Australian Government

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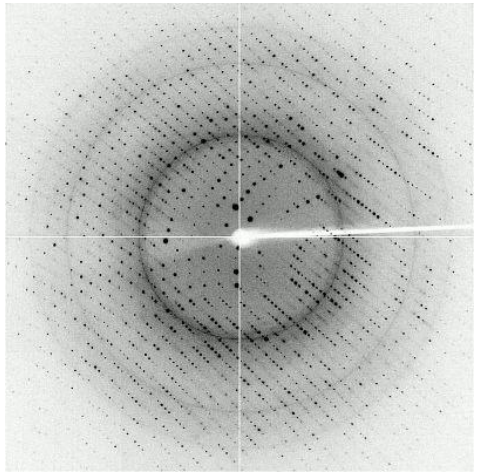
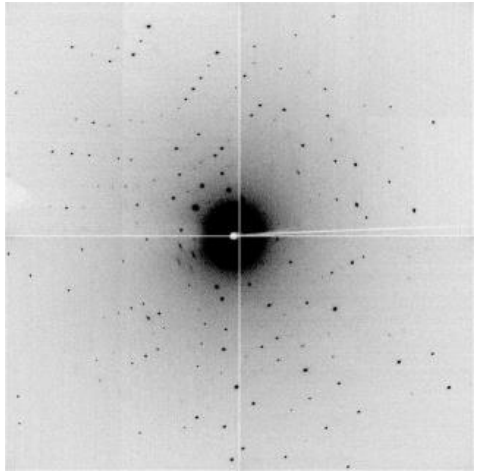


Crystallography



Dr Rosemary Young

Beamline Scientist – MX1/2

Australian Synchrotron

Science. Ingenuity. Sustainability.

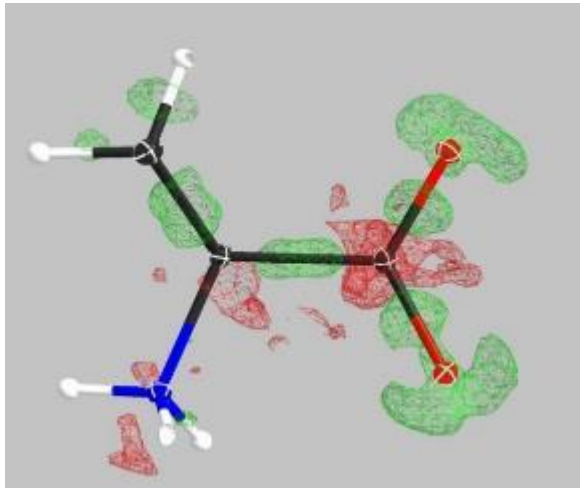
What is crystallography?

"To determine the atomic or molecular structure of a crystal by X-ray diffraction"

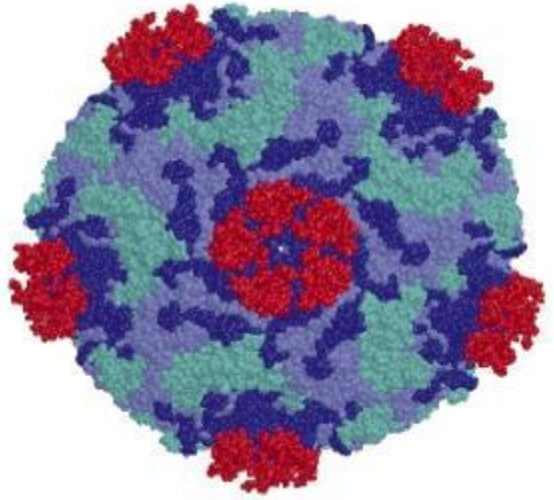
1. Have a (single) crystal

2. Perform an X-ray diffraction experiment

3. Determine the structure



~3 Å



~300 Å

Results:
Structure, connectivity, chirality, bonding, packing, porosity, supramolecular interactions ...

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Why do crystallography?

'Why water boils at 100°C and methane at -161 ° C;

why blood is red and grass is green; why diamond is hard and wax is soft;

why graphite writes on paper and silk is strong;

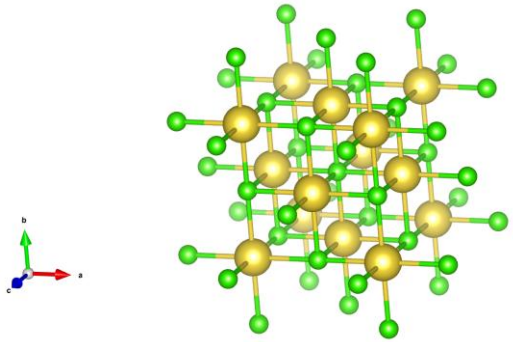
why glaciers flow and iron gets hard when you hammer it;

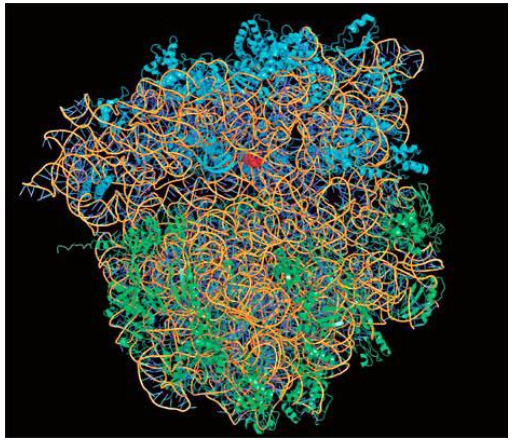
how muscles contract; how sunlight makes plants grow and how living organisms have been able to evolve into ever more complex forms…?

The answers to all these problems have come from structural analysis'

Max Perutz (Nobel Prize 1962)

Salt – Nobel Prize 1915





Ribosome –
Nobel Prize 2009

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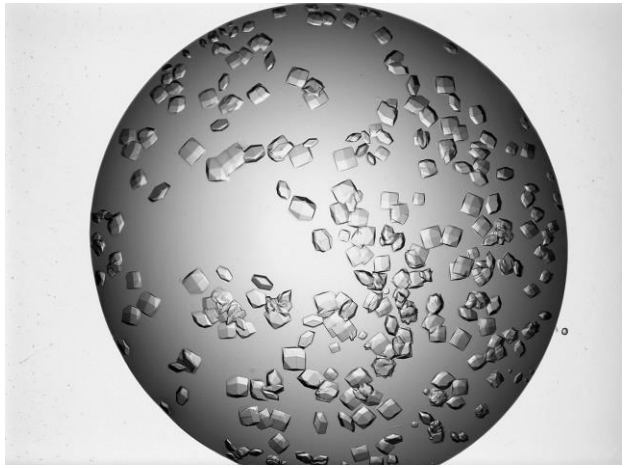
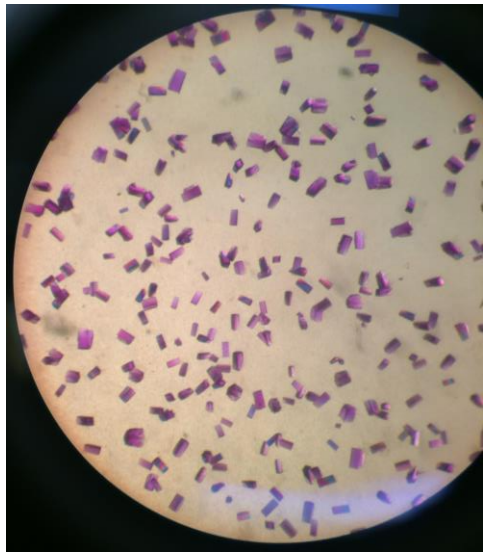
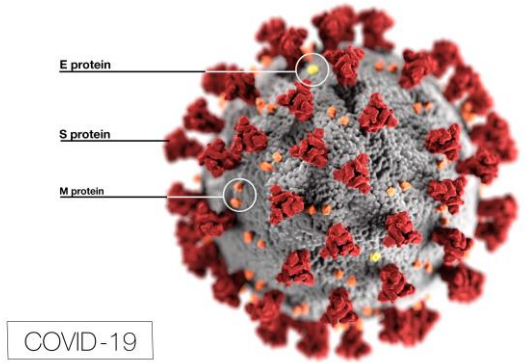
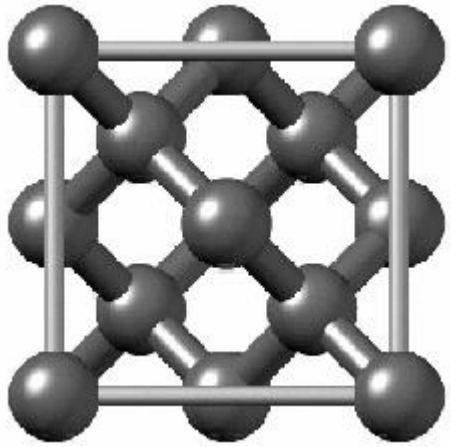
What is a crystal?

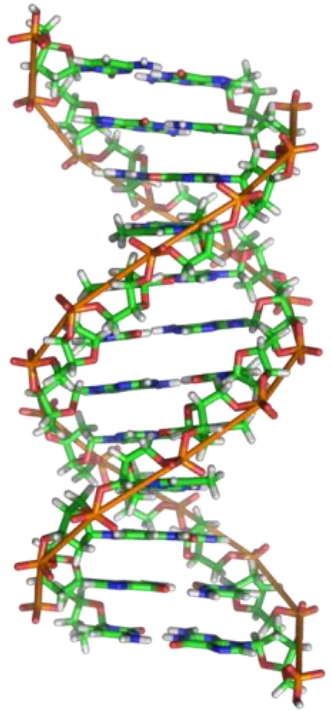
- A solid with highly ordered components











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How do we find the crystal structure?

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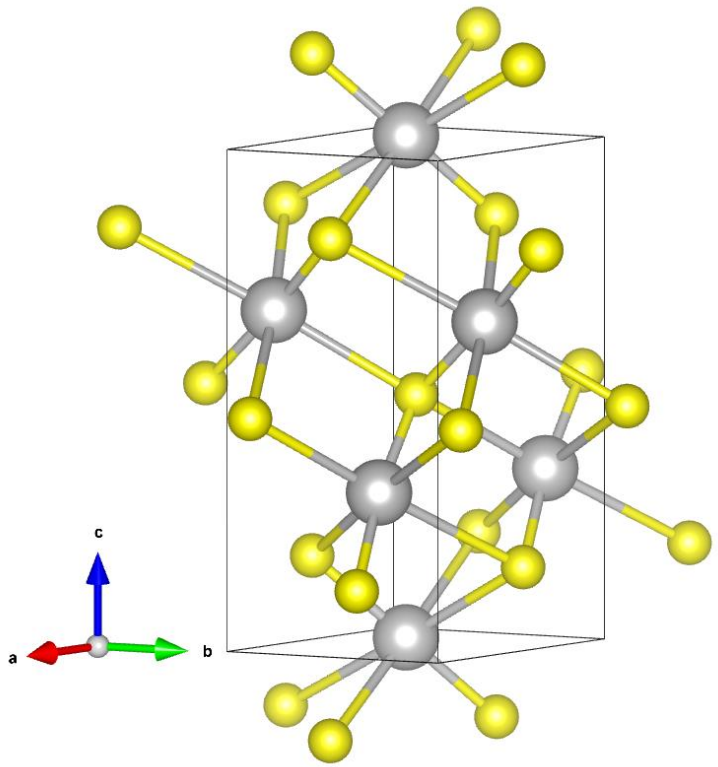
Crystals and Symmetry

- 1 mg of matter will contain around 10^{19} atoms.
- Symmetry provides a systematic way of describing where all those atoms are

Crystallographic Definitions



- **Lattice** – an infinite array of points in space where each point has identical surroundings
- **Crystal structure** – the periodic arrangement of atoms in a solid
- **Unit Cell** – the smallest component from which the entire crystal can be built up, with purely translational displacements

