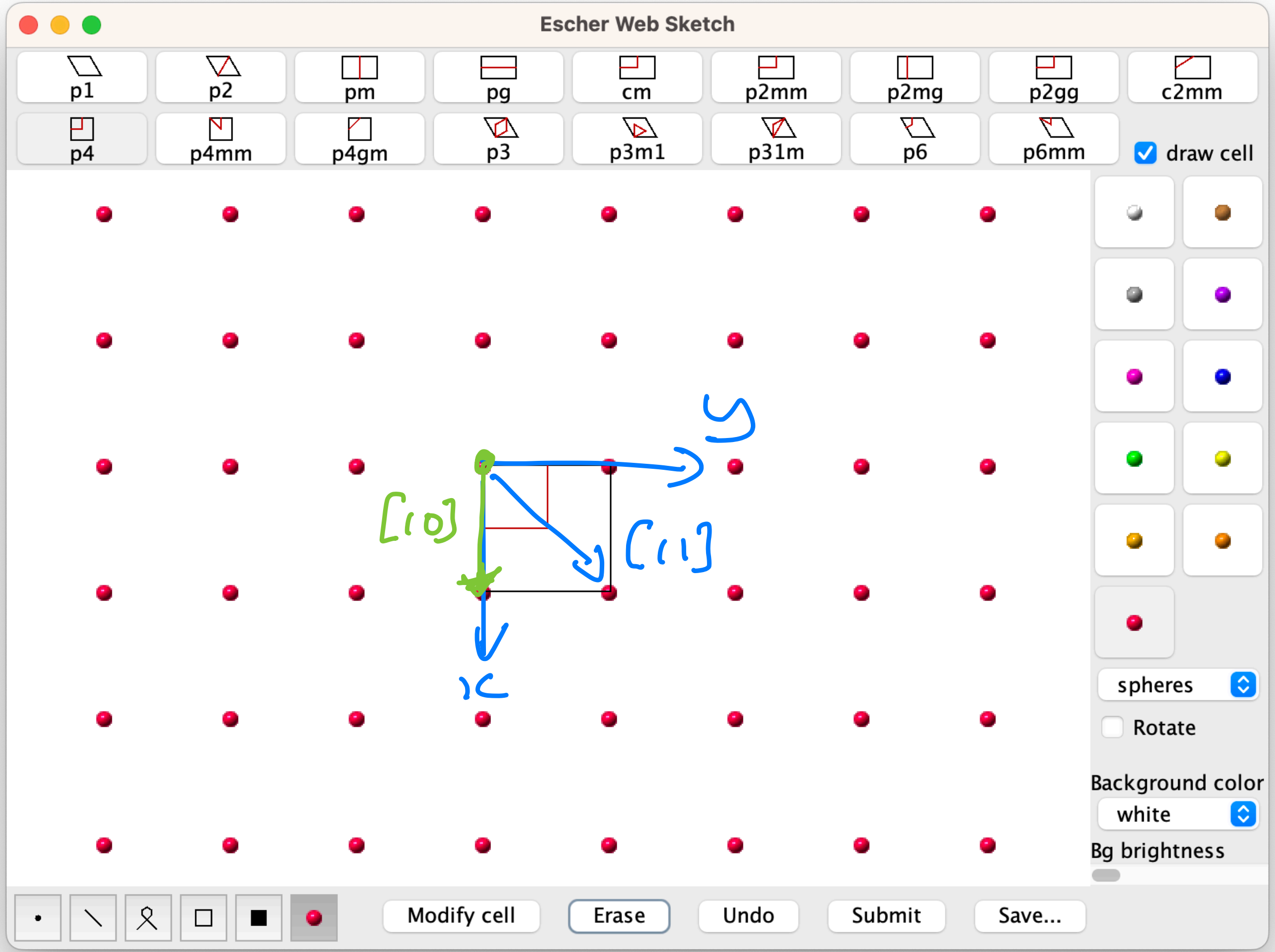


# Lattice vectors

- Lattice vector: a vector joining any two lattice points
- Written as linear combination of unit cell vectors $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$:
  $\mathbf{t} = U\mathbf{a} + V\mathbf{b} + W\mathbf{c}$
- Write in square brackets: $\mathbf{t} = [U\ V\ W]$

# Lattice vectors (2D)

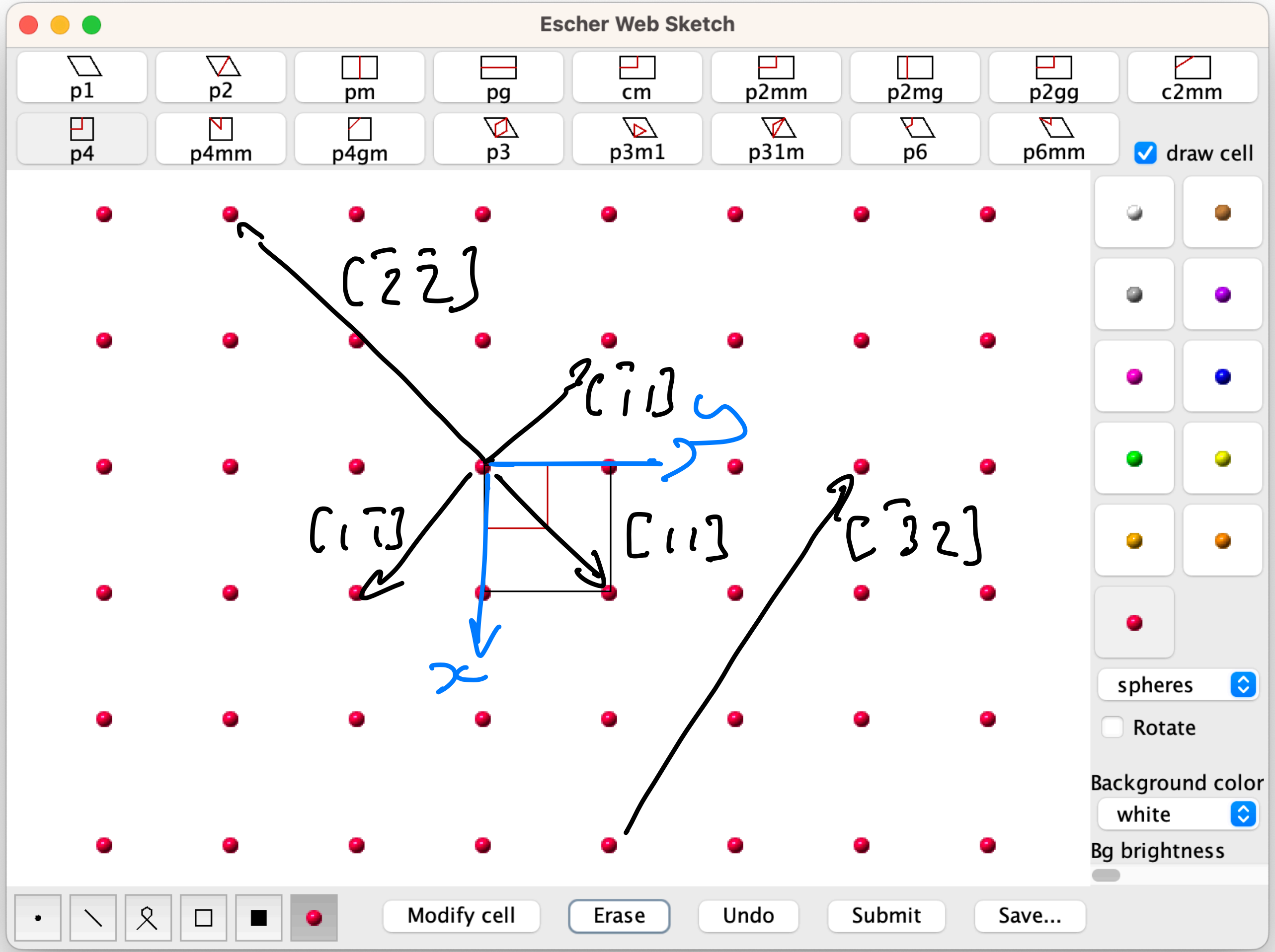
- For 2D lattice on right, draw lattice vectors:
  - Parallel to $[1\ 0]$
  - On the diagonal $[1\ 1]$



