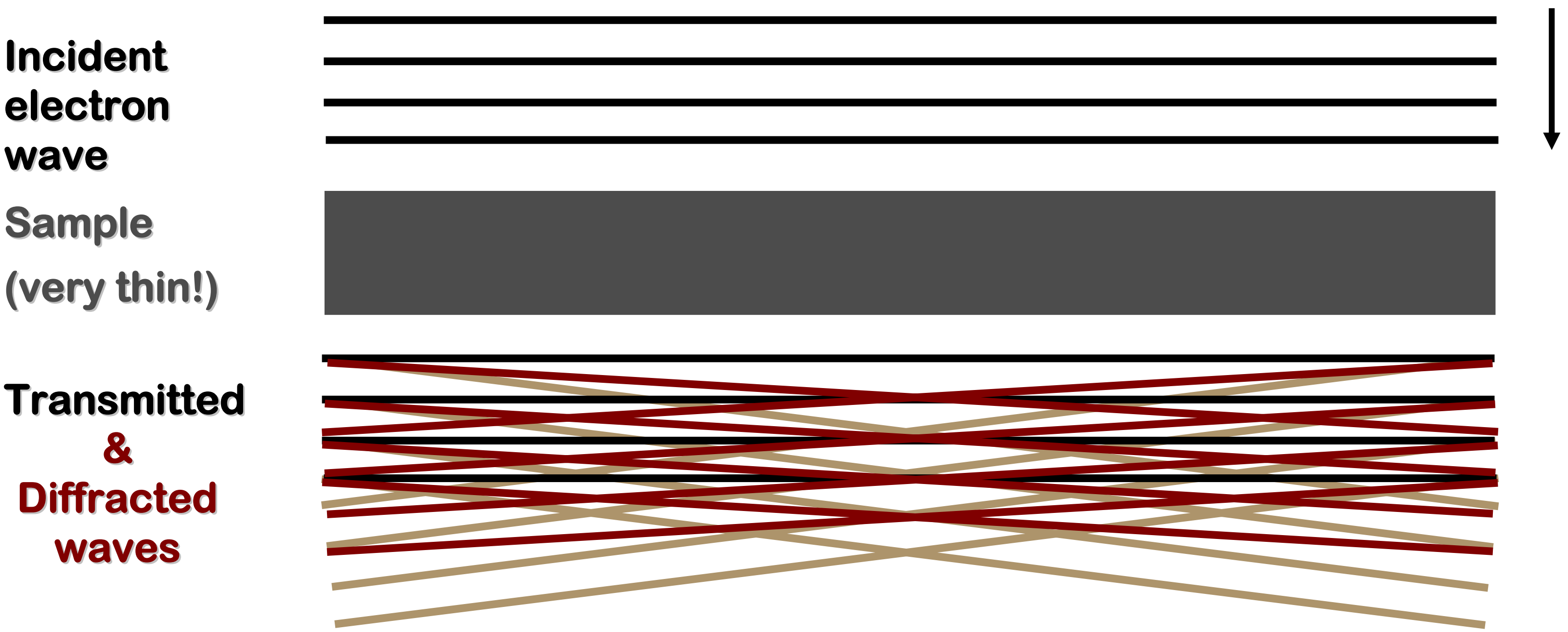
Overview of Phase Contrast & High resolution TEM