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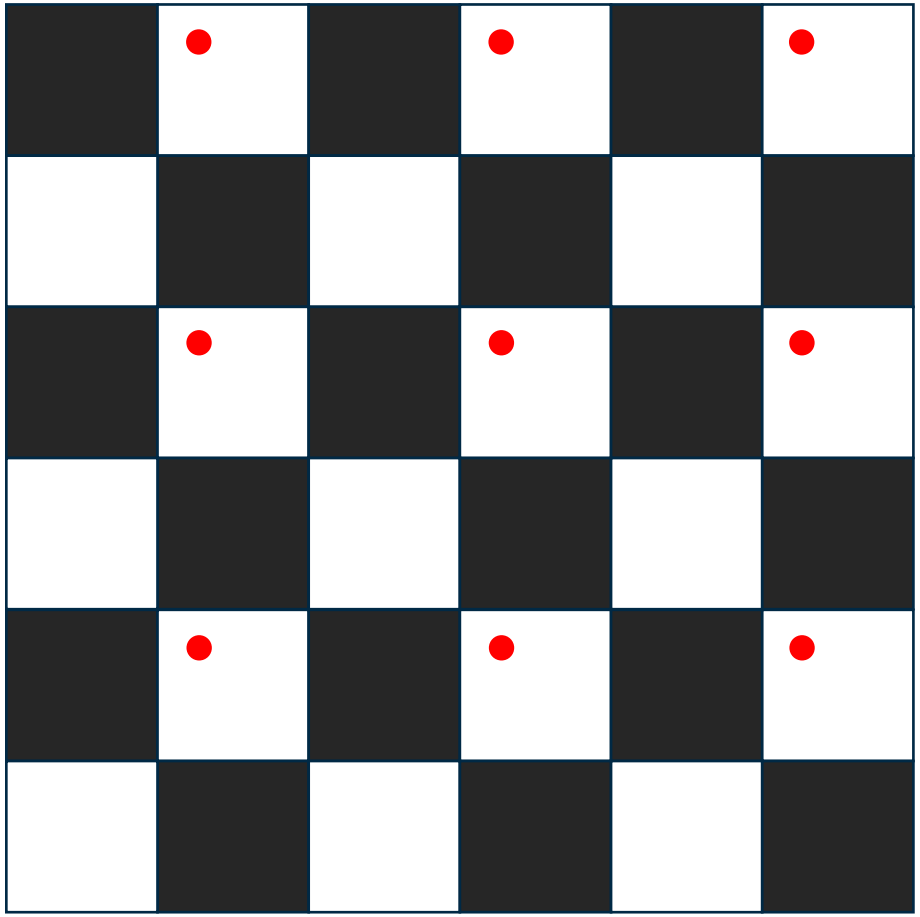
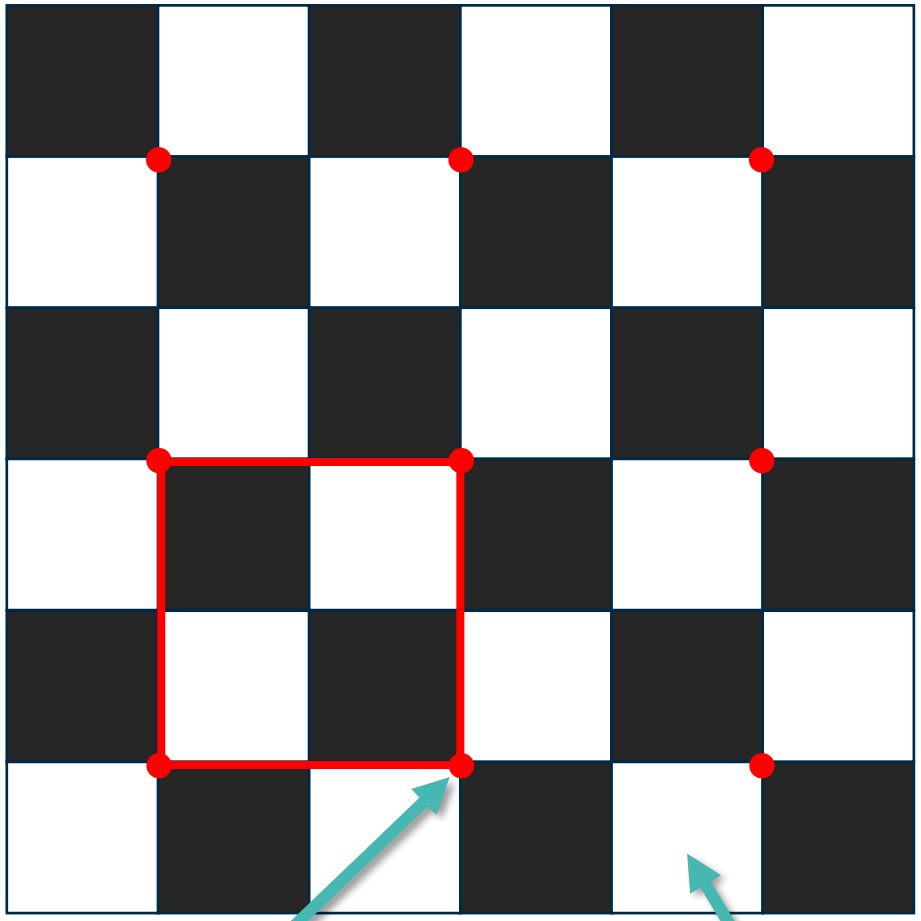
Lattice and structure



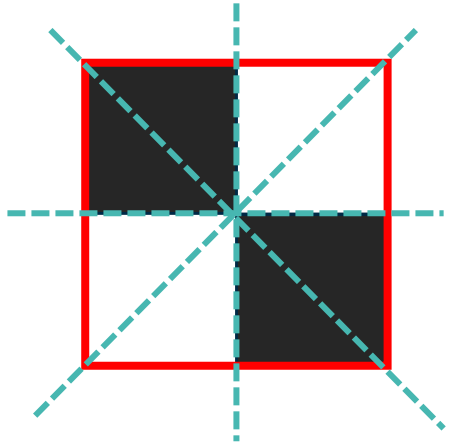
- Identical points in the pattern define a lattice.

- Lattice points can be chosen anywhere (but we tend to choose high-symmetry points).

Crystallographic Definitions



Unit cell



Repeats in all directions

Asymmetric unit

Smallest unit taking into account symmetry

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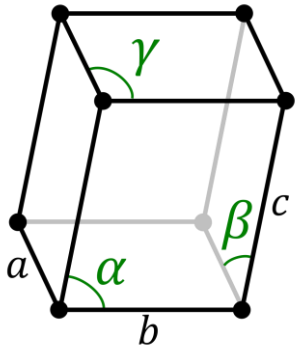
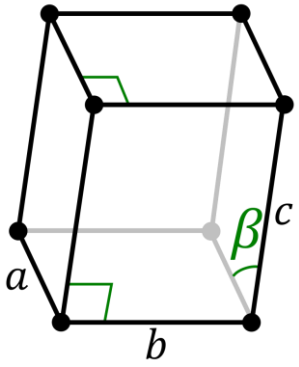
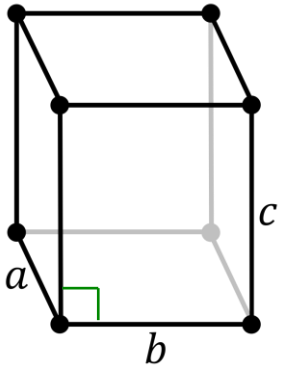
Unit cell in three-dimensions



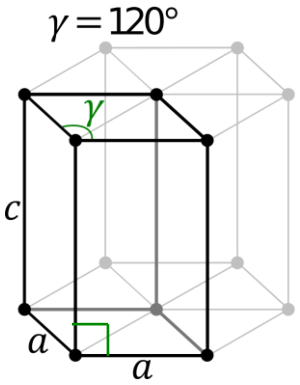
Triclinic
a≠b≠c
α ≠ β ≠ γ



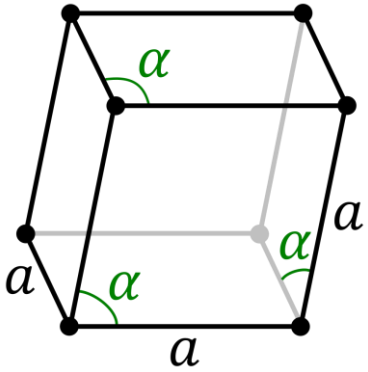
Monoclinic
a≠b≠c
α = γ = 90°, β ≠ 90°



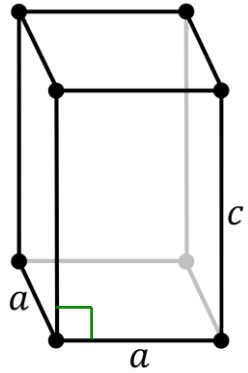
Orthorhombic
a≠b≠c
α = β = γ = 90°



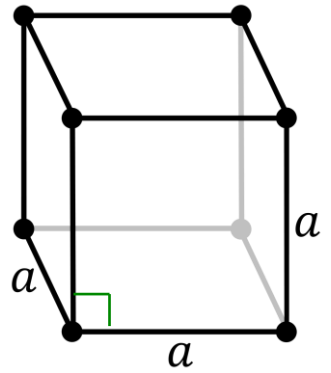
Hexagonal
a=b≠c
α = β = 90°, γ = 120°



Rhombohedral
a=b=c
α = β = γ ≠ 90°



Tetragonal
a=b≠c
α = β = γ = 90°



Cubic
a=b=c
α = β = γ = 90°

- 14 Bravais lattices (unit cells)
- 7 Crystal Systems

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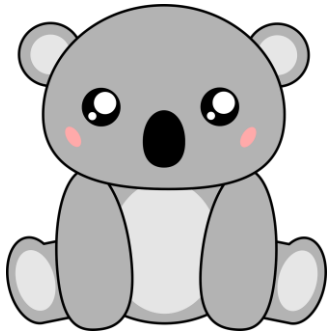
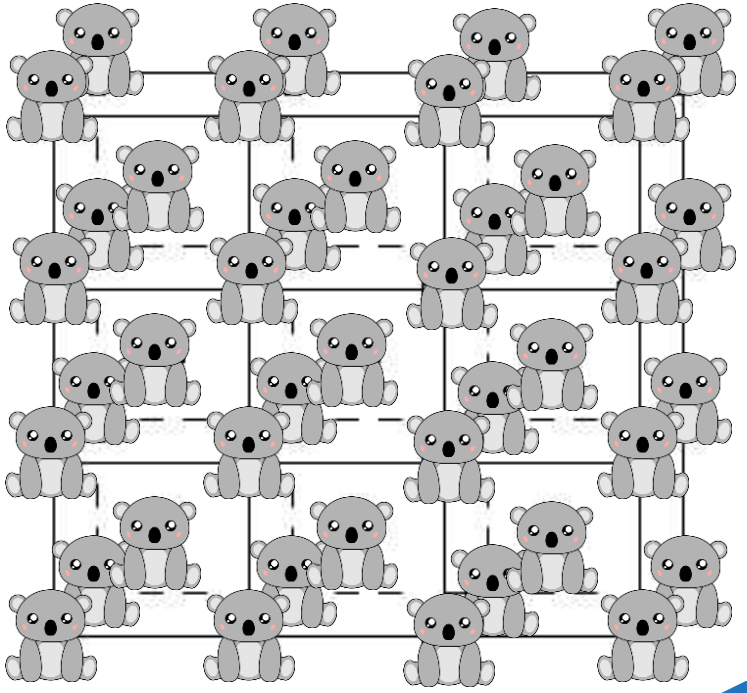
Symmetry in solids

- **Molecular symmetry**
  - Symmetry of isolated objects
  - Point group symmetry
  - 32 point groups

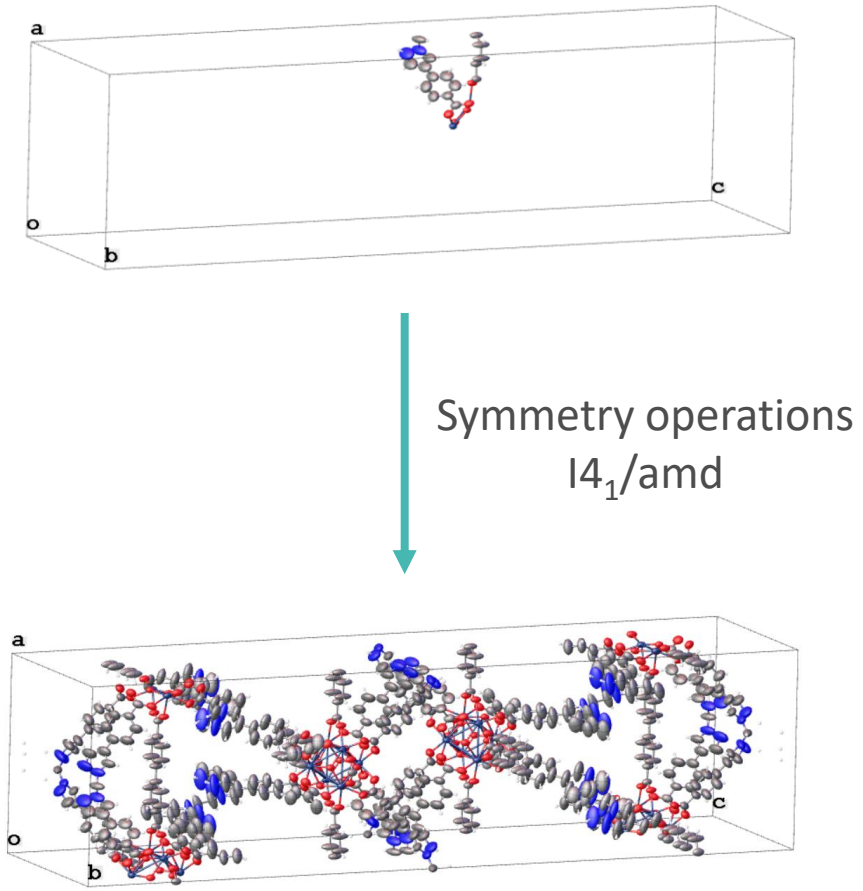
- **Crystallographic Symmetry**
  - Symmetry of periodic arrays
  - Space group symmetry
  - 230 space groups





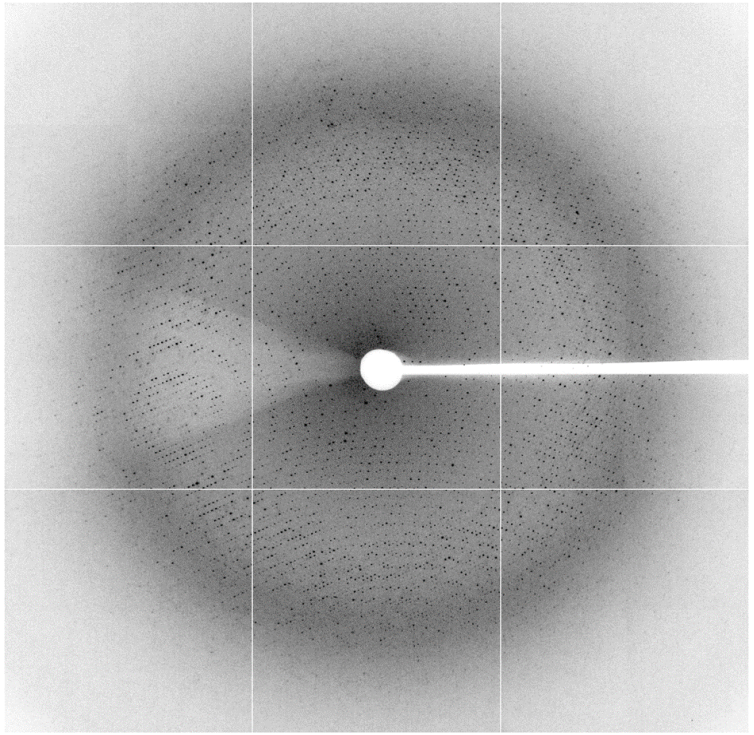
Asymmetric unit

- Smallest portion of the structure that must be specified before space group symmetry defines the entire structure
- Crystallographically unique (independent) atoms
- Can be equal to/more/less than one molecule (molecular solids)
- Can be equal to/more/less than the formula unit (extended solid)