# Lattice vectors (2D)

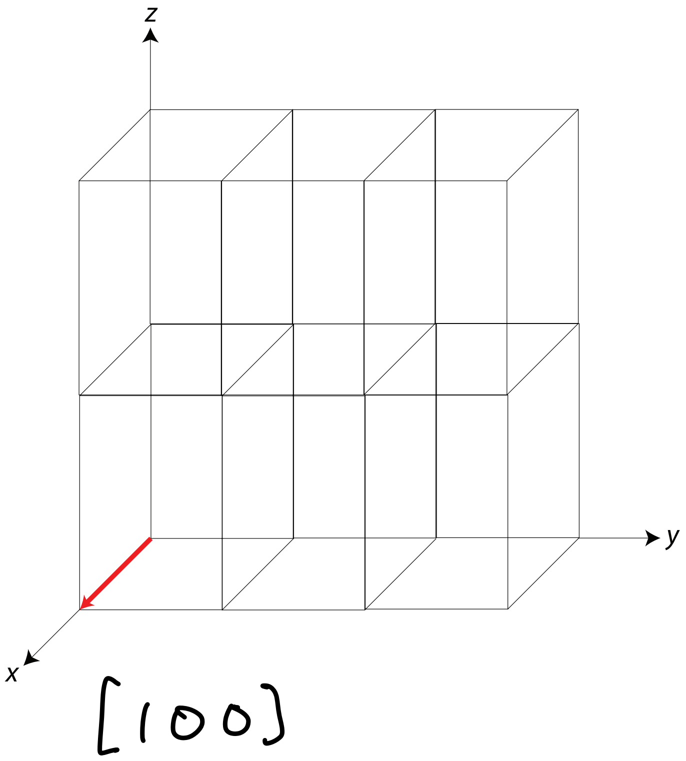
- Now draw:
  - [1 1]
  - [1 $\bar{1}$]
  - [$\bar{1}$ 1]
  - [$\bar{3}$ 2]
  - [$\bar{2}$ $\bar{2}$]

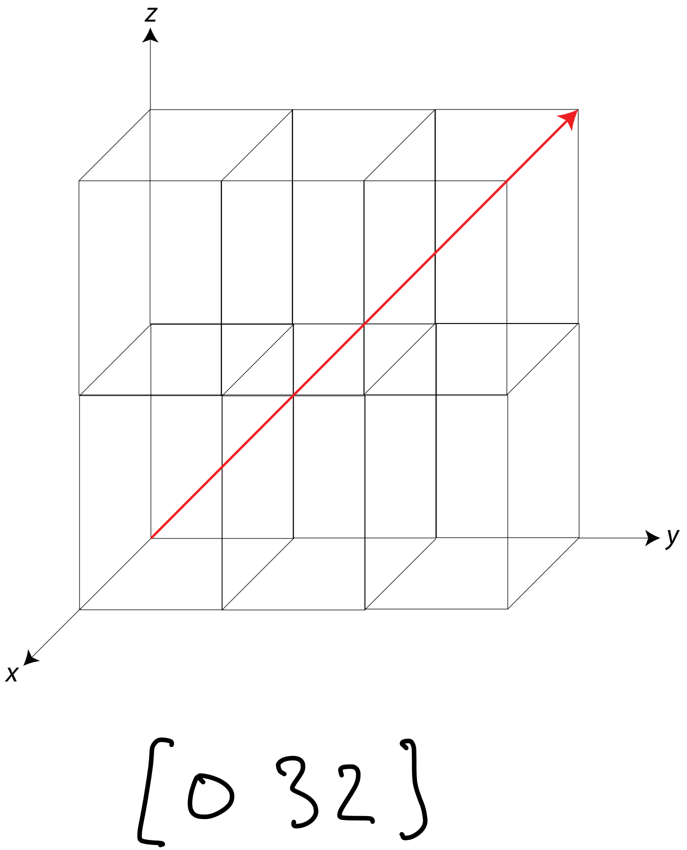
**Families of similar directions are given in angular brackets**
$< U\ V\ W >$

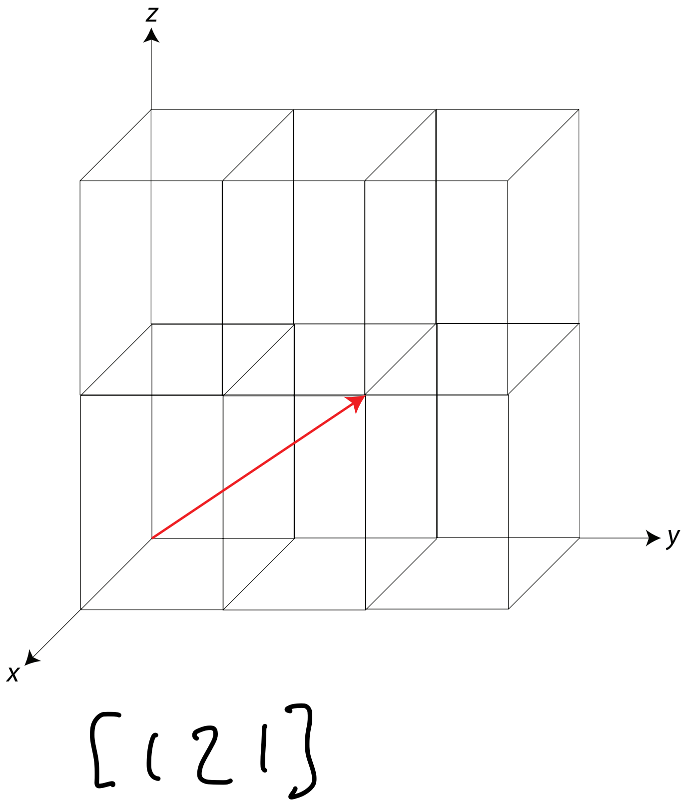


# EPFL Lattice vectors (3D)

- Now look at examples in 3D:



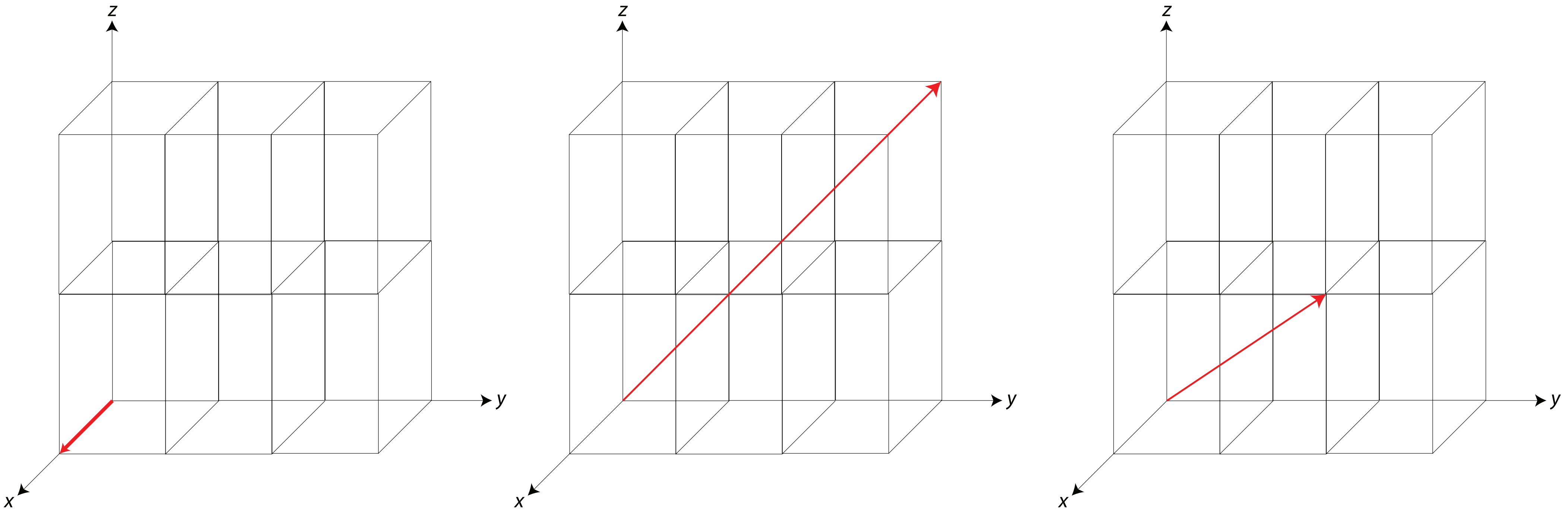
# Lattice vectors (3D)

[100]

<100> – family of dir$^{n}$s

e.g. cubic ↳ [100], [010], [001], $[\bar{1}00]$, $[0\bar{1}0]$, $[00\bar{1}]$

- Now look at examples in 3D:

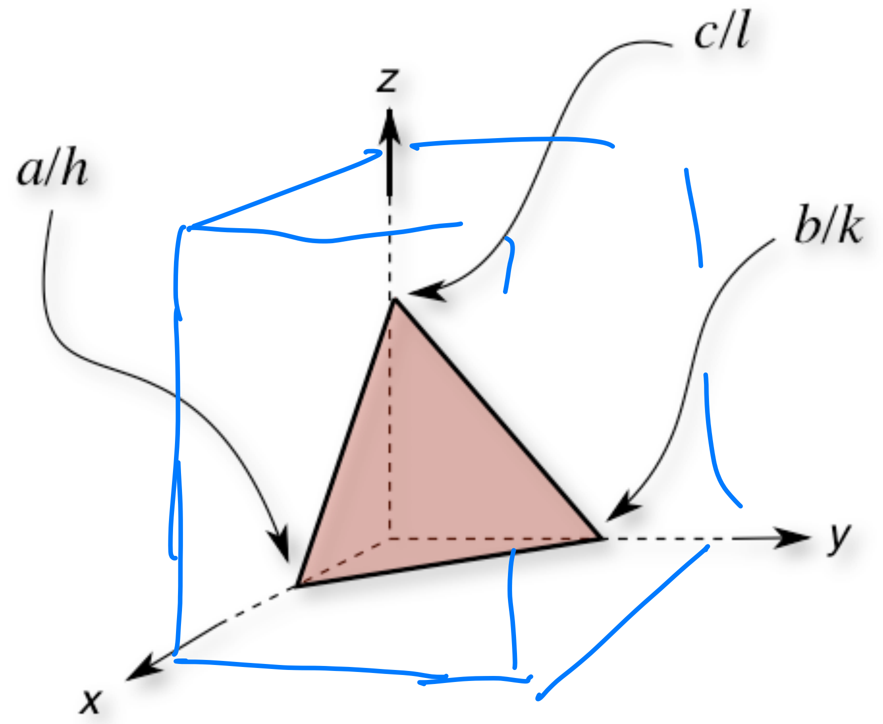



Important in TEM diffraction because we "look" down the lattice vectors ("zone axes")