Lecture 14

High-resolution EM
general idea



Transmitted & diffracted waves each have a different phase

Result is an interference pattern - our 'phase contrast' or HREM image

High-resolution EM
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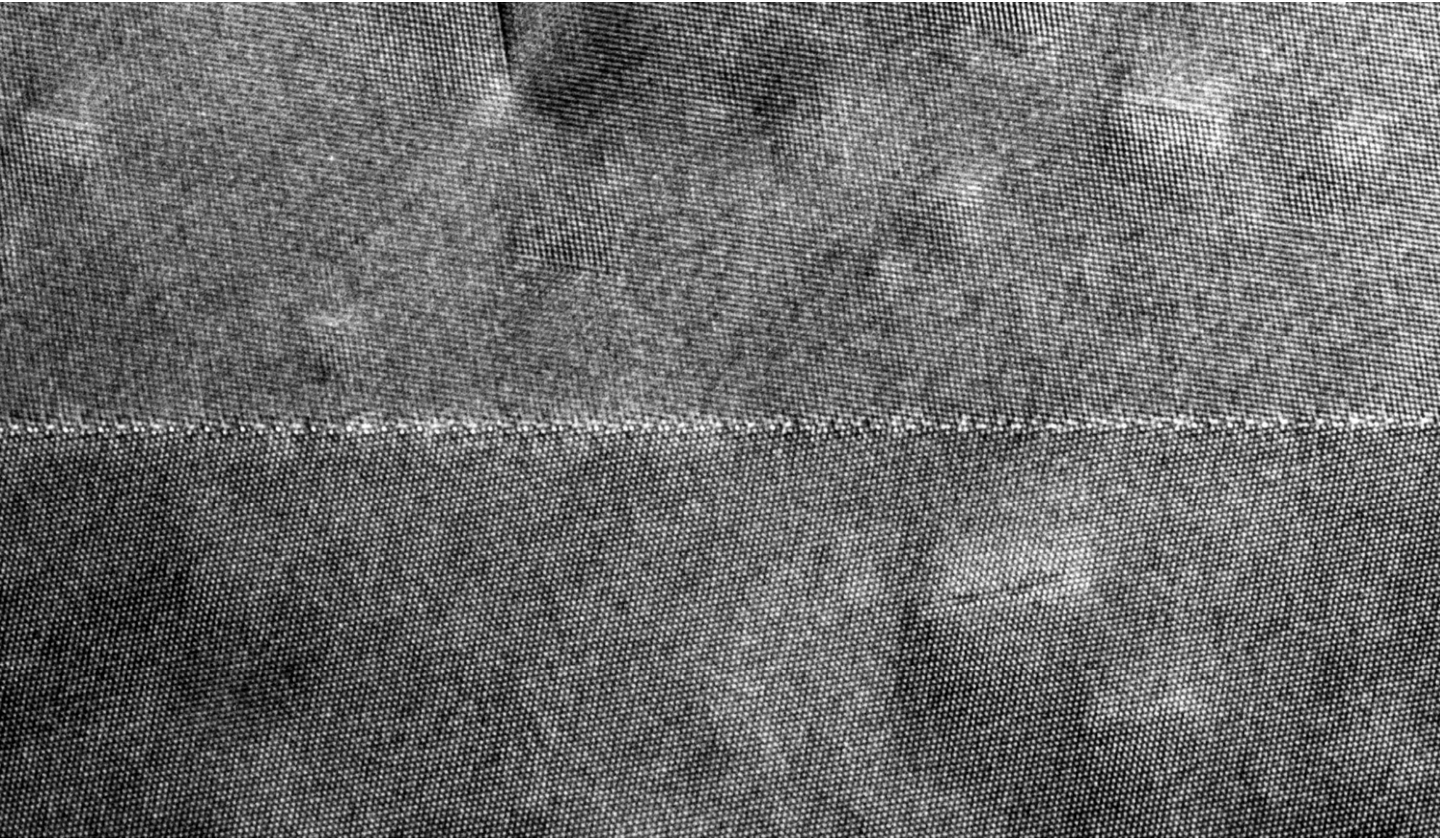