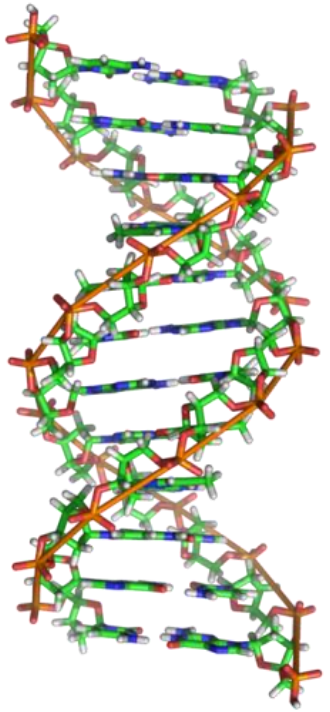
Diffraction

How to go from this (or this):

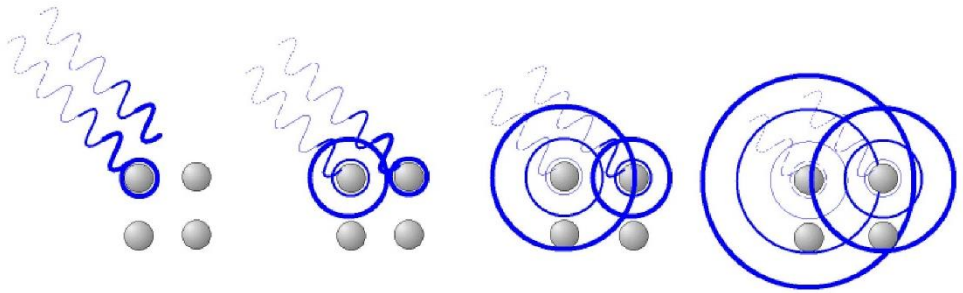


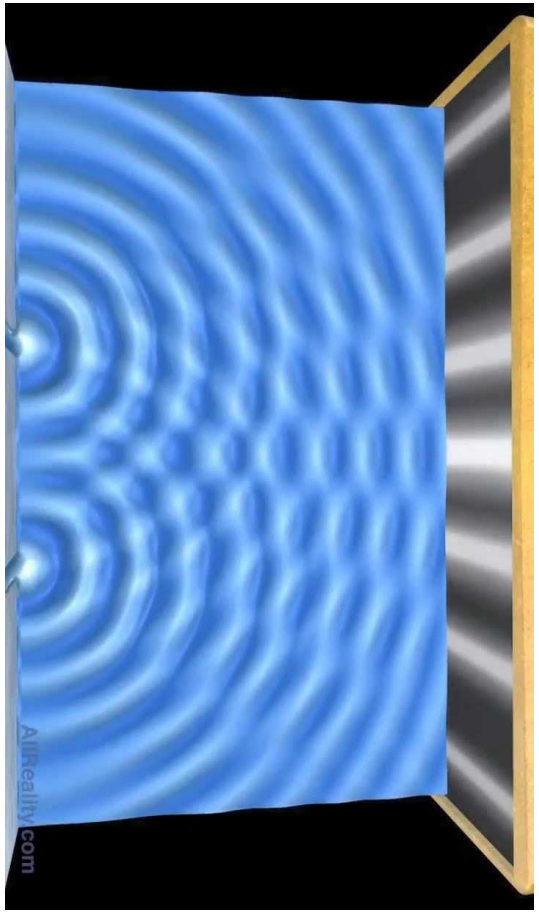
Forwood, 2015ish

To this:



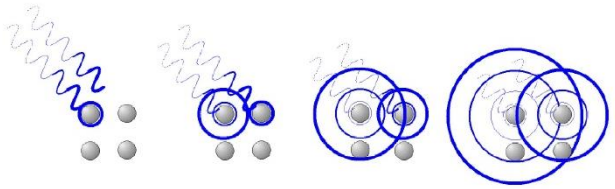
Diffraction theory

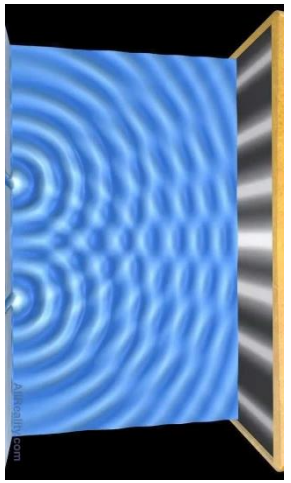


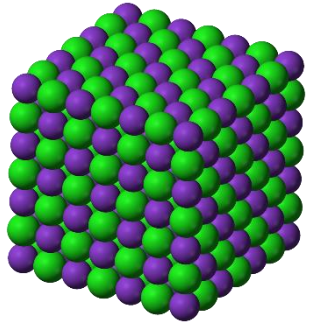


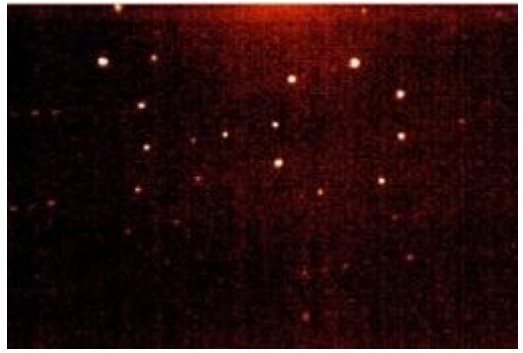
Diffraction theory

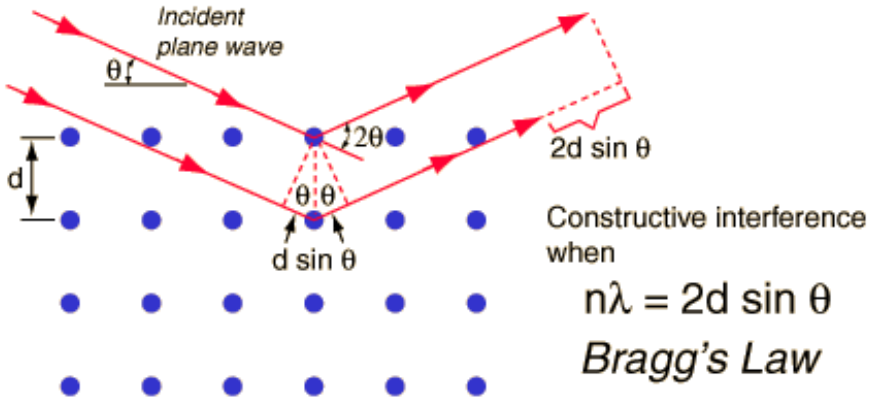
- Crystal lattices have regularly-spaced planes of atoms
- We only observe diffracted X-rays when Bragg's law is satisfied -> constructure interference
- In phase in a few selected directions











http://hyperphysics.phy-astr.gsu.edu

Bragg & Bragg: 1912-1913 (Nobel Prize 1915)

n is an integer
λ is the X-ray wavelength
d is the inter-planar spacing
2θ is the diffraction angle

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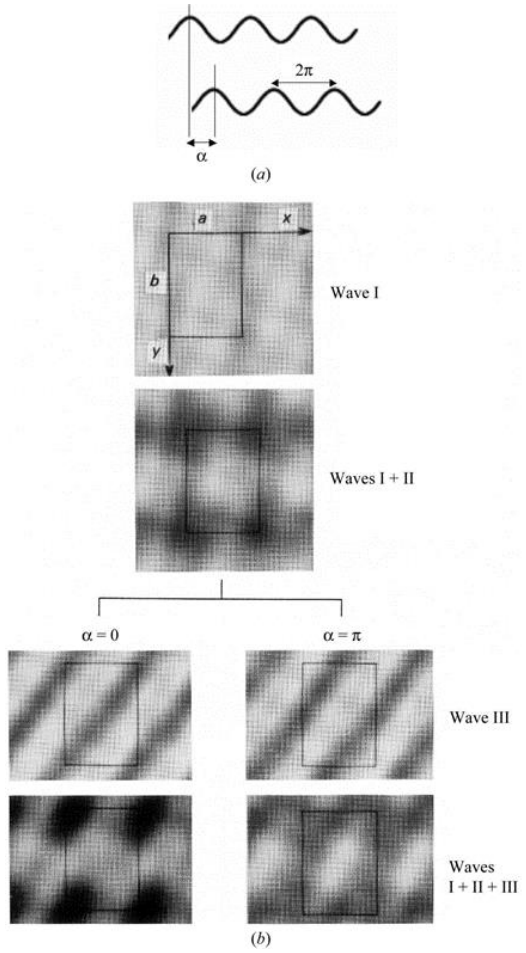
Phase problem



Diffraction intensity $\sim$ $F(hkl) = \sum_j b_j \, e^{2\pi i(hx_j + ky_j + lz_j)}$

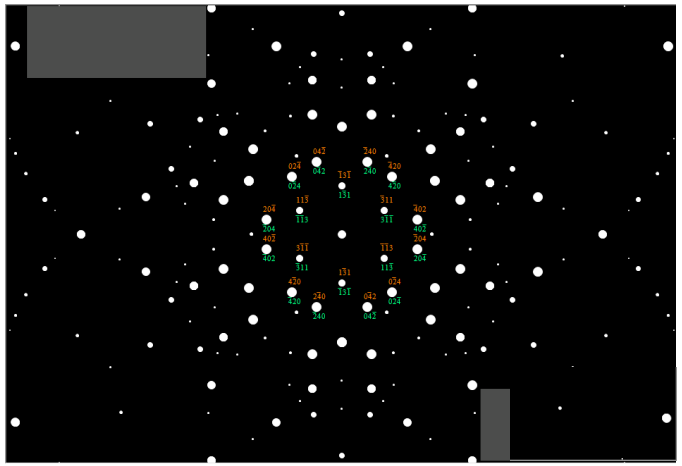
- Needs to be noted that we actually measure $I_{(hkl)}$
- We have information on the **amplitude** of the structure factor not its phase
- Hence direct Fourier transforms to obtain crystal structures is not possible – need to fit models

Powder vs Single Crystal

- Indexing is harder with powder diffraction.
- Anisotropic atomic displacement parameters also more challenging to determine
- Whole powder pattern analysis methods such as Rietveld analysis allow quite detailed information to be extracted

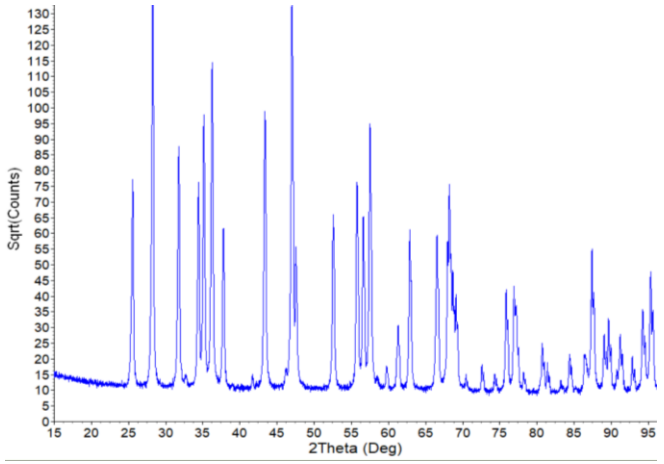
Single crystal: 3D diffraction data

→ 3D unit cell



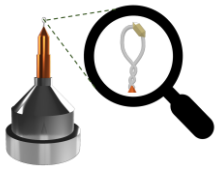
Powder diffraction: 1D diffraction data

→ Unit cell size & shape can be ambiguous

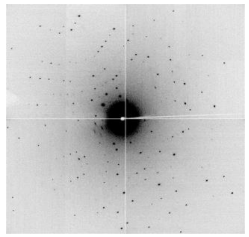


Timeline of an X-ray crystallography experiment

1. Grow a crystal (minutes - months...)



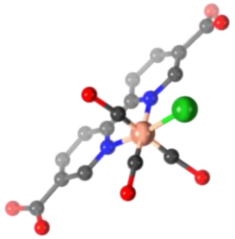
2. Mount it on a loop (seconds - minutes)



3. Collect a dataset (seconds)

4. Data processing (minutes)

Synchrotron



5. Solving and refining the crystal structure (hours - days)

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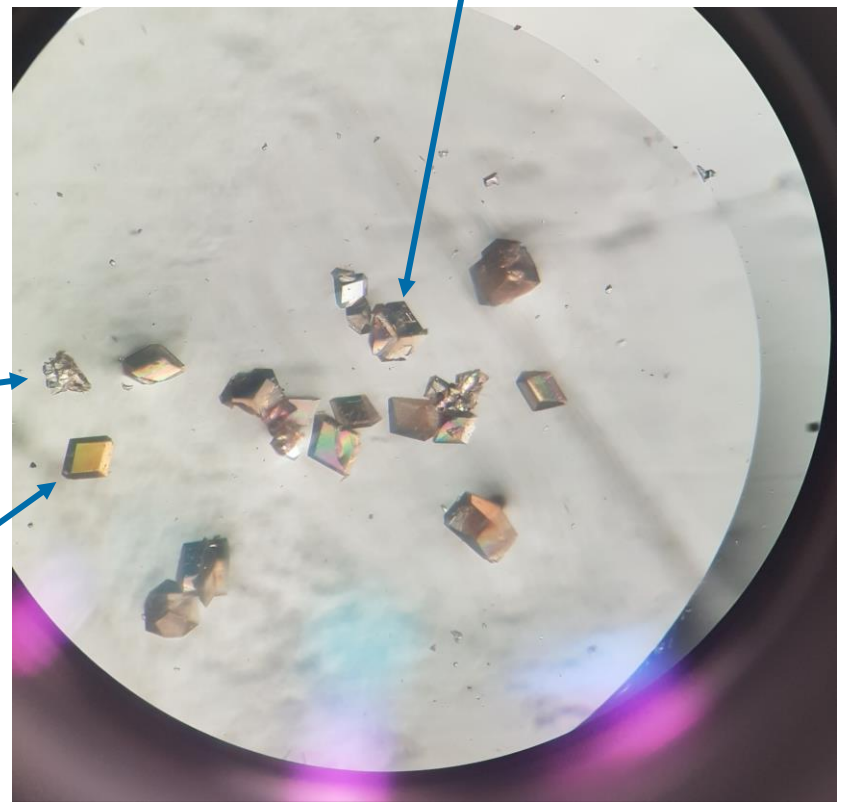
Growing good crystals

- Sharp edges
- Regular faces
- Clear
- Extinguish under cross polarized light



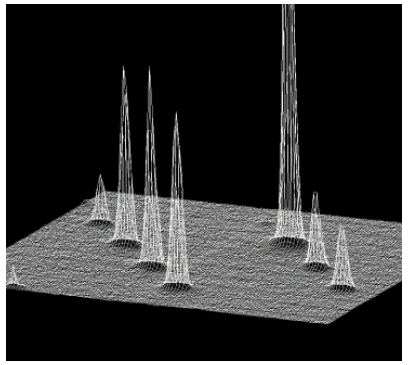
Methods – slow evaporation, vapour diffusion, liquid/liquid diffusion, gel diffusion, solvothermal, slow cooling, sublimation

https://www2.chemistry.msu.edu/Facilities/Crystallography/downloads/xtalgrow.pdf

Why use a synchrotron?