# Lattice planes

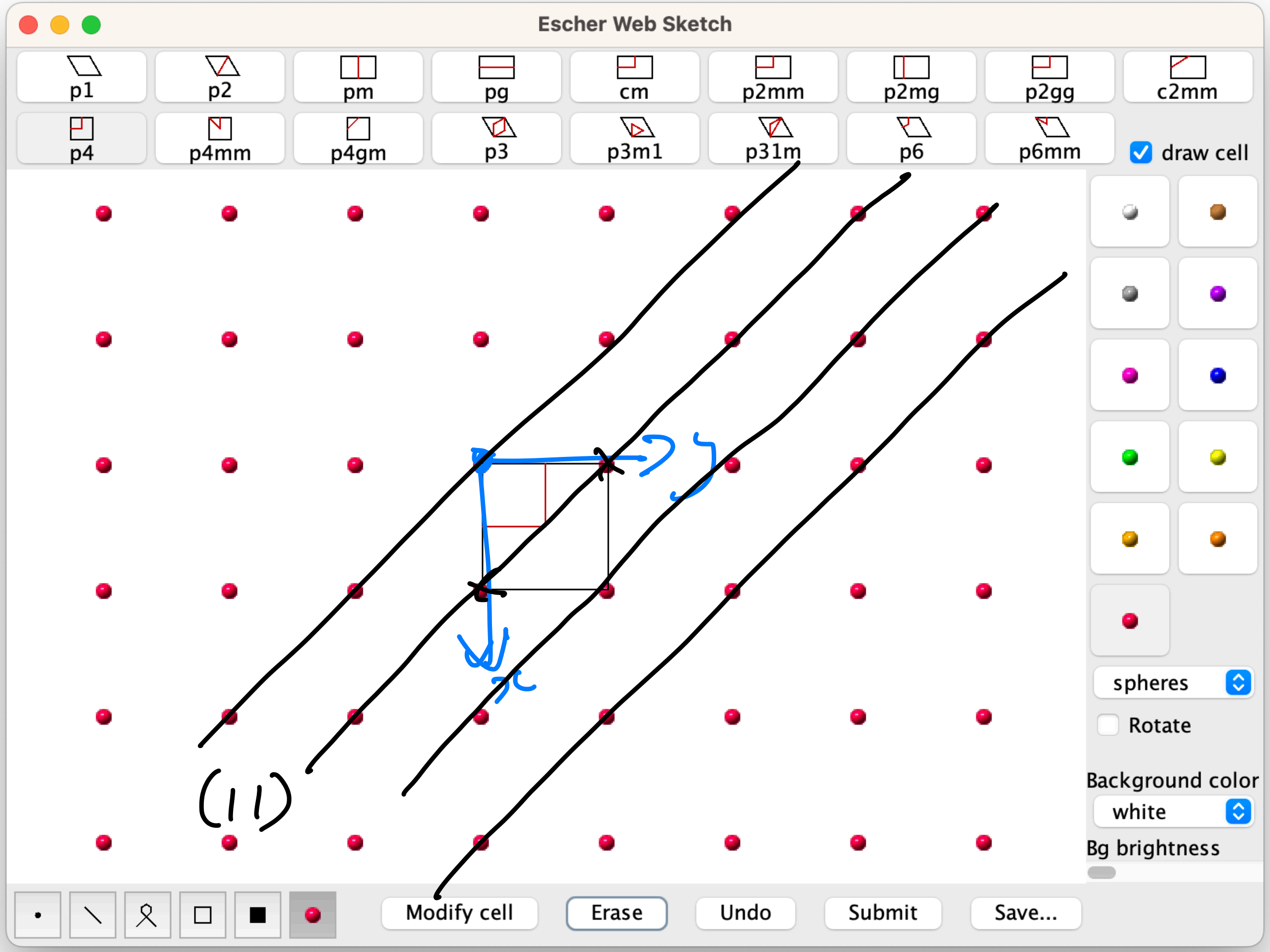
- Lattice plane is a plane which passes through any 3 lattice points which are not in a straight line
- Described using Miller indices $(h\ k\ l)$ where the first plane away from the origin intersects the $x$, $y$, $z$ axes at:

$a/h$ on the $x$ axis
$b/k$ on the $y$ axis
$c/l$ on the $z$ axis



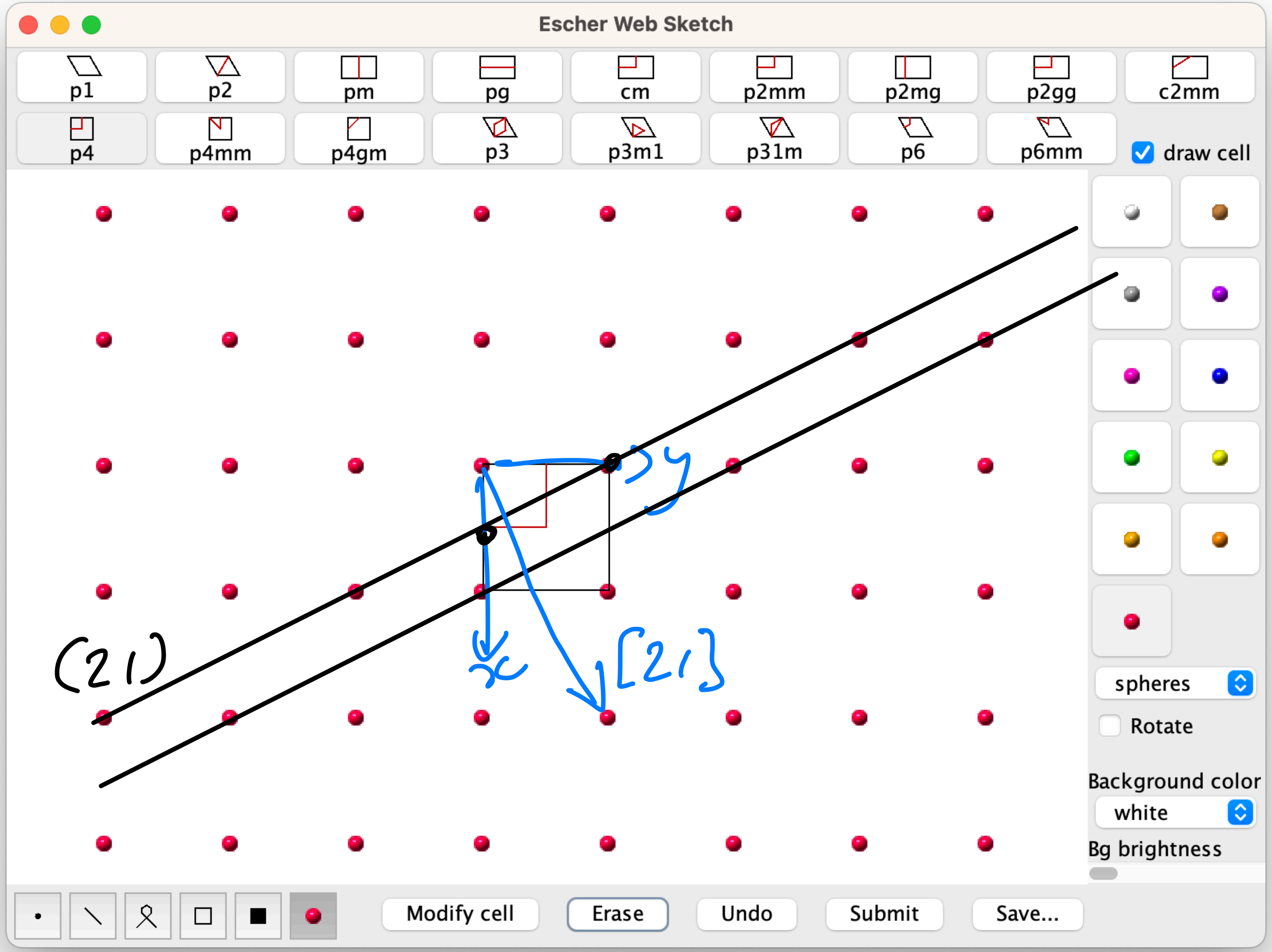
# Lattice "planes" (2D)

- In 2D correspond to lattice *lines*
- Draw the $(1\ \ 1)$ lattice line:



# Lattice “planes” (2D)

- In 2D correspond to lattice *lines*
- Draw the $(2\ 1)$ lattice line and $[2\ 1]$ lattice vector