Image courtesy U. Dahmen, NCEM, LBNL

High-resolution EM
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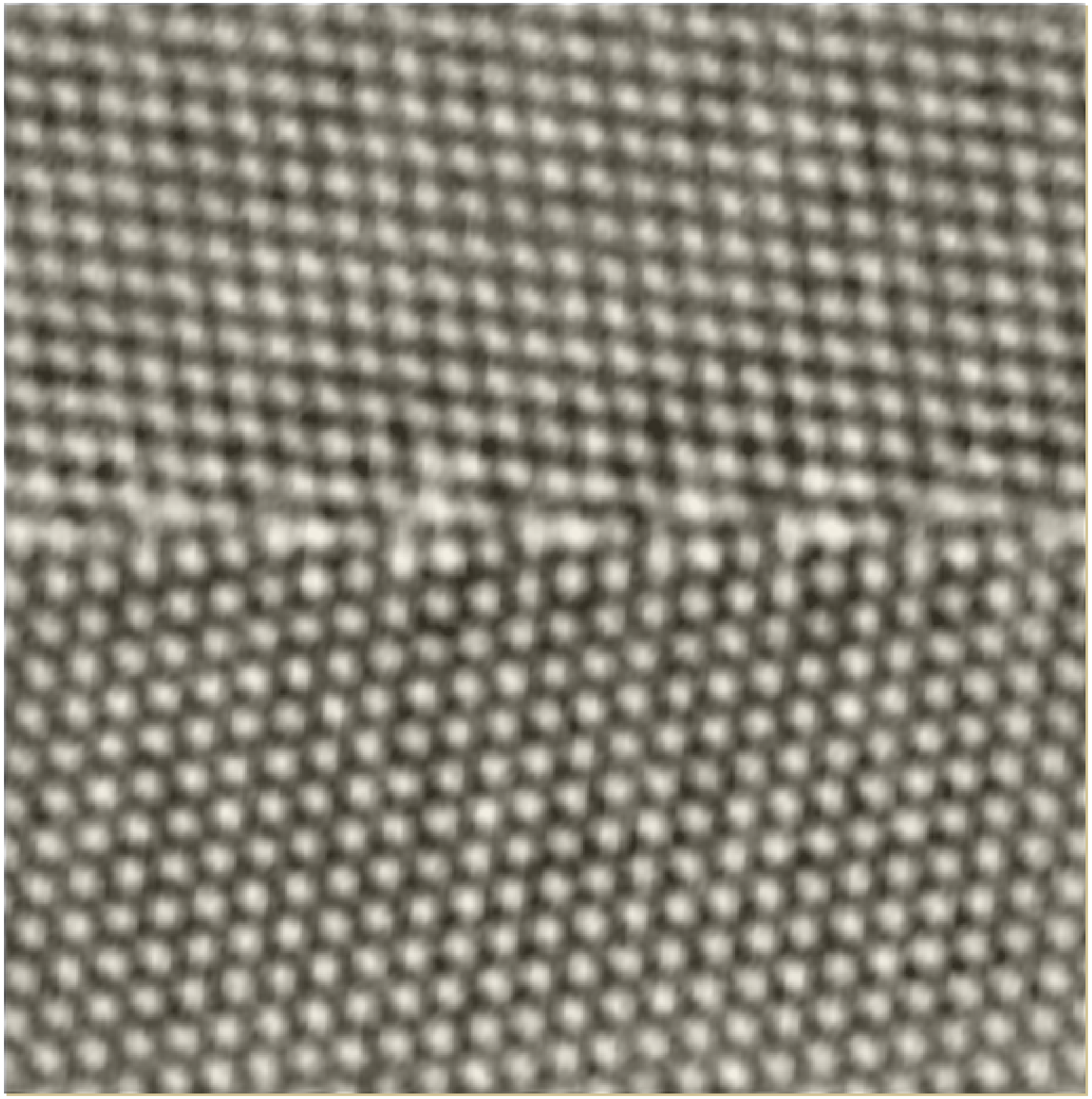

Image courtesy U. Dahmen, NCEM, LBNL

High-resolution EM

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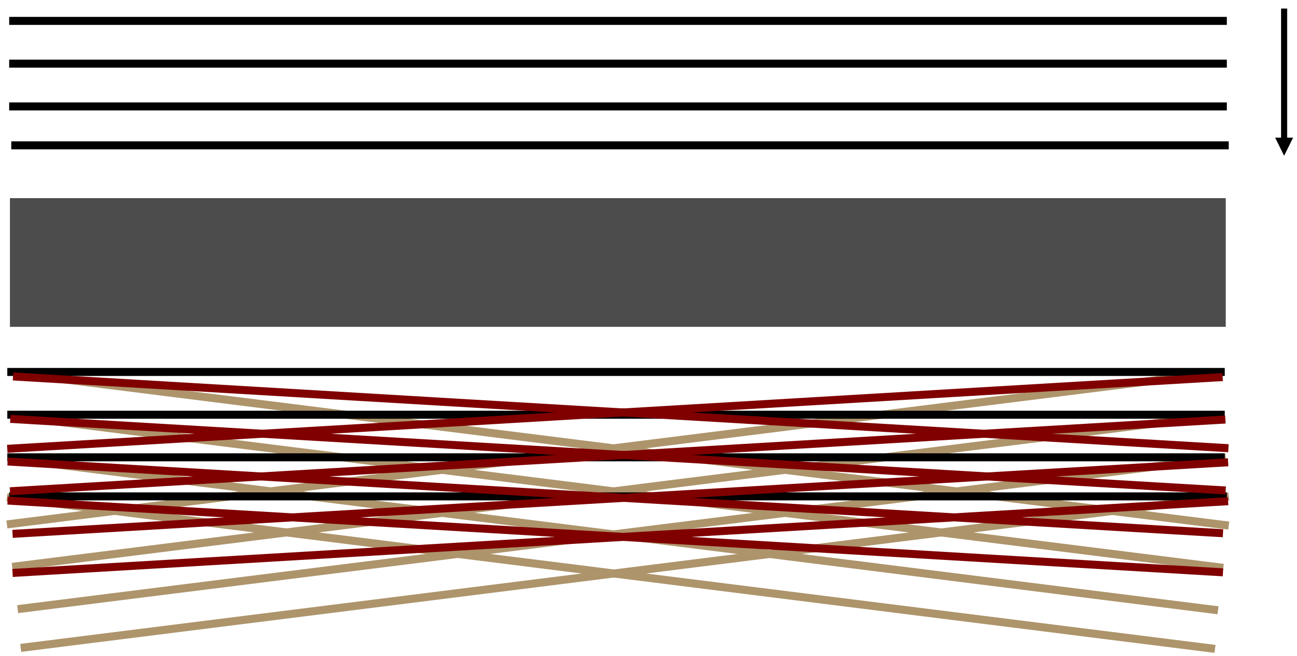
Incident electron wave