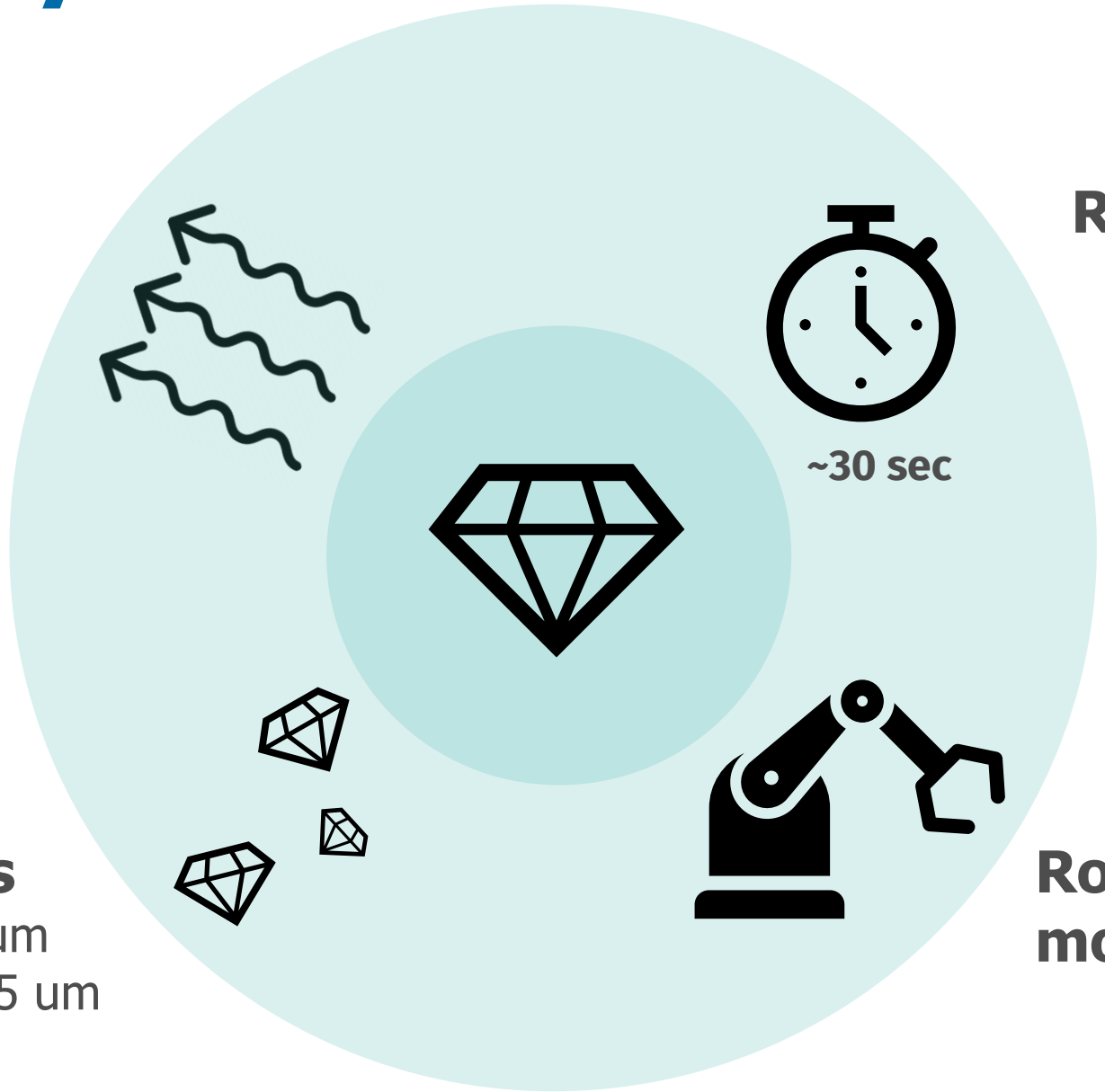
X-ray beam

High flux
Small beam
High signal/noise
Tunable wavelength



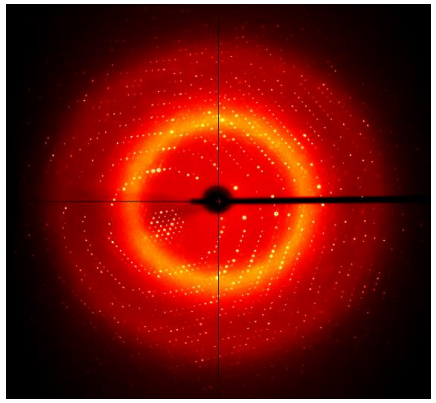
Small crystals

Chemical <1 um
Biological >3-5 um



Rapid data collection

Serial collections



Robotic sample mounting

Remote access

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Chemical or "small molecule" crystallography

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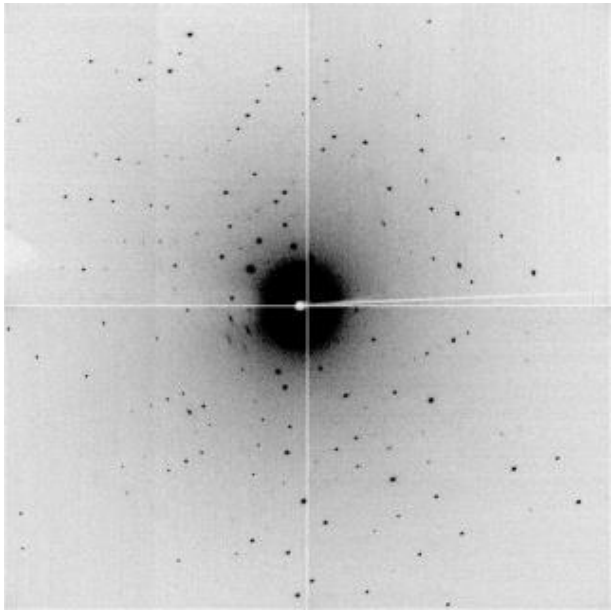
What's the difference between anyway?

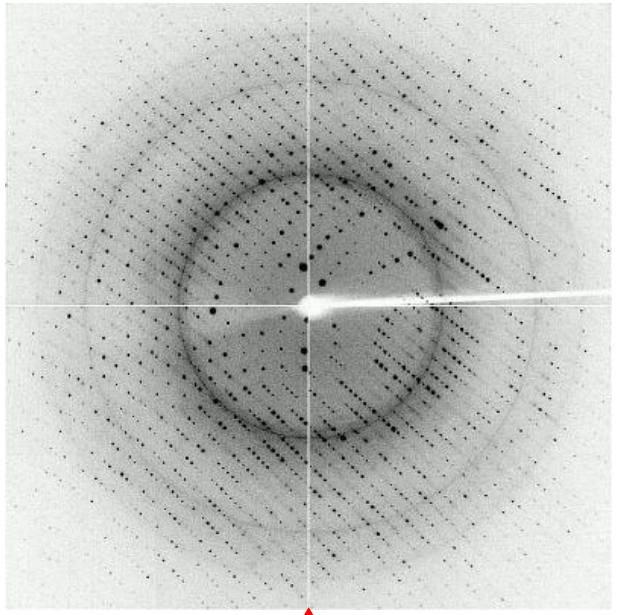
- ~~Size of molecule~~
- ~~Size of unit cell~~
- ~~Size of asymmetric unit~~
- Use of direct methods
- Publication resolution limits
- Software

Chemical



0.76 Å
(17.444 keV, 0.71 Å)

Protein



1.76 Å resolution
(13.0 keV, 0.95 Å)

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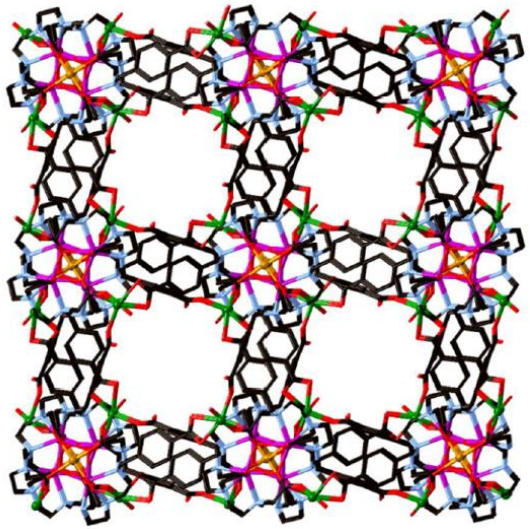
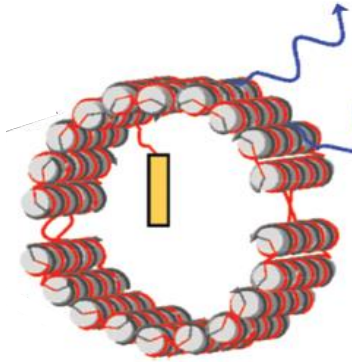
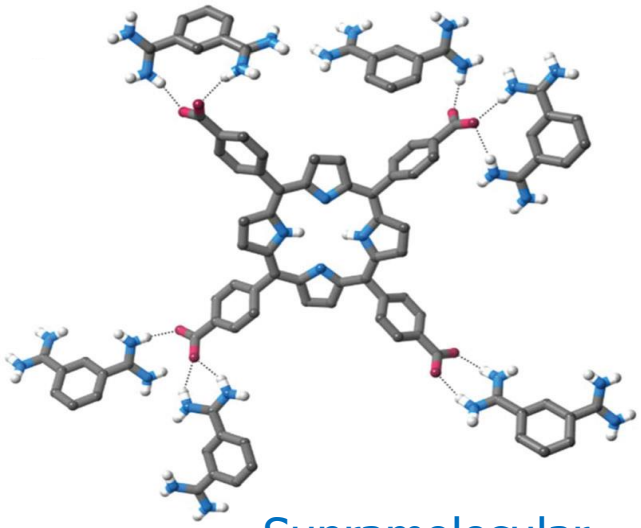
Chemical Crystallography & Advanced Materials