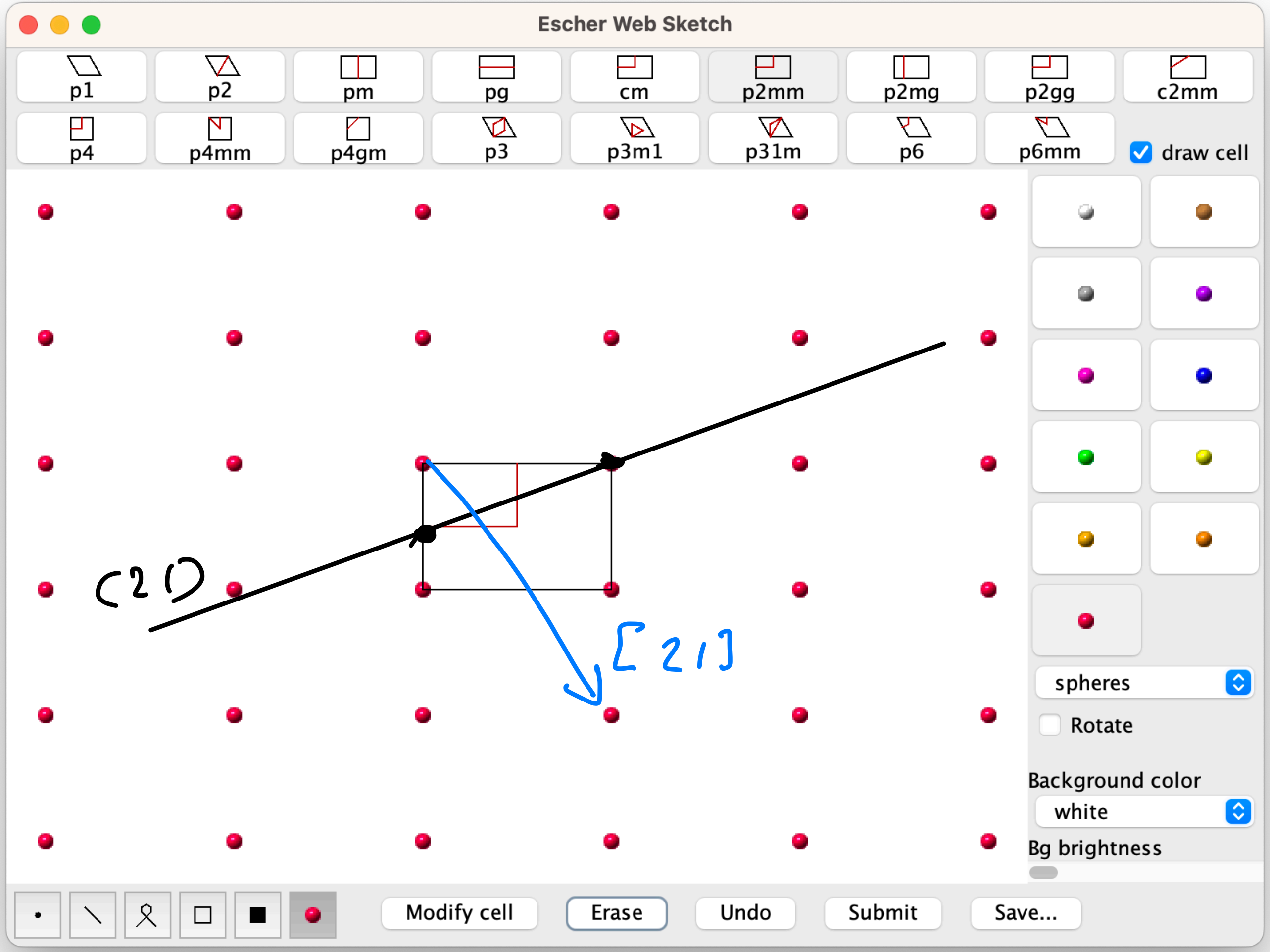


# Lattice “planes” (2D)

- In 2D correspond to lattice *lines*
- Draw the $(2\ 1)$ lattice line and $[2\ 1]$ lattice vector

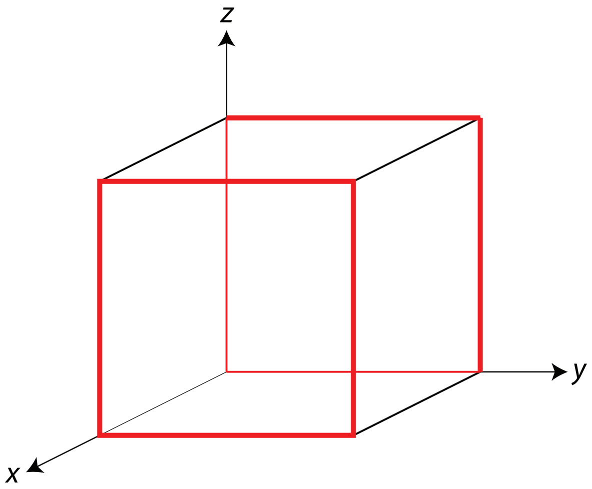
~~Perpendicular~~

\- lattice not square

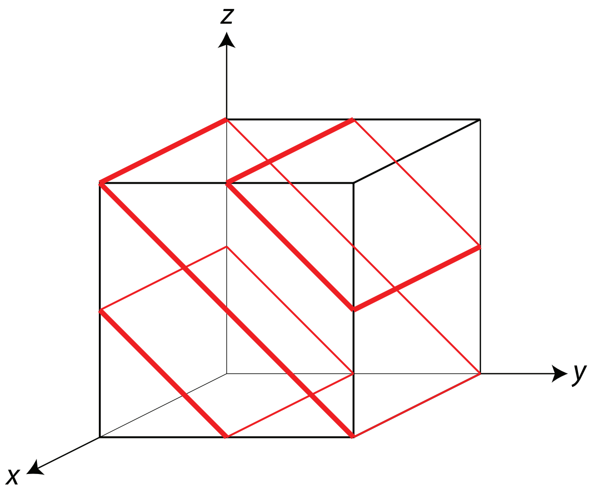


# Lattice planes (3D)

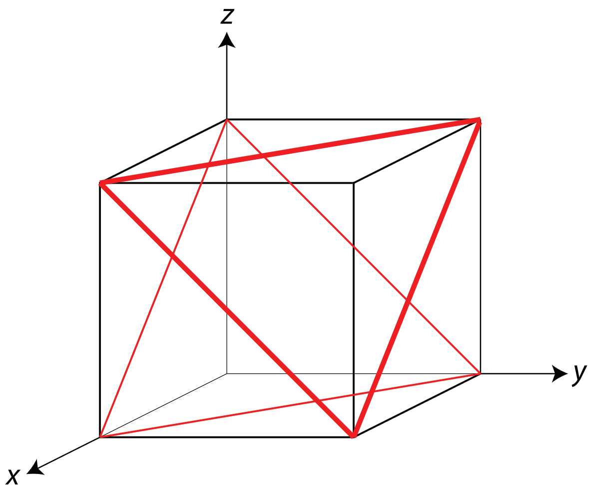
- Some examples to “solve”:




(100)




(022)

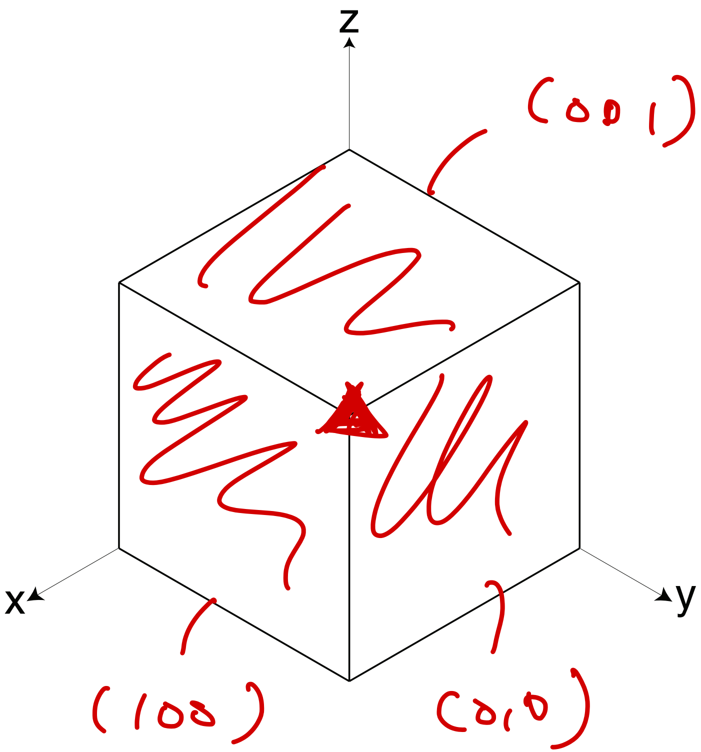



(111)