Sample

(very thin!)

Transmitted & Diffracted waves



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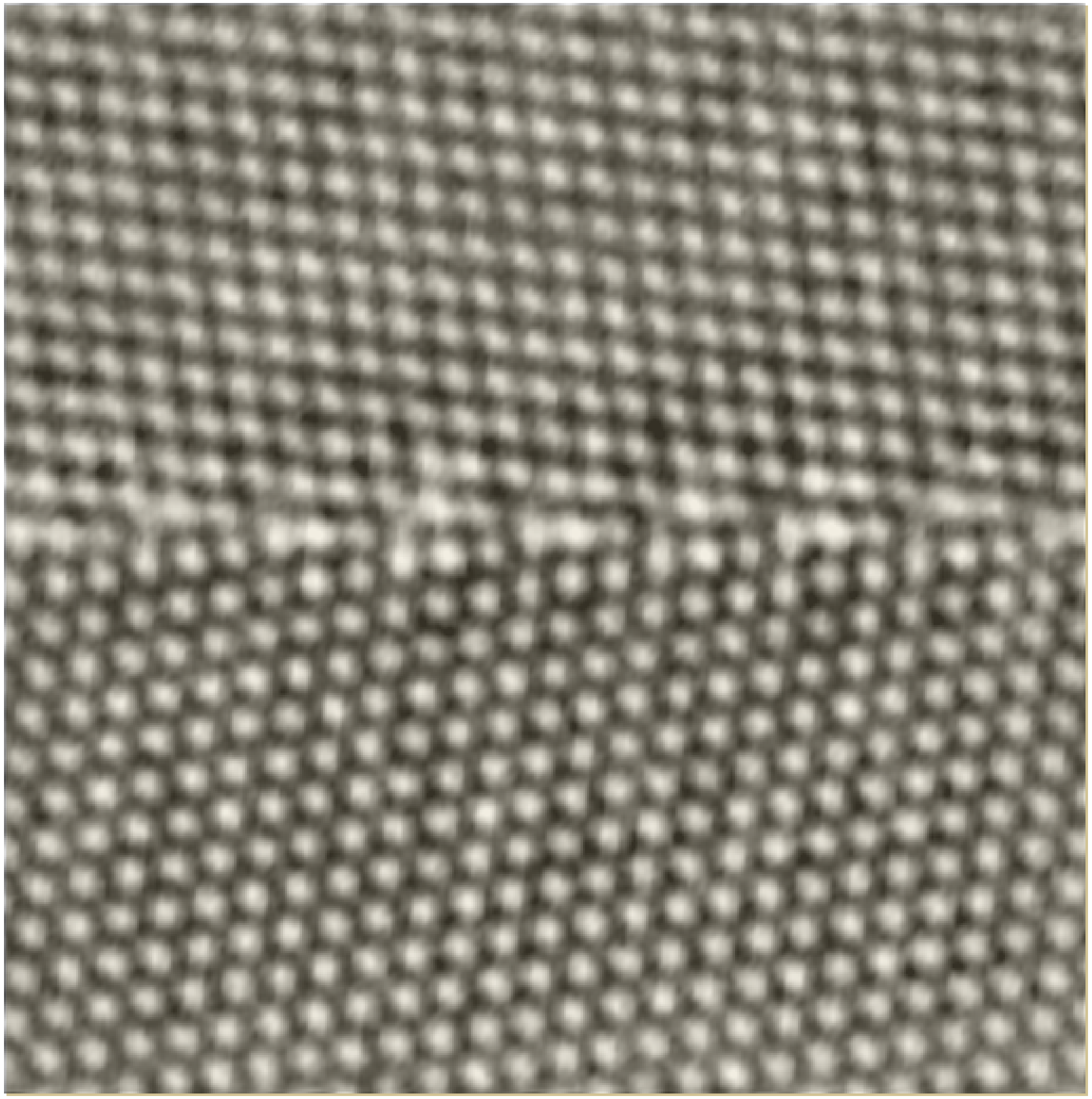