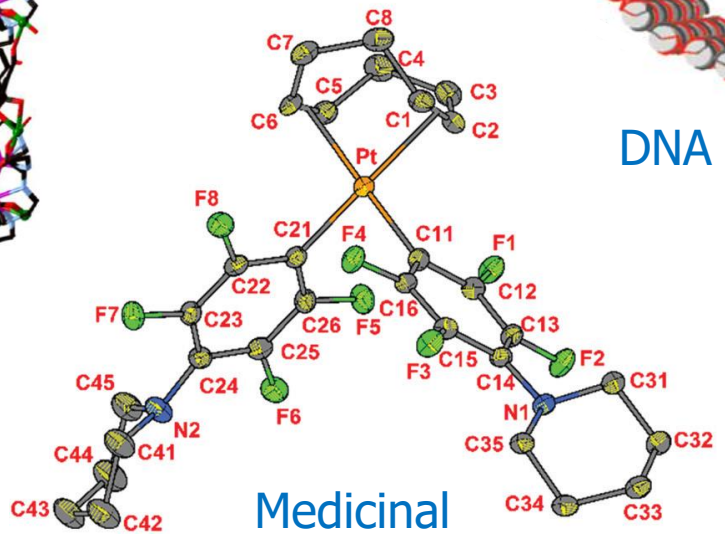
Gas Separation & Storage



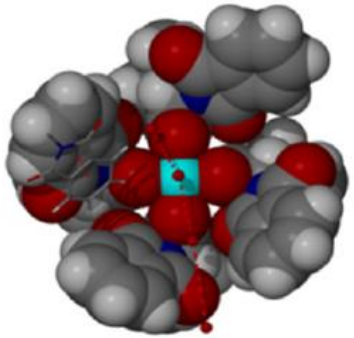
DNA Origami



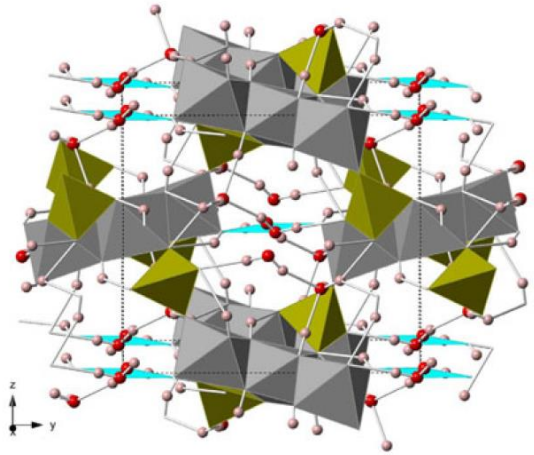
Supramolecular Frameworks



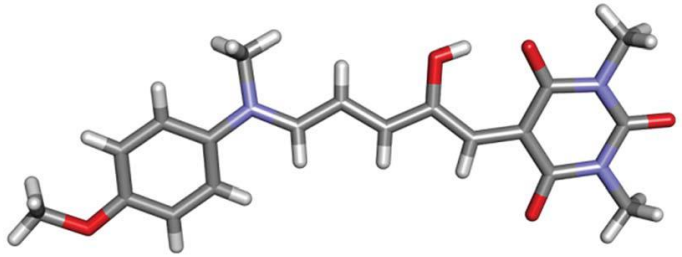
Medicinal Chemistry



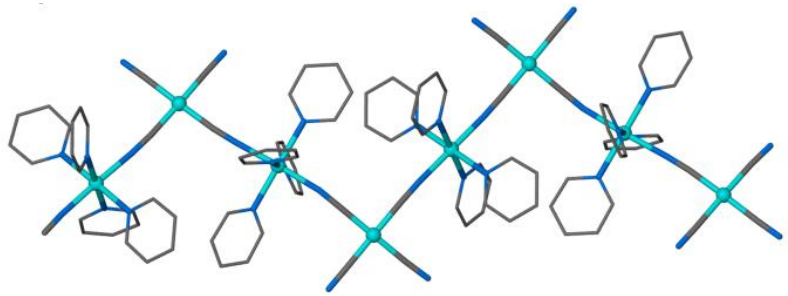
Catalysts



Mineralogy

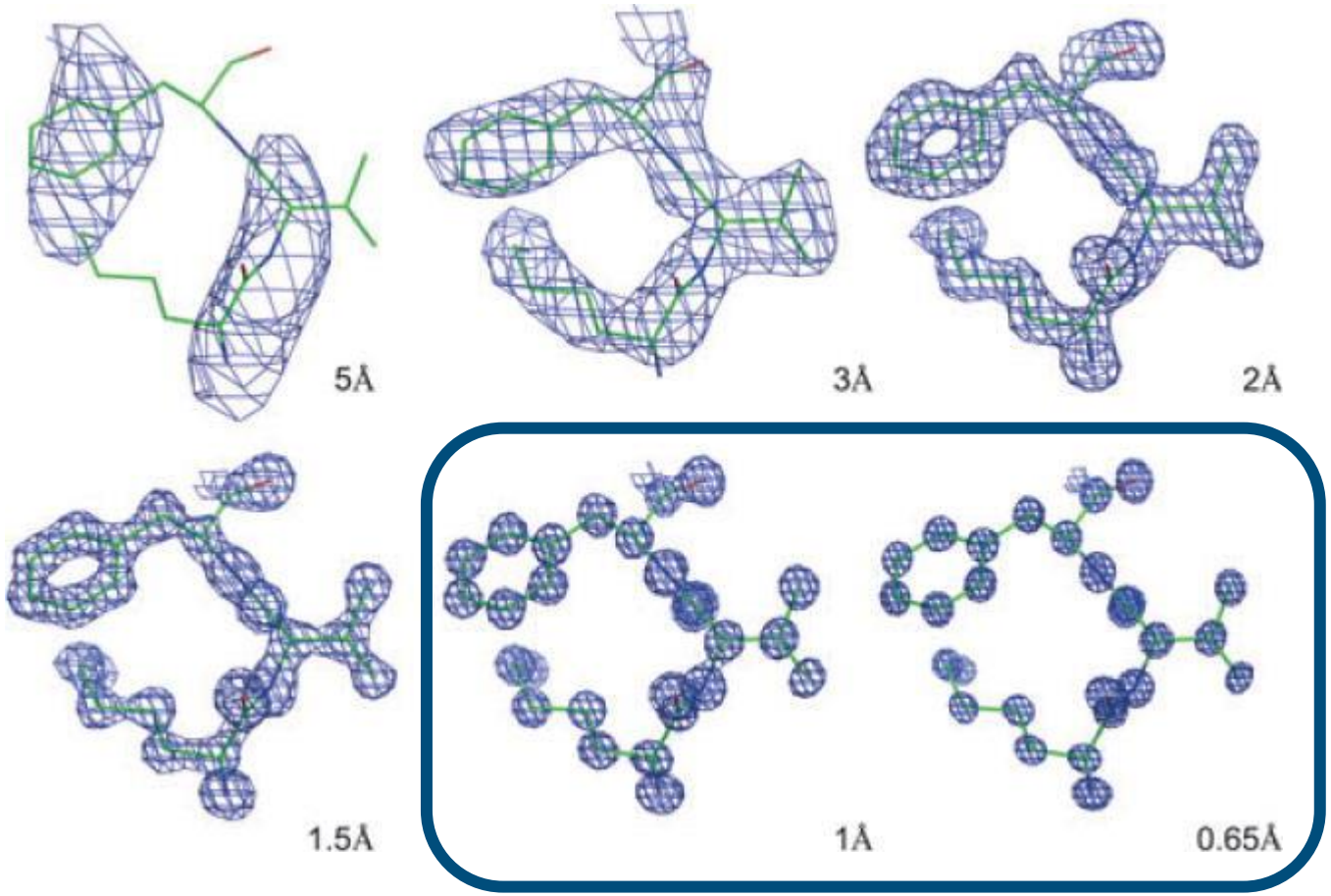


Photochromic Switches



Coordination Polymers

Different requirements for different users



CX

- Heavy-atom phasing (SAD/MAD)
- Elemental composition
- Temperature
- Radiation sensitivity
- Space groups
- Cryoprotectants

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4465431/

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Chemical Crystallography at MX1/MX2

- X-ray energy set at 17.444 keV = 0.71Å (Mo K alpha)
- Detector at closest approach – highest resolution
- Different processing pipeline for data indexing and reduction

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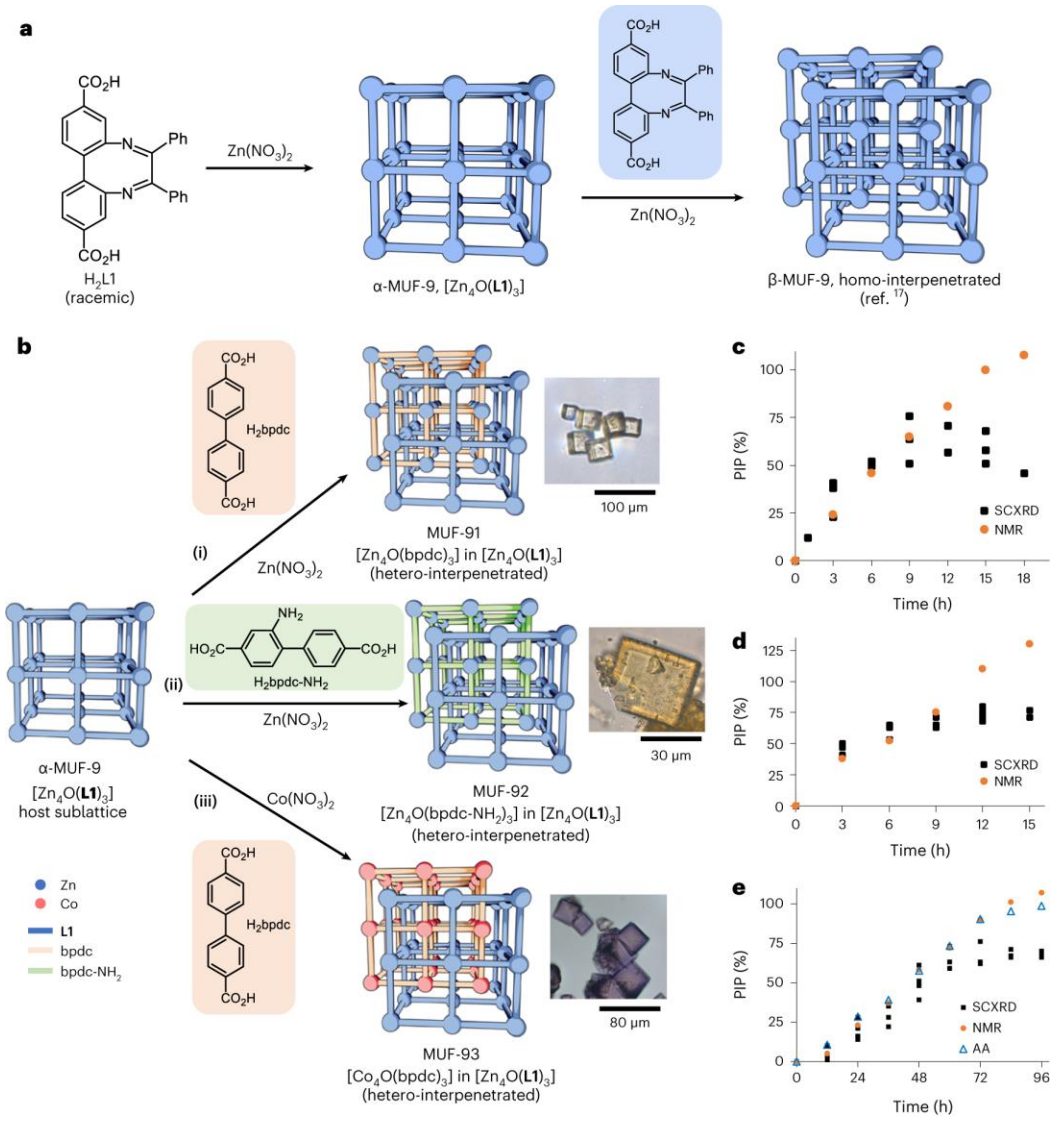
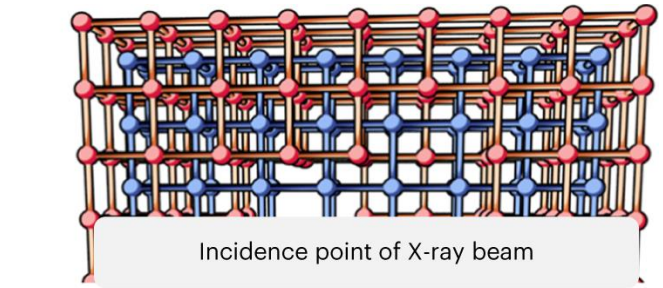
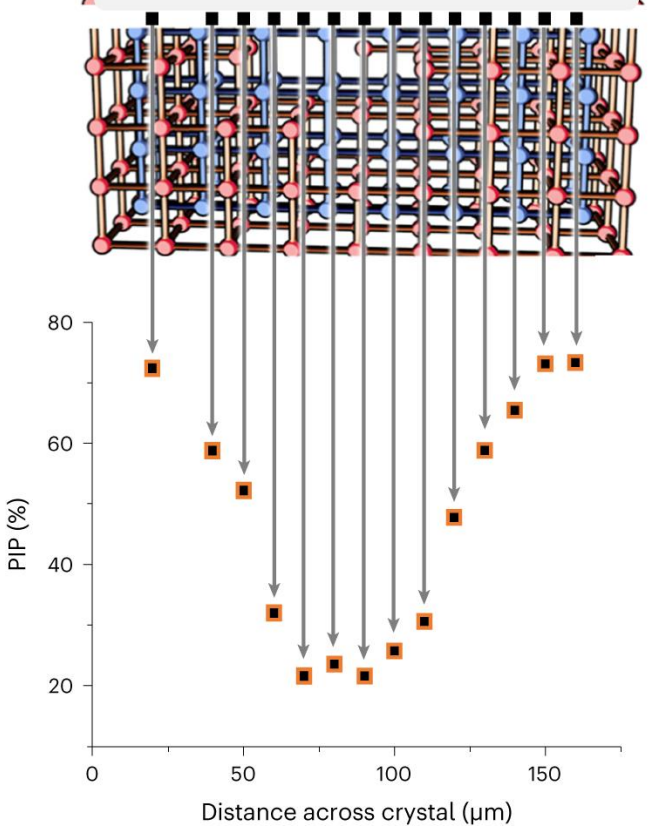
Framework catalysts for chiral synthesis