# Lattice planes and symmetry

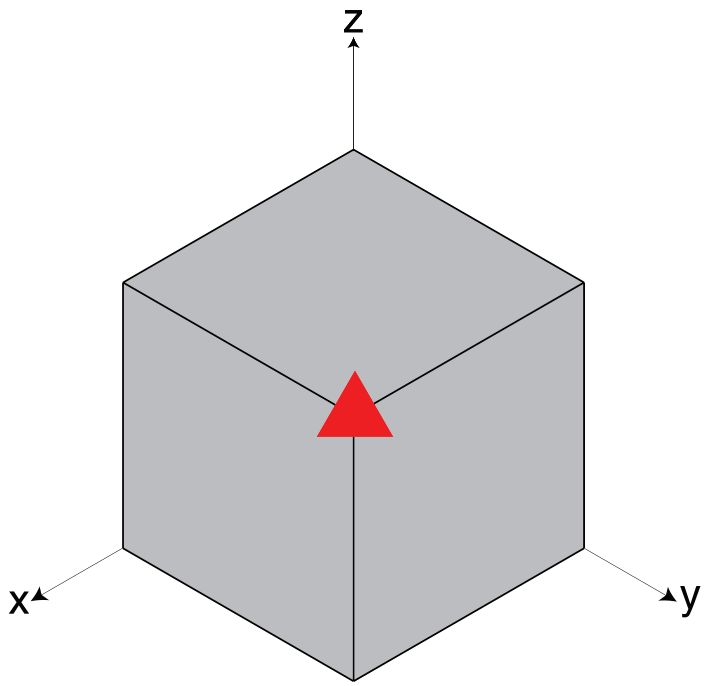
- Families of lattice planes are equivalent lattice planes related to each other by the crystal symmetry
- E.g. in cubic lattices the 3-fold rotation axis on the $[1\ 1\ 1]$ body diagonal relates the planes $(1\ 0\ 0),(0\ 1\ 0),(0\ 0\ 1)$:

$(\bar{1}00), (0\bar{1}0), (00\bar{1}) \rightarrow \{100\}$



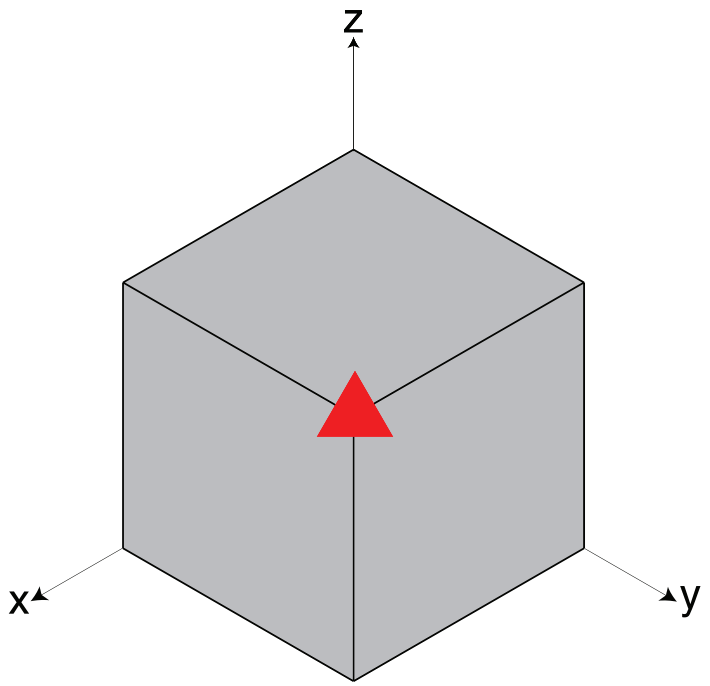
# Lattice planes and symmetry

- Families of lattice planes are equivalent lattice planes related to each other by the crystal symmetry
- E.g. in cubic lattices the 3-fold rotation axis on the $[1\ 1\ 1]$ body diagonal relates the planes $(1\ 0\ 0)$,$(0\ 1\ 0)$,$(0\ 0\ 1)$:



# Lattice planes and symmetry

- Families of lattice planes are equivalent lattice planes related to each other by the crystal symmetry
- E.g. in cubic lattices the 3-fold rotation axis on the $[1\ 1\ 1]$ body diagonal relates the planes $(1\ 0\ 0),(0\ 1\ 0),(0\ 0\ 1)$:



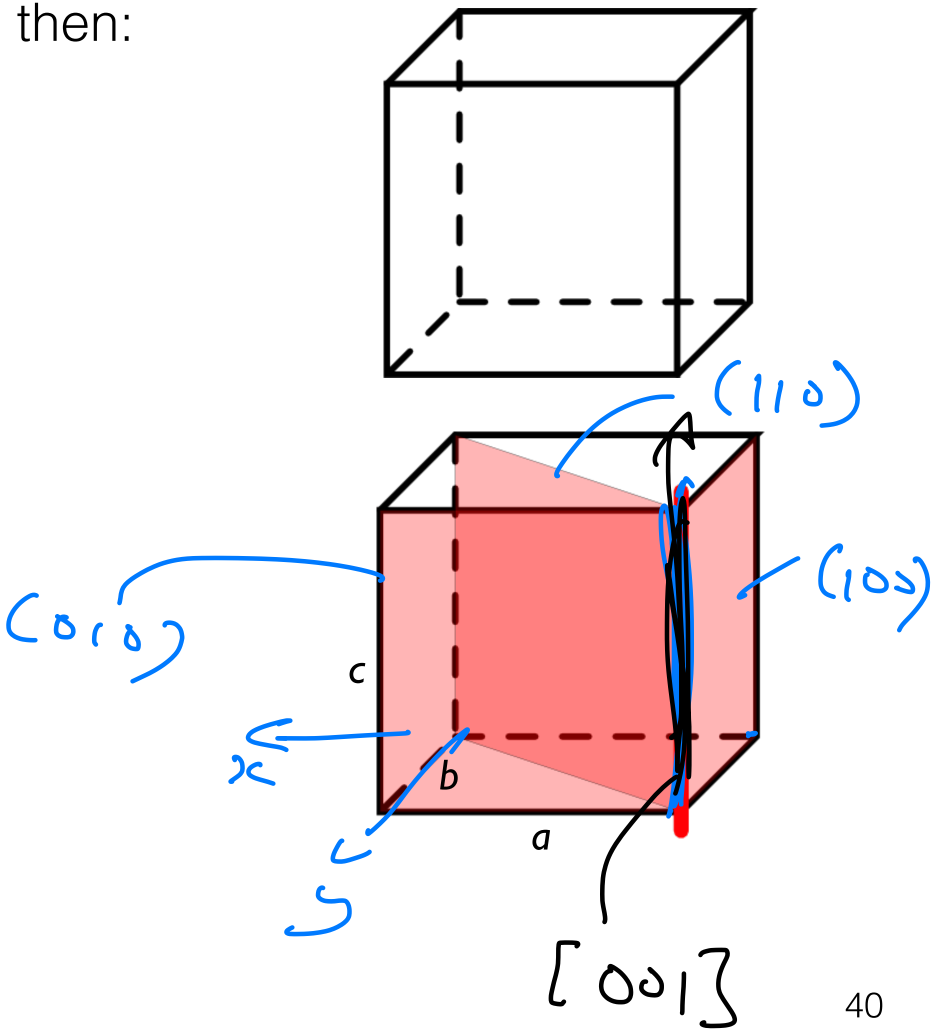

Family of planes given by curly brackets, e.g. for cubic:

$\{1\ 0\ 0\} = (1\ 0\ 0),(0\ 1\ 0),(0\ 0\ 1),(\bar{1}\ 0\ 0),(0\ \bar{1}\ 0),(0\ 0\ \bar{1})$

# Weiss Zone Law

If the lattice vector $[U\ V\ W]$ lies in the plane $(h\ k\ l)$ then:

$$hU + kV + lW = 0$$



# Weiss Zone Law

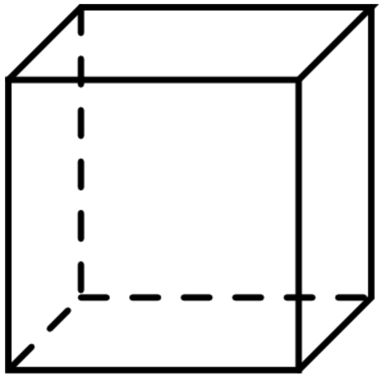
If the lattice vector $[U\ V\ W]$ lies in the plane $(h\ k\ l)$ then:

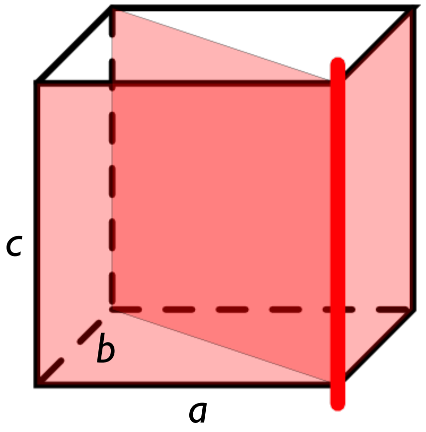
$$hU + kV + lW = 0$$

Electron diffraction:

Electron beam oriented parallel to lattice vector called the ***zone axis***

Diffracting planes must be parallel to electron beam
– ***therefore they obey the Weiss Zone law****