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Why are the phases different?

Transmitted & diffracted waves are allowed wave functions in the crystal

- Together they form the “Exit Wave” which leaves the crystal

They solve Schrödinger’s Equation

$$\nabla^2\psi(\vec{r}) + \frac{8\pi me}{h^2}\left[E + V(\vec{r})\right]\psi(\vec{r}) = 0$$

Solutions are Bloch Waves:

$$b^{(j)}\left(\vec{k}^{(j)},\vec{r}\right) = \sum_{g} \underbrace{C_{g}^{(j)}}_{\text{Amplitude term}} \underbrace{\exp\left[2\pi i\left(\vec{k}^{(j)} + \vec{g}\right)\cdot\vec{r}\right]}_{\text{Phase term}}$$

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Looking at these Bloch waves:

$$b^{(j)}(\vec{r}) = \sum_{g} C_g^{(j)} \underline{\exp\left[2\pi i\left(\vec{k}^{(j)} + \vec{g}\right)\cdot\vec{r}\right]}$$

Phase term has to do with the strength & spacing of the periodic potential of the lattice along a given direction in the crystal (g)

Different diffracted waves have different phase shifts

The total "Exit Wave" is thus the sum over all of the Bloch waves

$$\psi_{total} = \sum_{j=1}^{n} \mathcal{A}^{(j)}\psi^{(j)} = \sum_{j=1}^{n} \mathcal{A}^{(j)} b\left(k^{(j)}, r\right)$$