S. Telfer, ***Nature Chemistry***, 2023, 1**5**, 1358-1364

In-crystallo experiments

Variable temperature

90-400 K
Automated ramping and data collection

Phase changes, spin-crossover

Micro-focus beam

7.5, 10 and 20 µm beams
Automated rastering for spatial analysis

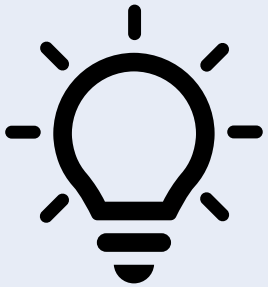
Bendy crystals, multiple domains

High pressure

Up to 5 GPa (50,000 atm)
Micro custom diamond anvil cells

Spin-crossover, molecular rotors

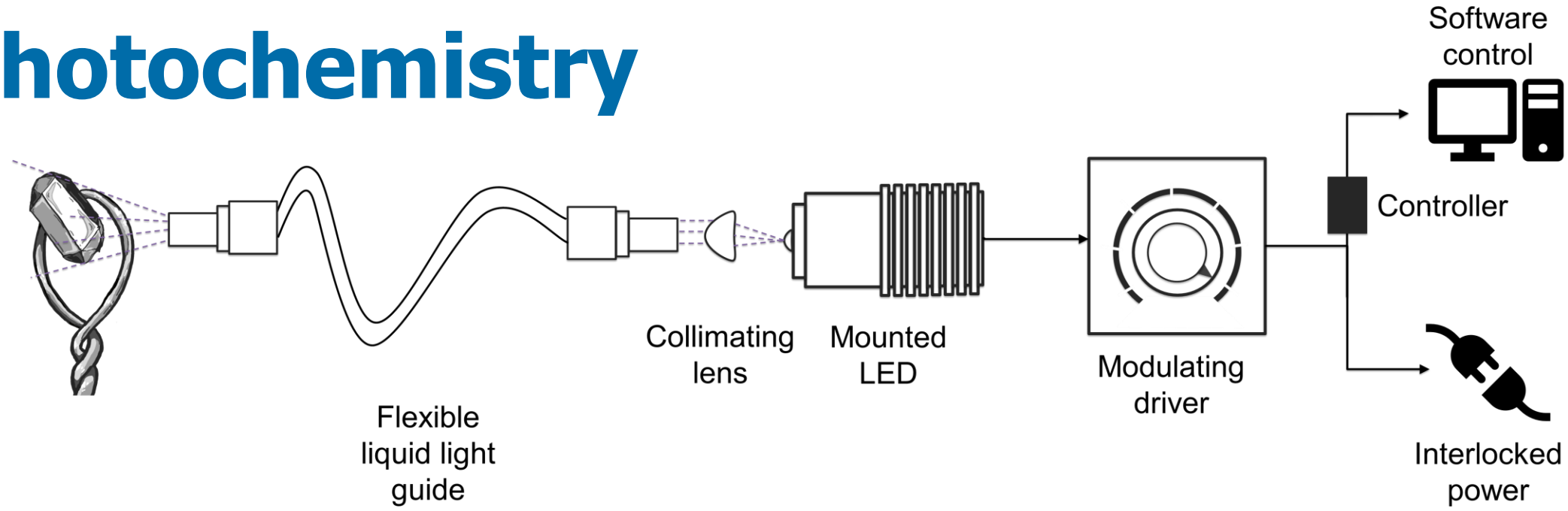
Photochemistry



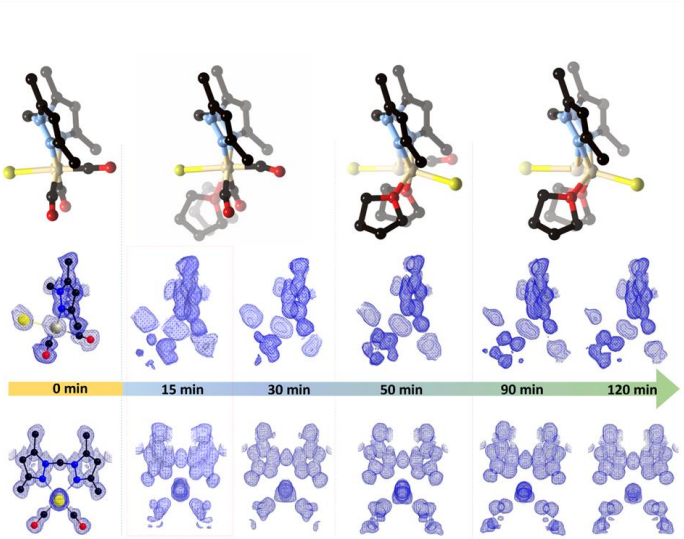
25 narrow-bandwidth LEDs
265-1050 nm

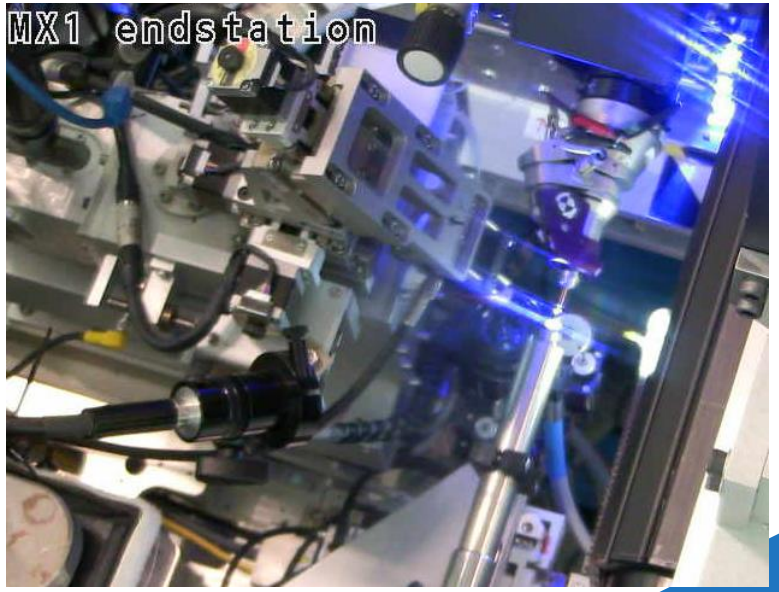
Redox activity, bond cleavage

Photochemistry



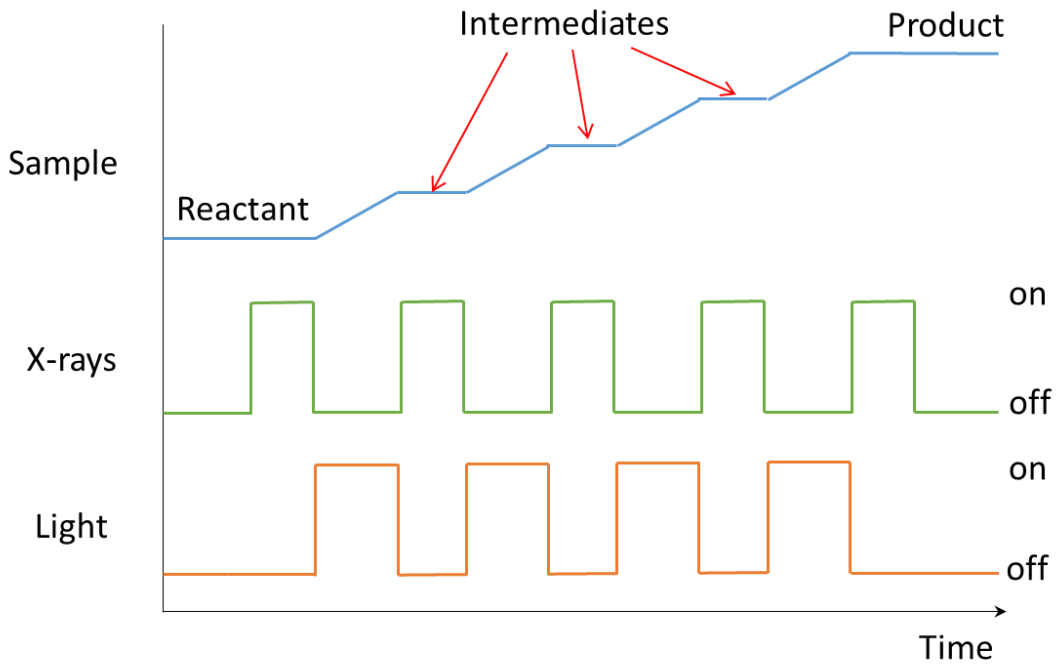
Studying irreversible photo-chemical reactions

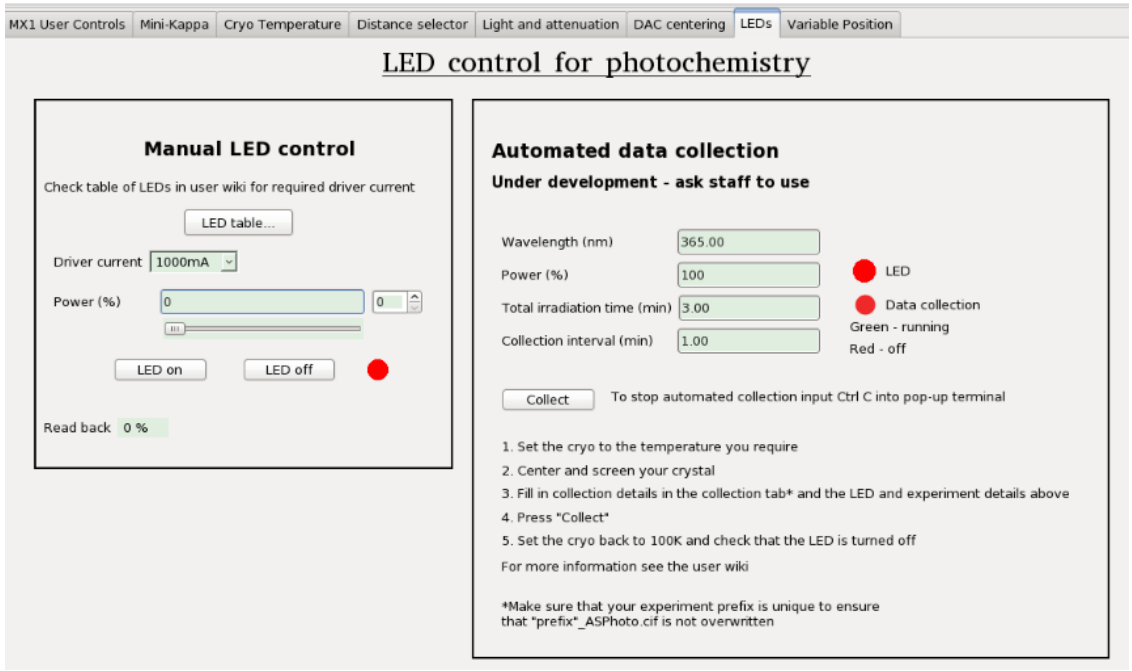




Young, R. J. *et al., Chemical Science,* **2023**, 10.1039/D3SC03553K

Photochemistry





25 narrow-bandwidth LEDs 265-1050nm

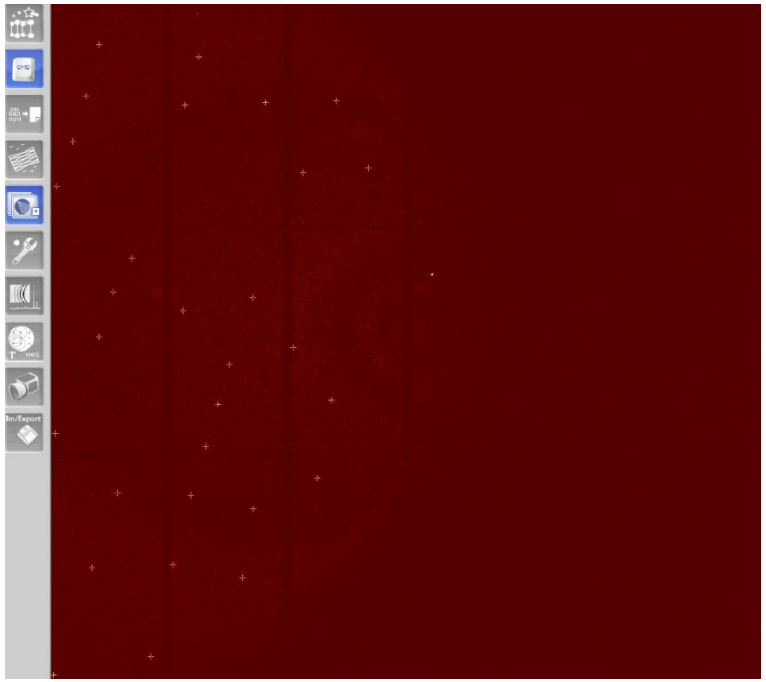
High Pressure

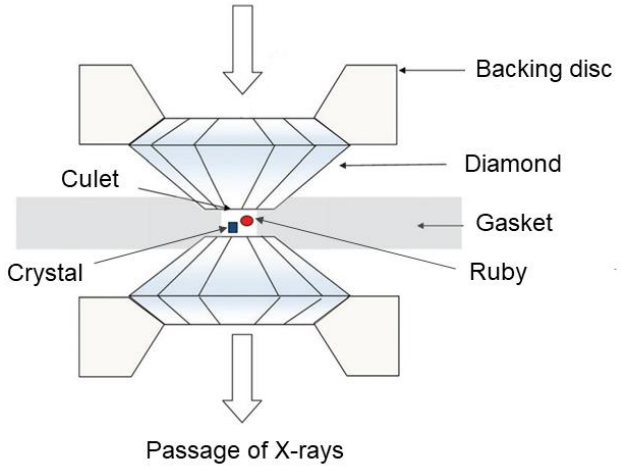
Up to ≈ 5 GPa
≈ 50,000 atm

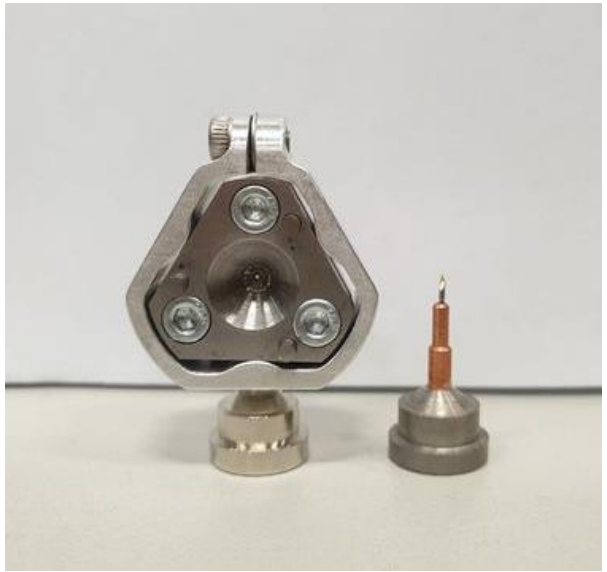
Steph Boer

Mini Diamond Anvil Cell can be mounted as a normal pin

Data collection at room temperature







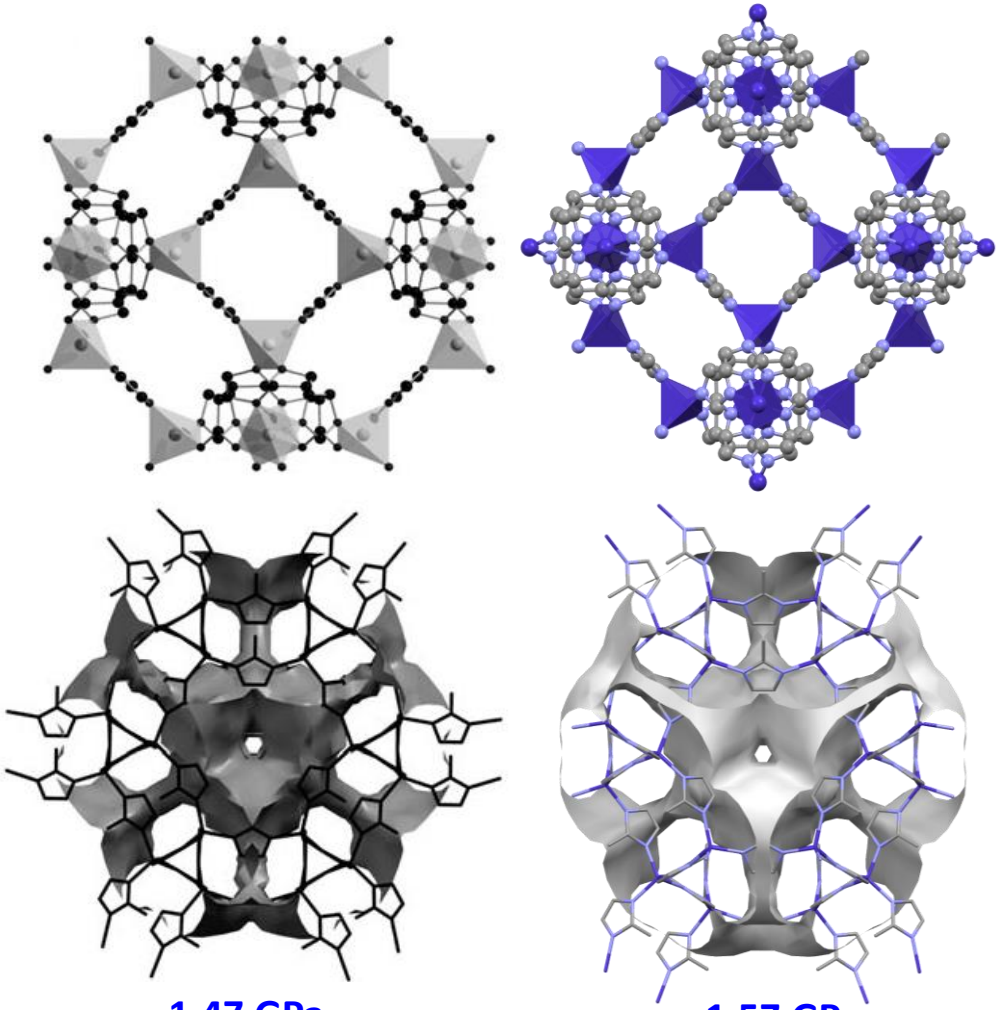
Moggach, S. A. *et al.*, (2008). *J. Appl. Cryst.*, **41**, (2), 249-251