# Weiss Zone Law

If the lattice vector $[U\ V\ W]$ lies in the plane $(h\ k\ l)$ then:

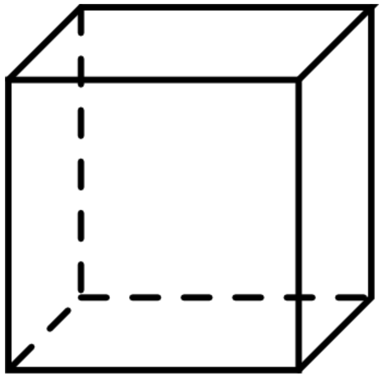
$$hU + kV + lW = 0$$

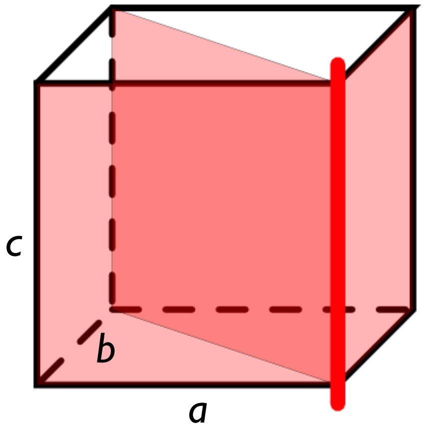
Electron diffraction:

Electron beam oriented parallel to lattice vector called the ***zone axis***

Diffracting planes must be parallel to electron beam
– ***therefore they obey the Weiss Zone law****

(*at least for zero-order Laue zone)





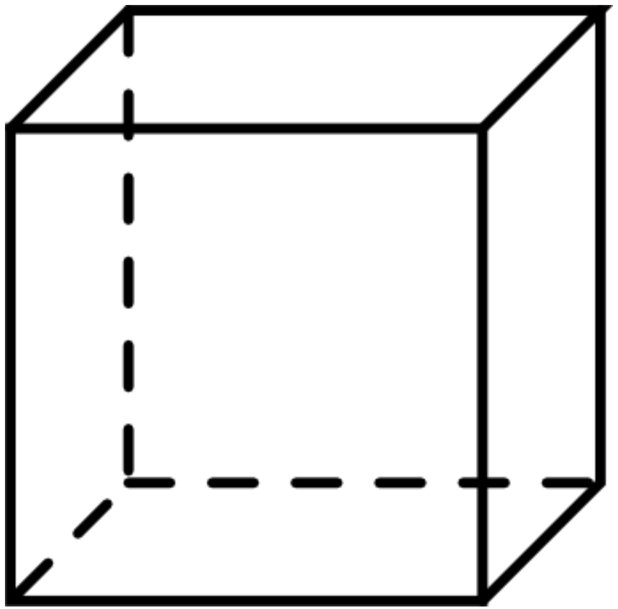
# Weiss Zone Law

- To obtain the zone axis defined by two non-parallel planes $(h_1\ k_1\ l_1)$ and $(h_2\ k_2\ l_2)$ calculate the cross-product:

$$U = k_1 l_2 - k_2 l_1$$

$$V = l_1 h_2 - l_2 h_1$$

$$W = h_1 k_2 - h_2 k_1$$



e.g. for planes $(1\ 0\ 0)$ and $(0\ 1\ 0)$:

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \otimes \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

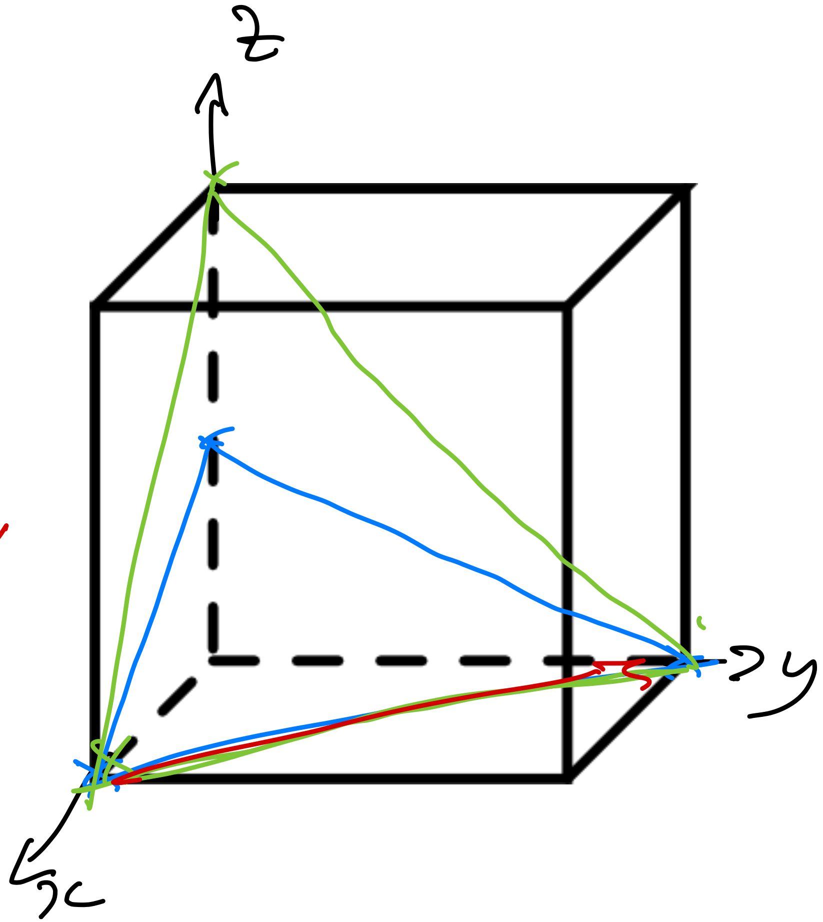
They define the $[0\ 0\ 1]$ zone axis

# Weiss Zone Law

- Draw the $(1\ 1\ 2)$ and $(1\ 1\ 1)$ planes
- What zone axis do they define?

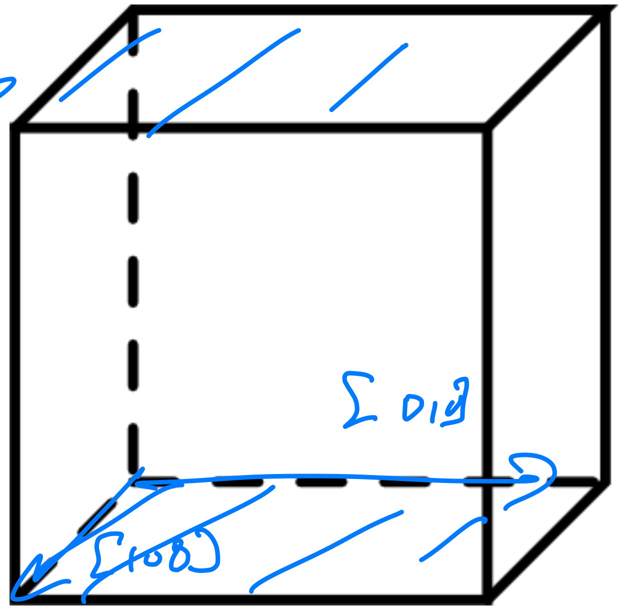
$[\bar{1}\,1\,0]$

$hu + kv + lw = 0$ ✓



# Lattice vectors defining planes

- Similarly, two non-parallel lattice vectors $[U_1\ V_1\ W_1]$ and $[U_2\ V_2\ W_2]$ define a lattice plane as their cross-product
- e.g. the plane containing the lattice vectors $[1\ 0\ 0]$ and $[0\ 1\ 0]$ is: $(0\ 0\ 1)$