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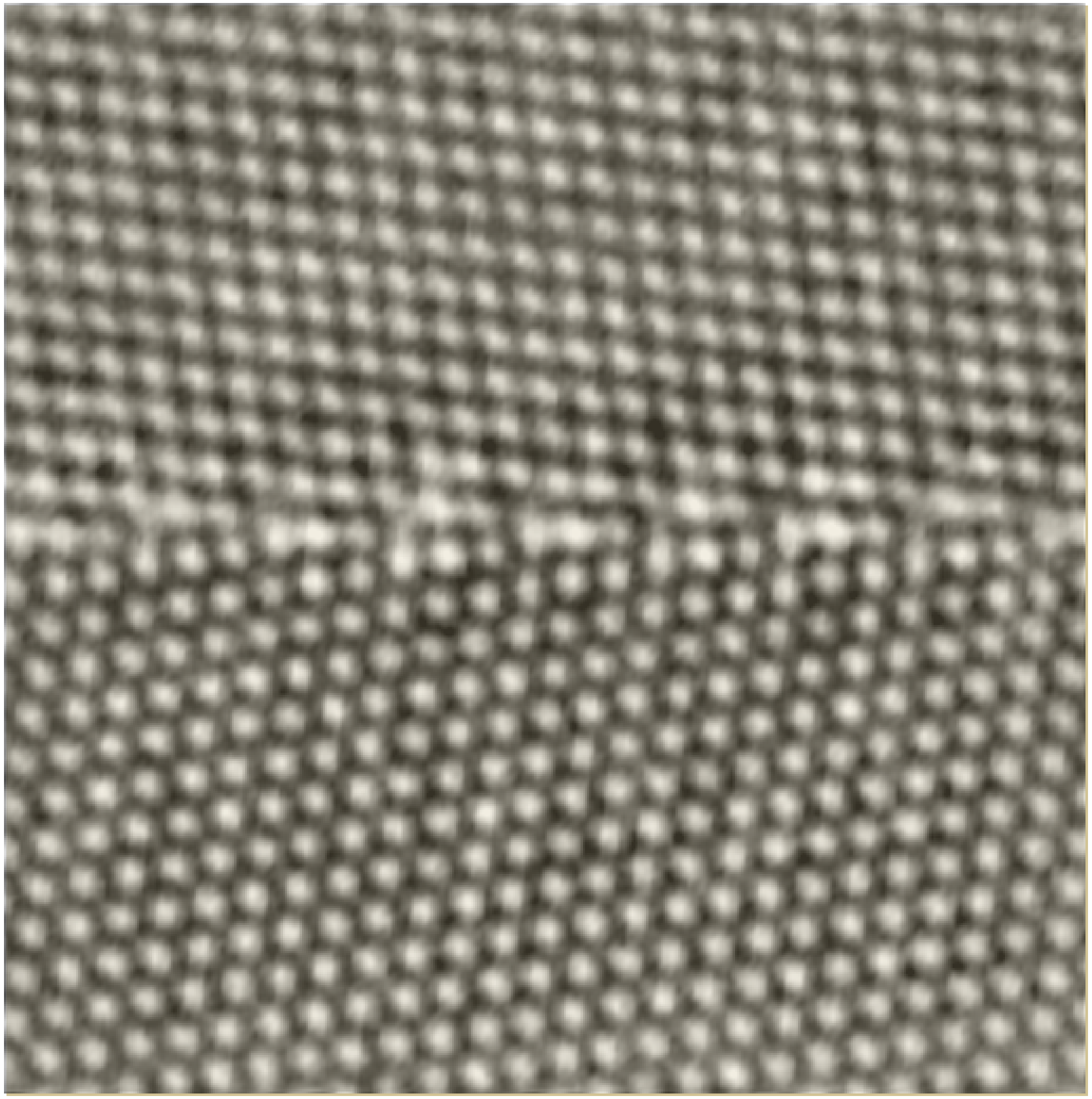

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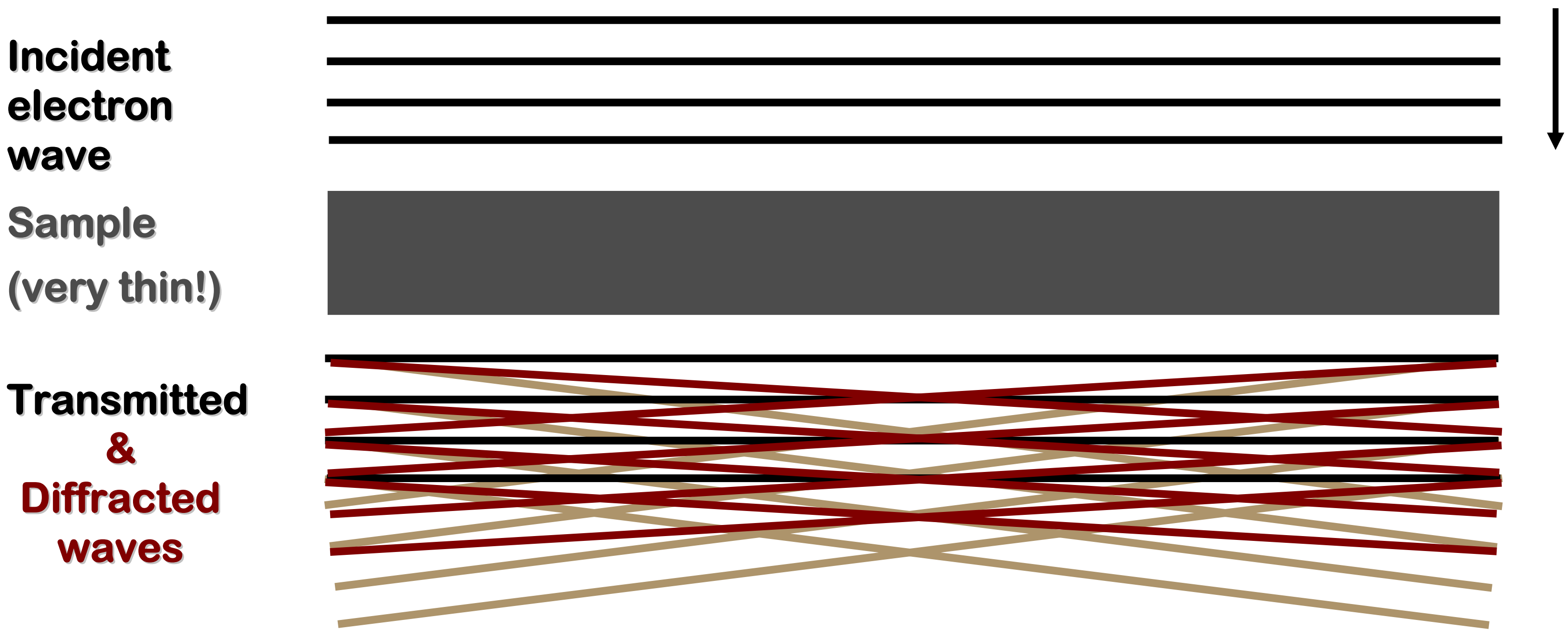