MOFs under pressure

	ZIF-8	ZIF-67
Diffractometer	Bruker Smart Apex diffractometer	MX1
Radiation	$Mo_{k\alpha}$ (λ = 0.71073 Å)	Synchrotron (λ = 0.71076 Å)
Detector	Apex 2 CCD	Eiger2 9M
Collection time	24 hours†	70 seconds
R_1*	0.0512	0.1290
R_{int}	0.073	0.0456
Completeness	0.996	0.925
Resolution	0.80 Å	0.80 Å
Reflections collected	14248	2784
Independent Reflections	956	875
GooF	0.964	1.808
Data/parameter	21.9	25.7

* [I>=2σ (I)

† Could be collect in ~1 hour with more modern instruments



1.47 GPa

ZIF-8
(Zn)

1.57 GPa

ZIF-67
(Co)

S. A. Moggach, T. D. Bennett, A. K. Cheetham, (2009*), Angew. Chem. Int. Ed.*, **48**, 7087 –7089

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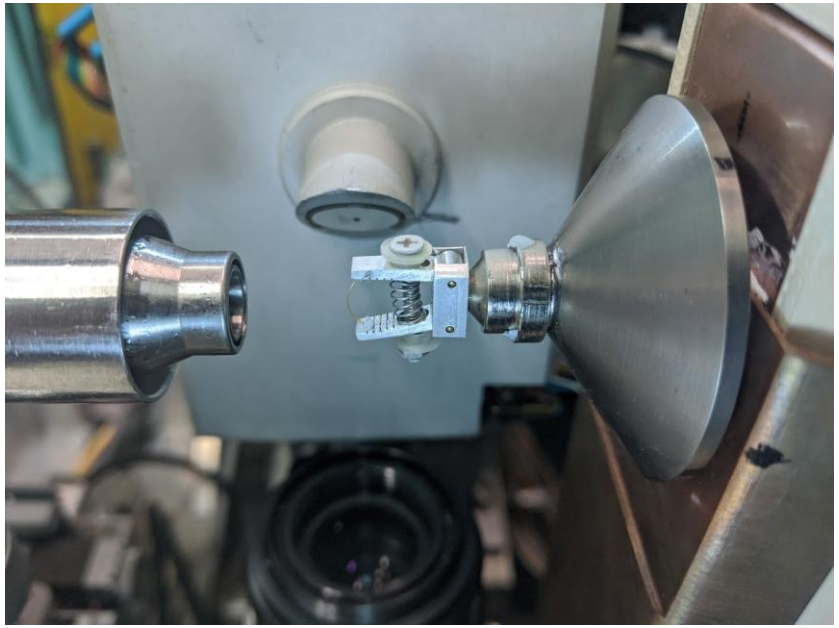
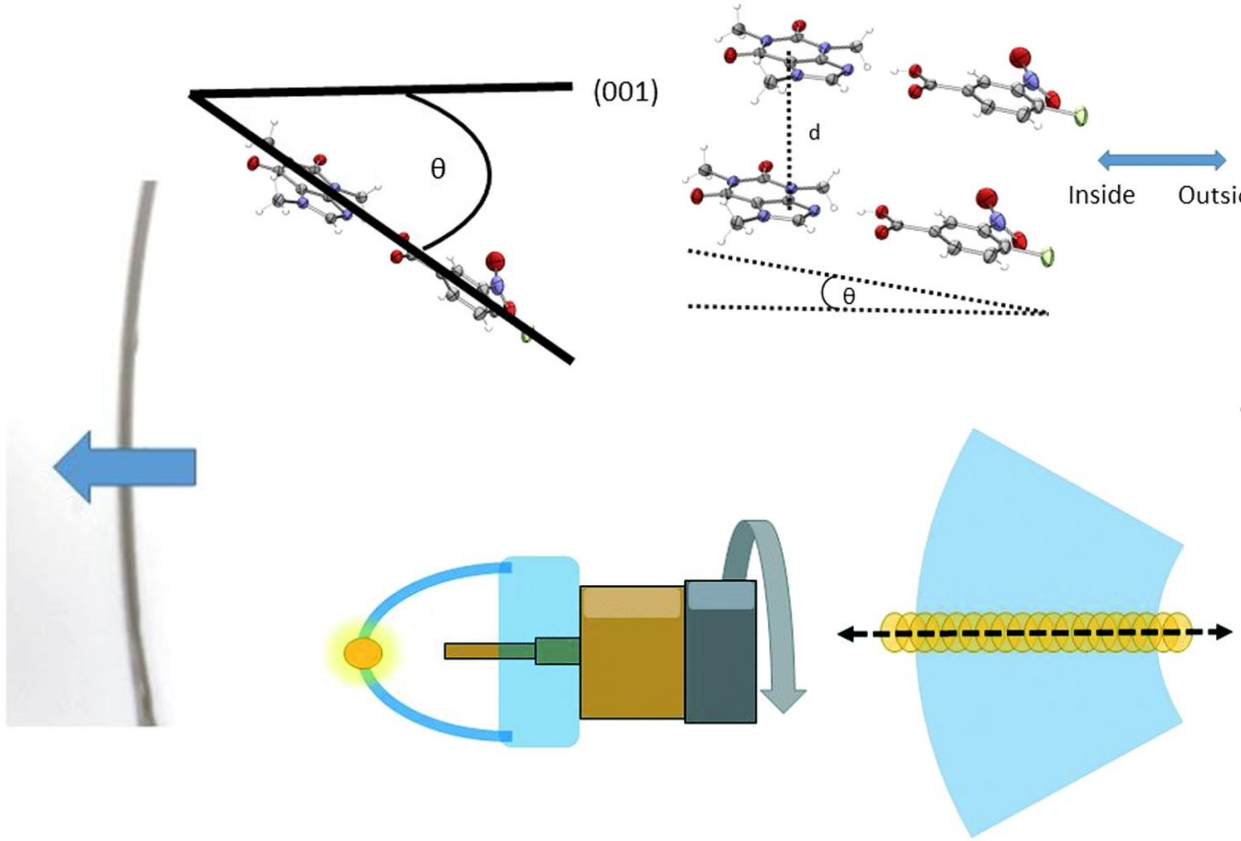
Position analysis

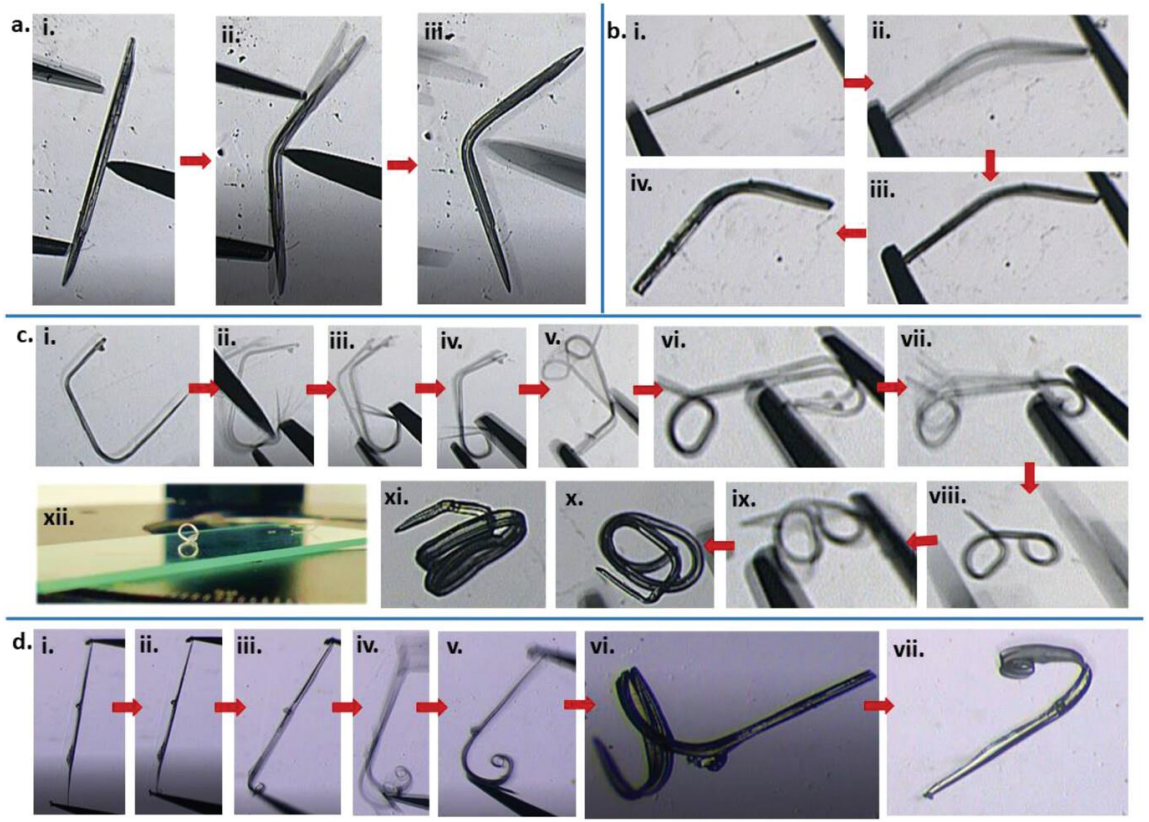
Amy Thompson, University of Queensland

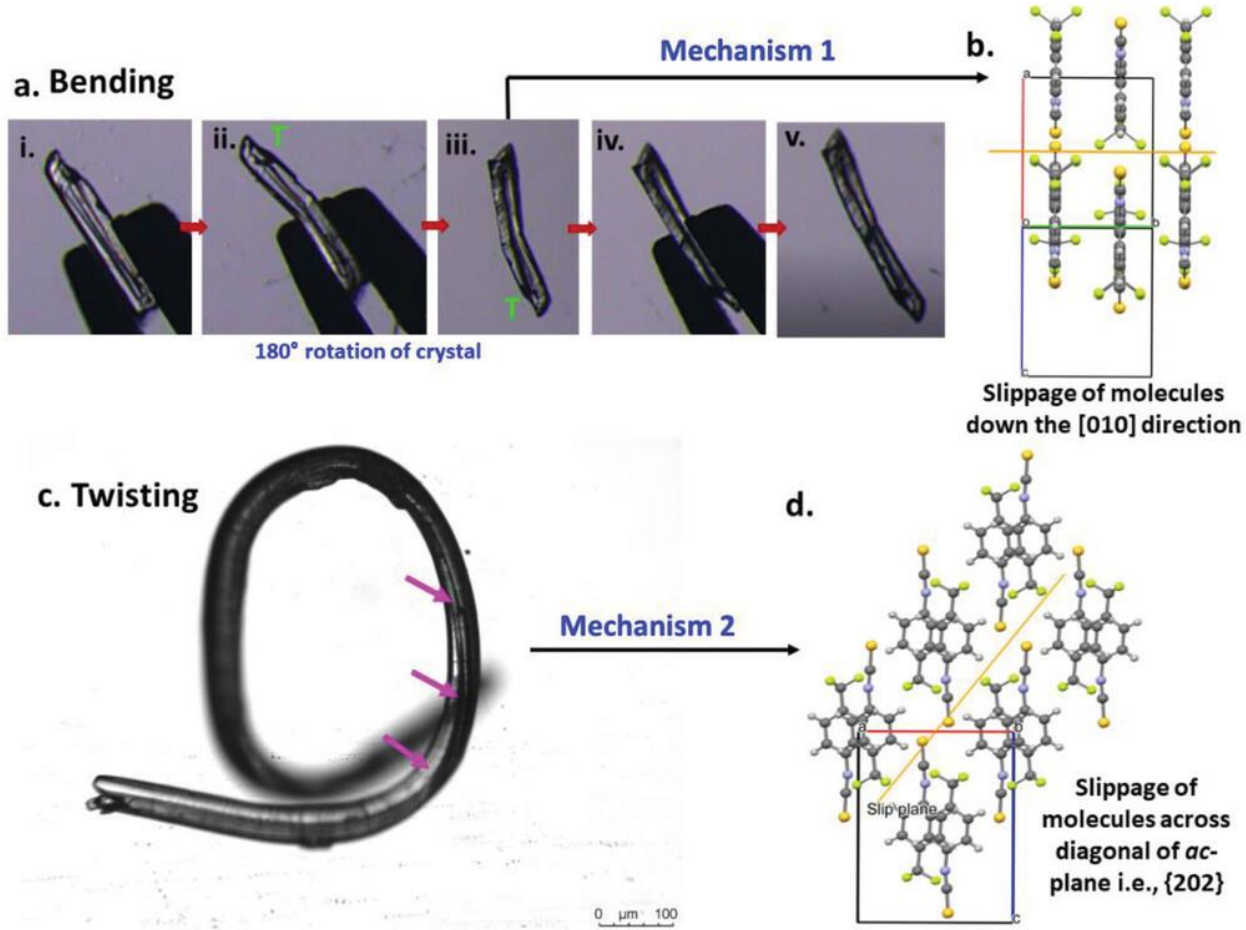
Mapping studies on MX2 using the 7.5 micron microcollimator