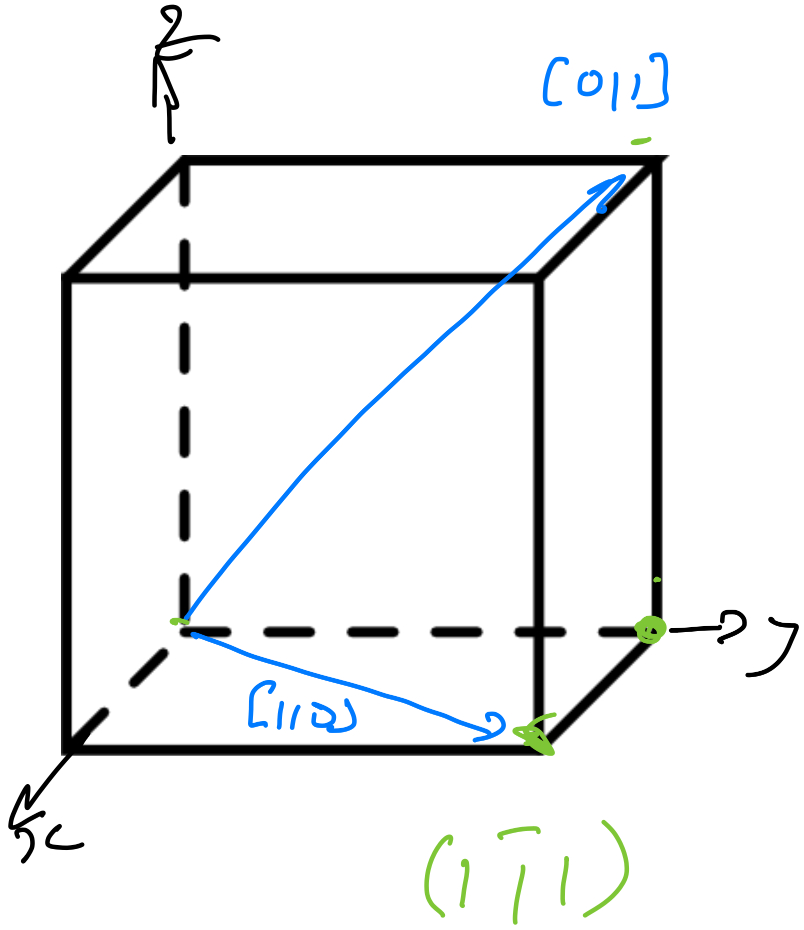


# Lattice vectors defining planes

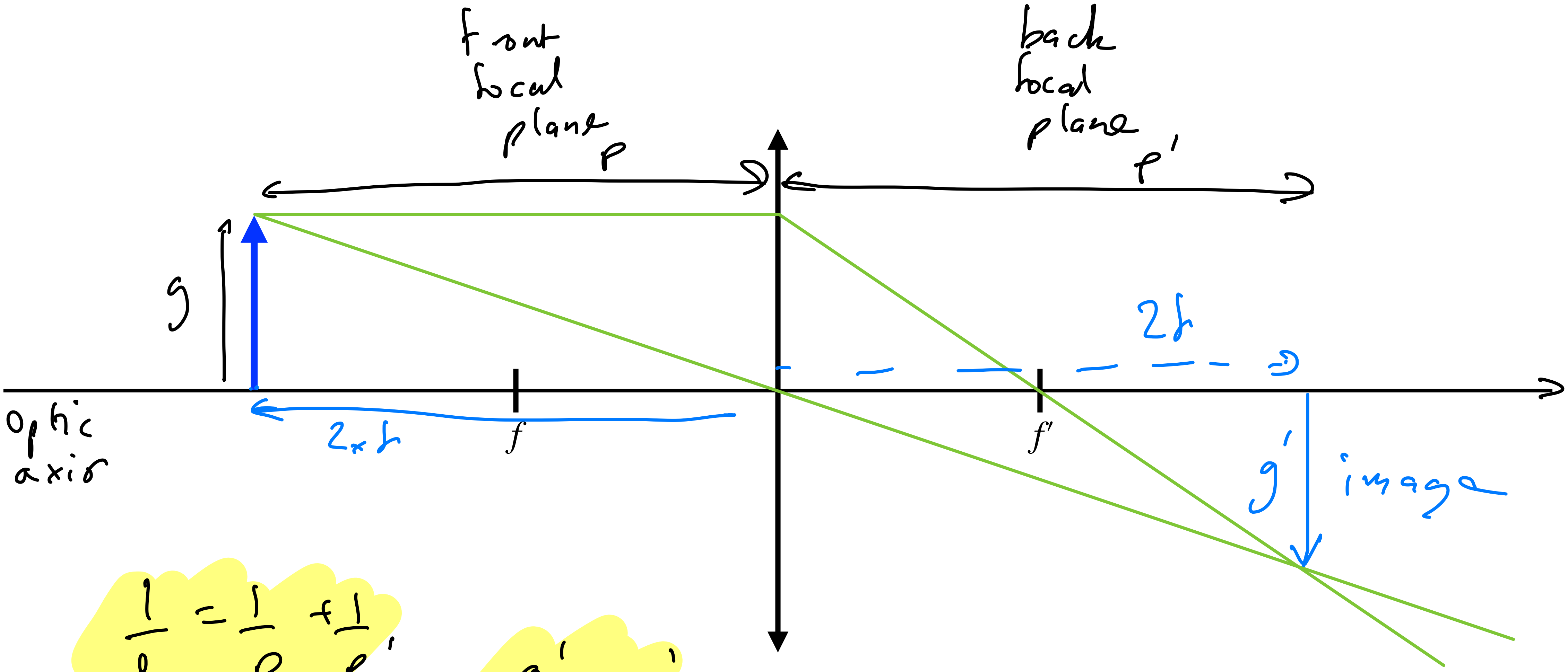
- Identify the plane containing the lattice vectors:

  [1 1 0] and [0 1 1]

  $(1\ \bar{1}\ 1)$



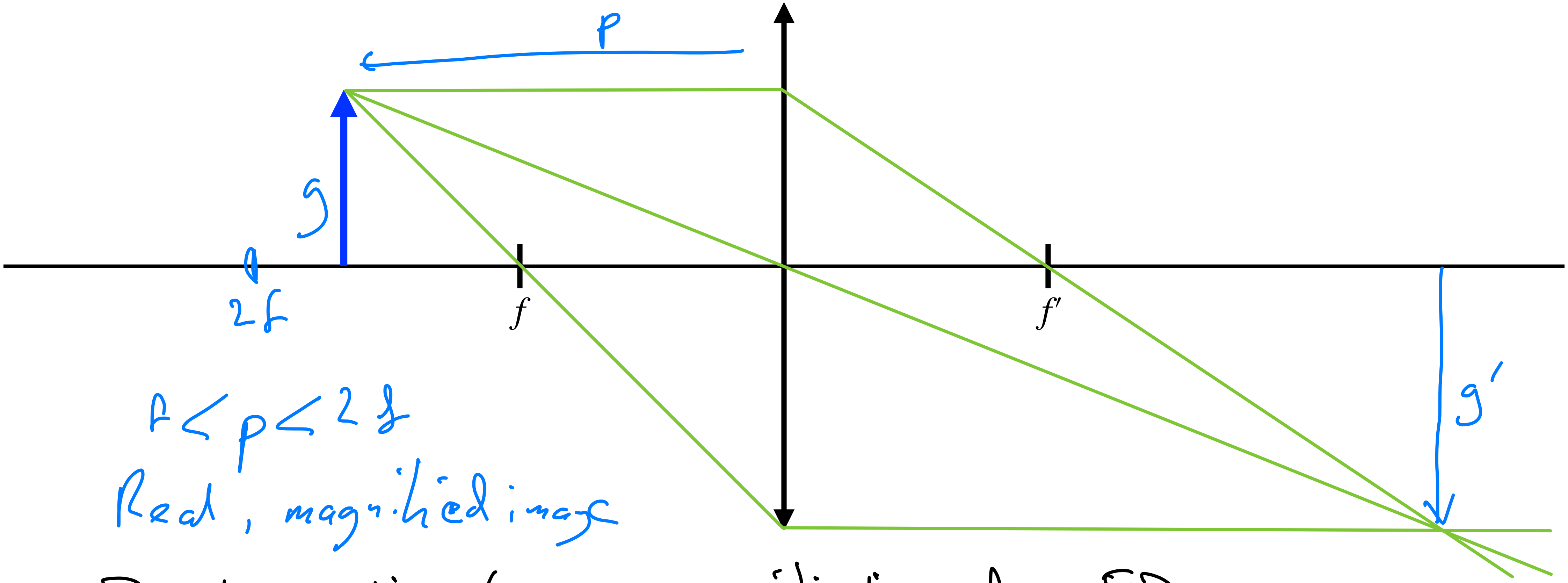
# Convergent lens ray diagram




$$\frac{1}{f} = \frac{1}{p} + \frac{1}{p'}$$

$$\frac{g'}{g} = \frac{p'}{p}$$

# Convergent lens ray diagram

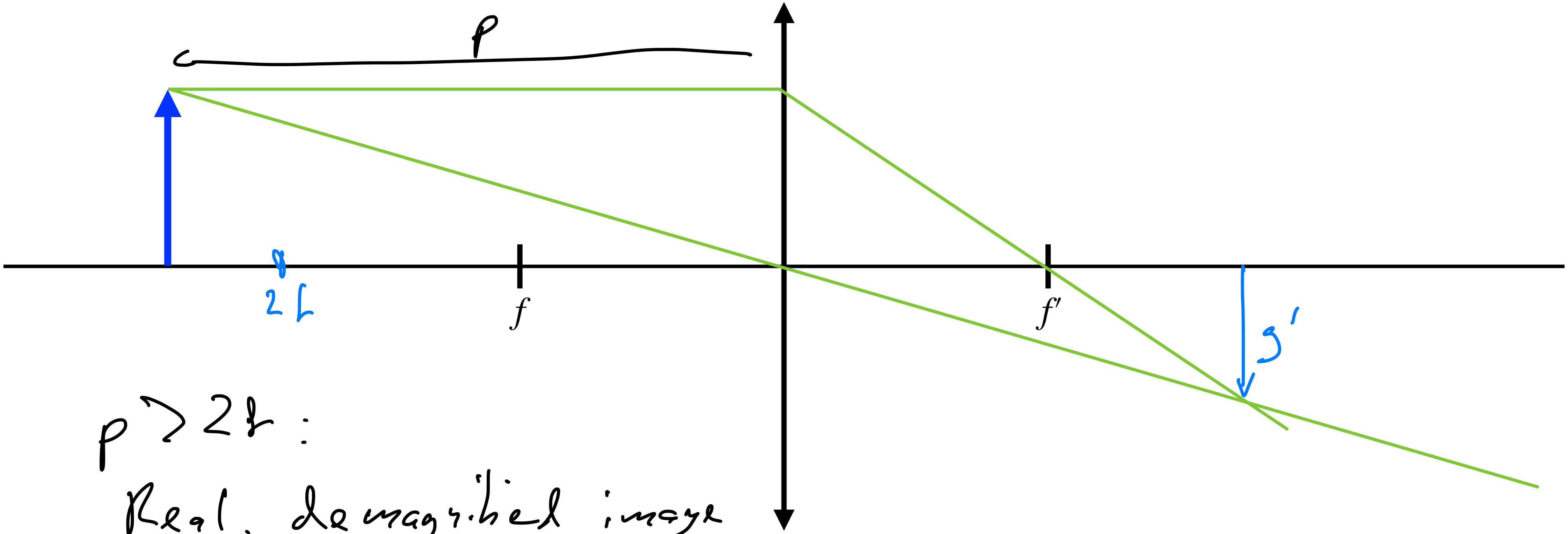



$f < p < 2f$

Real, magnified image

TEM objective lens: magnification of ~50x

# Convergent lens ray diagram




$p > 2f$ :

Real, demagnified image

# Convergent lens ray diagram

$p < f$

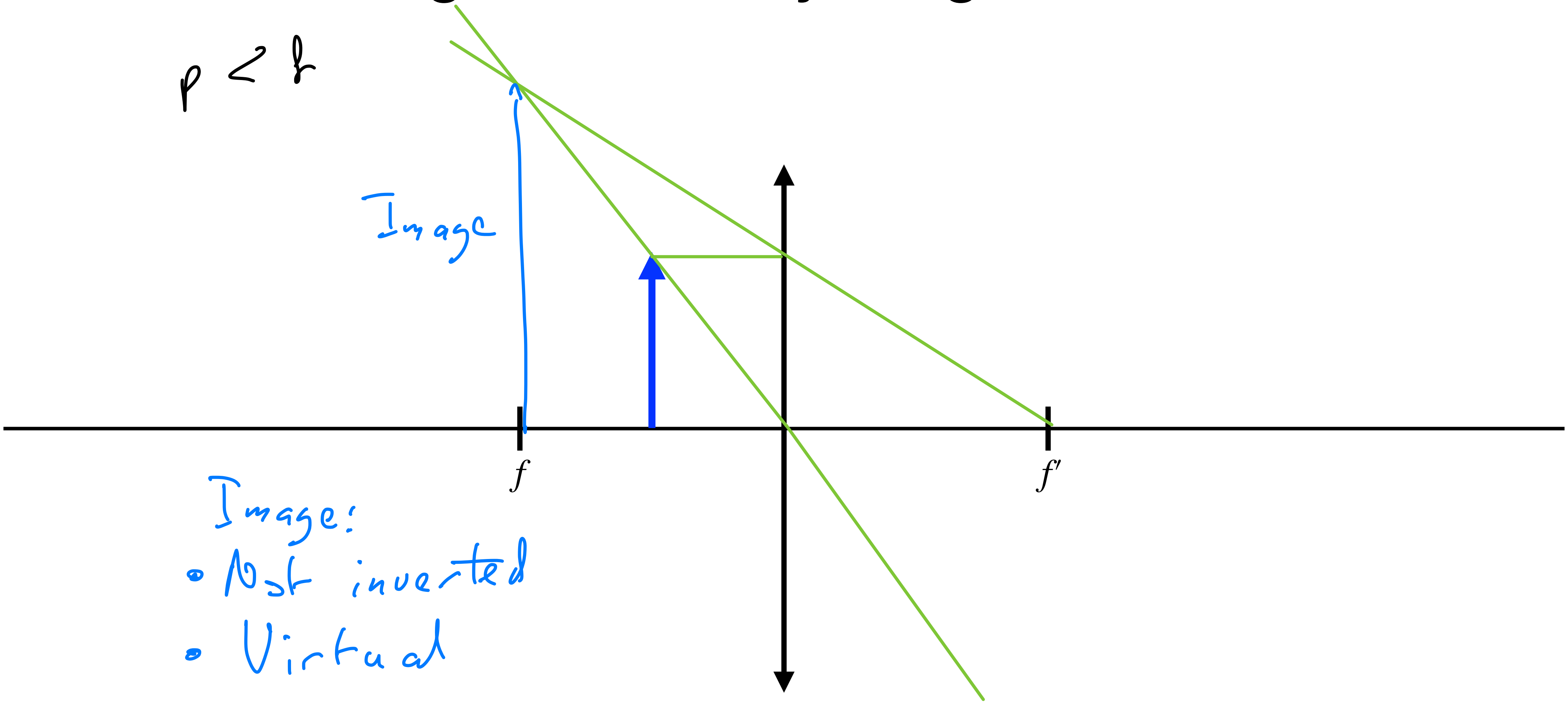
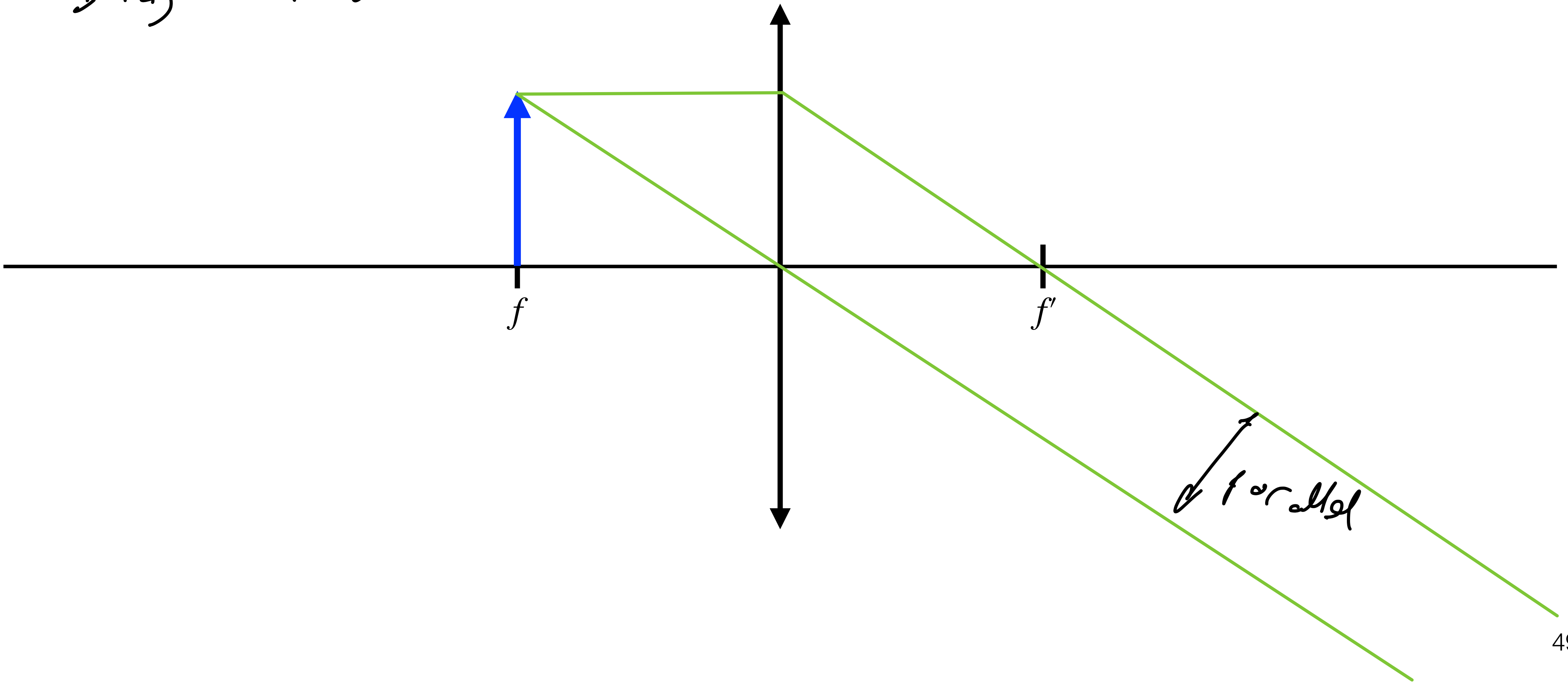



Image:

- Not inverted
- Virtual

# Convergent lens ray diagram

If object is at f
Image at ∞ !



# Resources

- Transmission Electron Microscopy: A Textbook for Materials Science
  Williams & Carter
  https://link.springer.com/book/10.1007/978-0-387-76501-3
- Transmission Electron Microscopy and Diffractometry of Materials
  Fultz & Howe
  https://link.springer.com/book/10.1007/978-3-642-29761-8
- Transmission Electron Microscopy: Physics of Image Formation
  Reimer and Kohl
  https://link.springer.com/book/10.1007/978-0-387-40093-8
- The basics of crystallography and diffraction
  Hammond
  https://academic.oup.com/book/43705