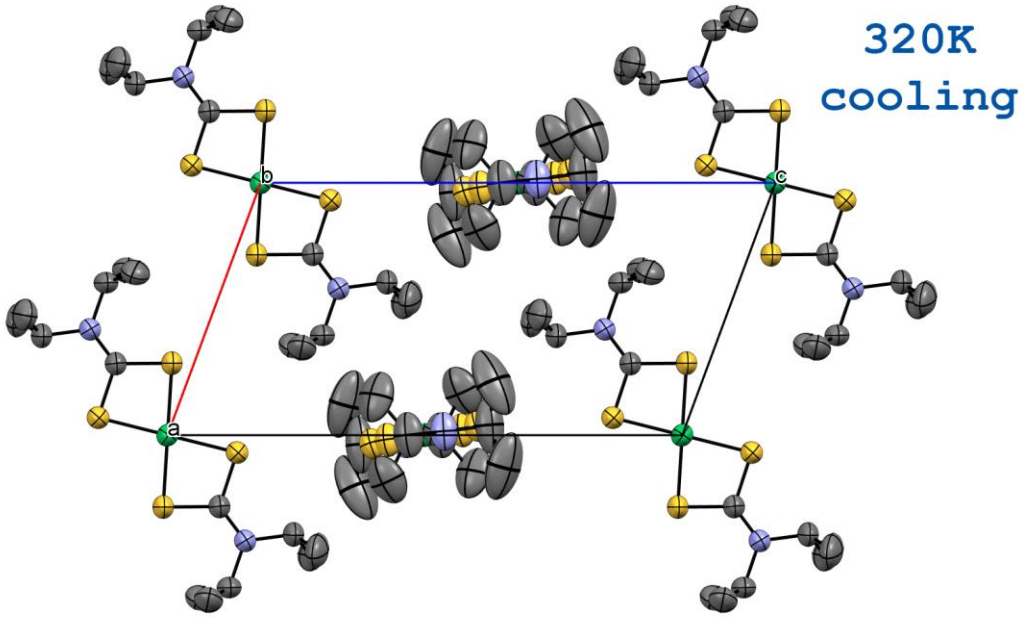
Thompson et al., *CrystEngComm*, **2021**, 23, 5731, *Nat Commun,* **2021**, 12, 5983

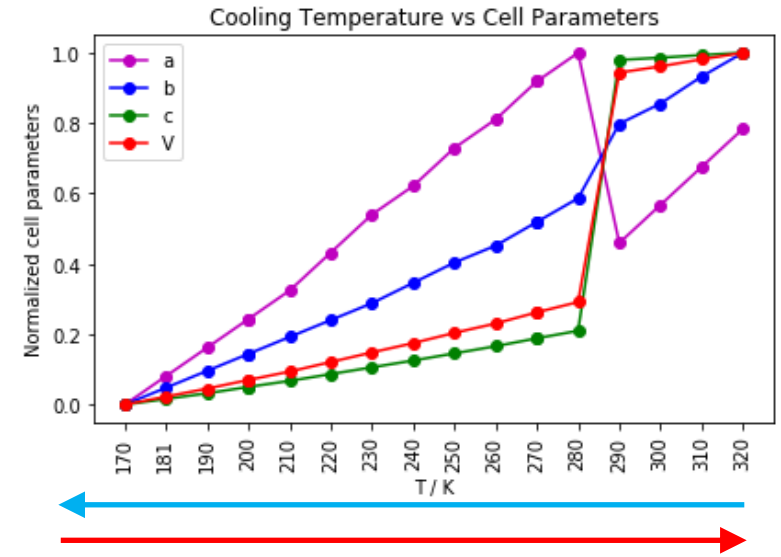


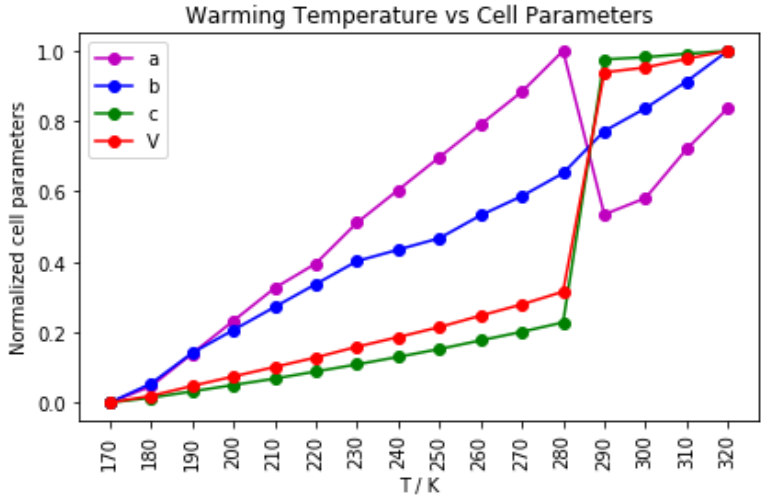


A. Hasija, et al, *Small* 2023, 19, 2206169. https://doi.org/10.1002/smll.202206169

Variable temperature: phase transition







- Temperature ramp
  - Ramp temperature and trigger data collection at temperature.
- Heat 5K every minute
- Collect every 2 mins (10K),
- 32 full data collections in 60 minutes
- 240° sweep, 12 s, 200Hz

Alexander Angeloski, *et. al.*, UTS

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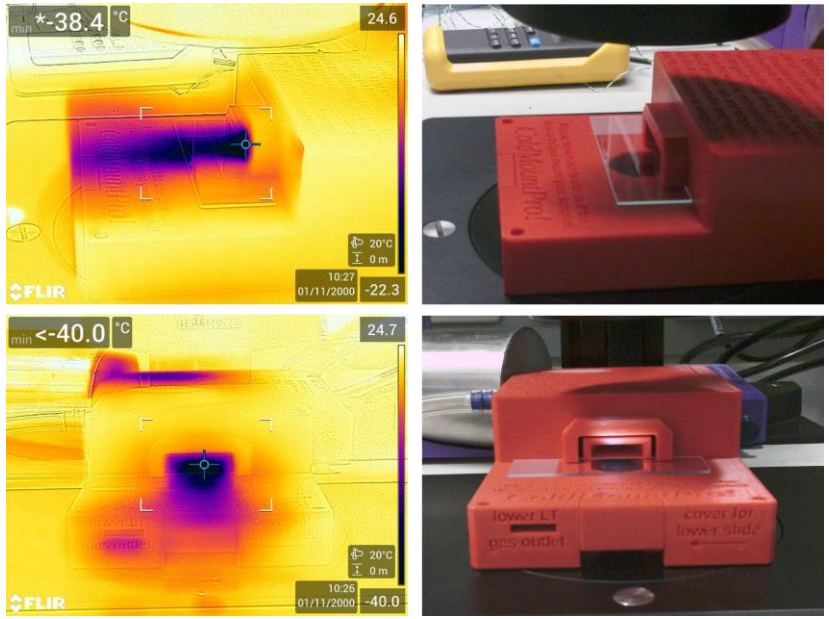
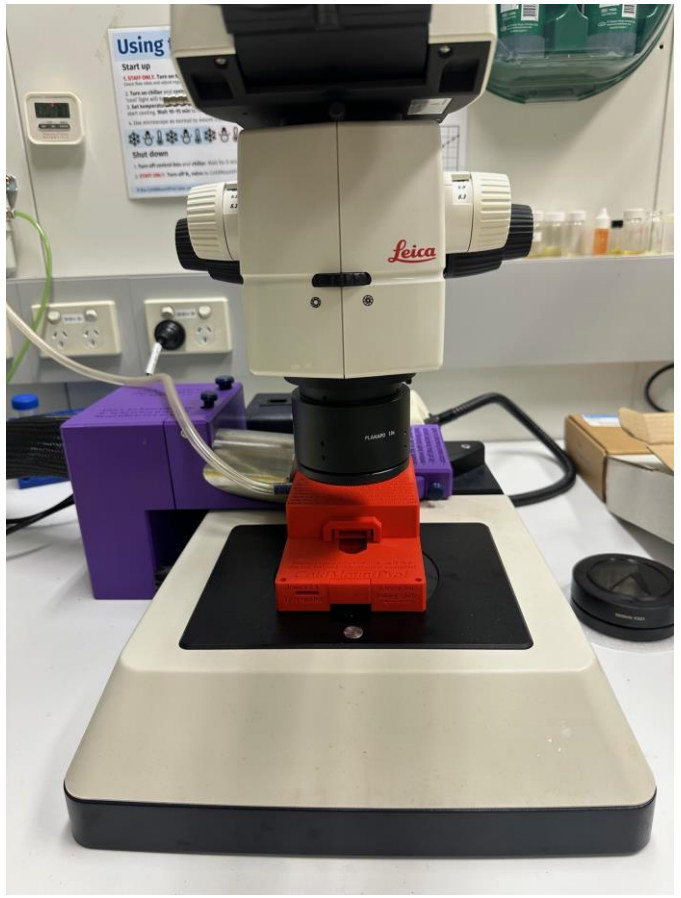
Handling Sensitive Crystals (ColdMountPro)





Australian National University

Designed and built by Dr Michael Gardiner

-80 to +40°C

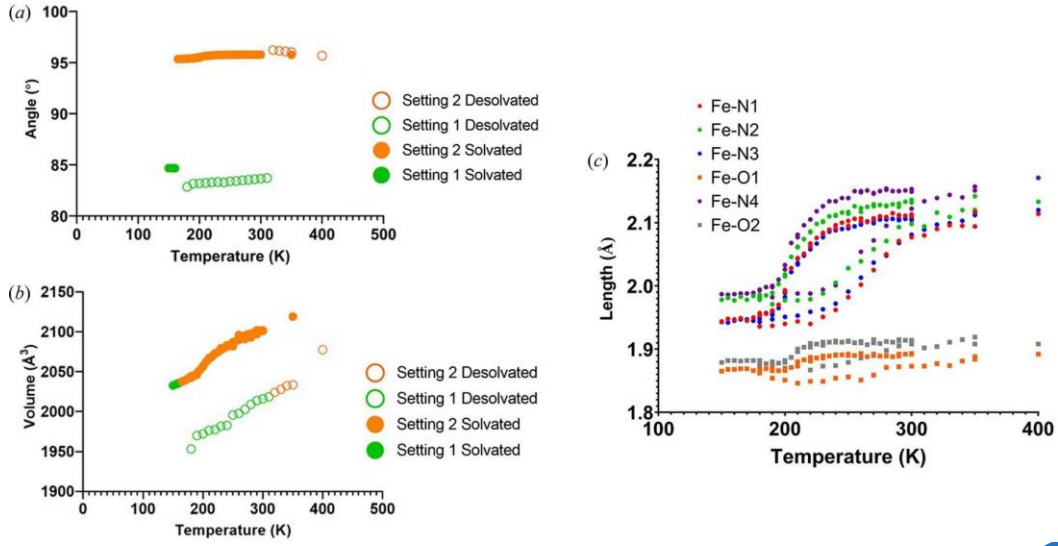
Excellent for reactive or fragile crystals
Easy to use (stays cold and doesn't ice up for hours!)

ANSTO

CX-ASAP

Chemical Xtallography – Australian Synchrotron Auto-Processing

- Open-source data processing and refinement software
- Modular architecture to allow for job-specific pipelines
- Perfect for dynamic crystallographic experiments
  - Variable temperature
  - High pressure
  - Photocrystallography
  - Application of force on crystals (bendy crystals)

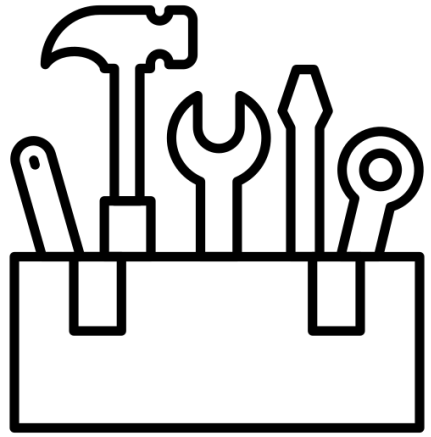


Thompson, A. J., Smith, K. M. L., Clegg, J. K., Price, J. R. (**2023**): CX-ASAP: A high throughput tool for the serial refinement and analysis of crystallographic data collected under varying conditions, *J. Appl. Cryst*, 56. https://doi.org/10.1107/S1600576723000298

Multi-purpose beamlines

Disadvantages

- Changing between collection modes takes time and staff intervention
- Not as optimised as specialised beamlines for the intended experiment



Advantages

- Access a wide range of techniques, software and equipment
- More varied expertise
- Mixing of user communities
- 'Outside-the-box' experiments

ANSTO

Thank you!

MX Staff

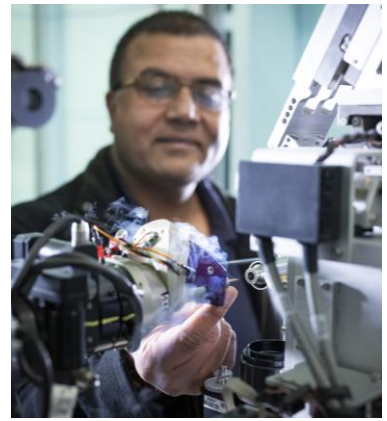
MX1/2

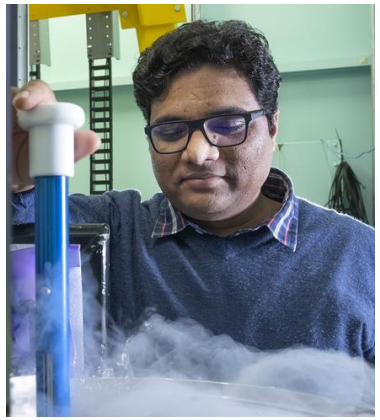
Alan Riboldi-Tunnicliffe
Rachel Williamson
Santosh Panjikar
Stephen Harrop
Chris Szeto
Yogesh Khandokar
Stephanie Boer
Rosie Young

MX3

Tom Caradoc-Davies
Daniel Eriksson
Eleanor Campbell







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