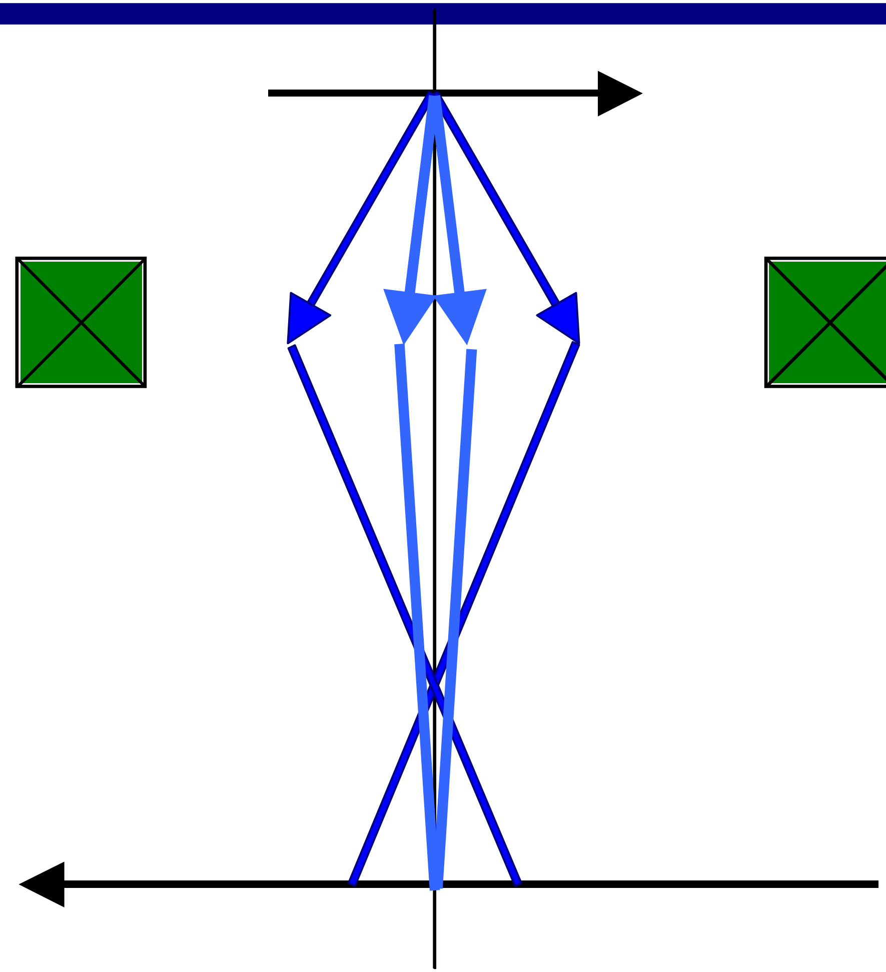
So, appears "simple" enough …

(1) Calculate the phase differences for the different diffracted waves

(2) Create an interference pattern from the overlap of these phases in two-dimensions

High-resolution EM
general idea

- Not even this "simple"
- The TEM has very poor lenses
  - Spherical aberration in particular
- This aberration causes diffracted waves to be 'phase shifted' by the objective lens
  - Complex dependence on wavelength, C_s, diffraction vector and defocus
  - Magnitude of shift varies with distance from optic axis
    - And thus diffraction angle
    - Thus each diffracted wave undergoes a different phase shift
- Complicates image interpretation



Spherical aberration

High-resolution EM
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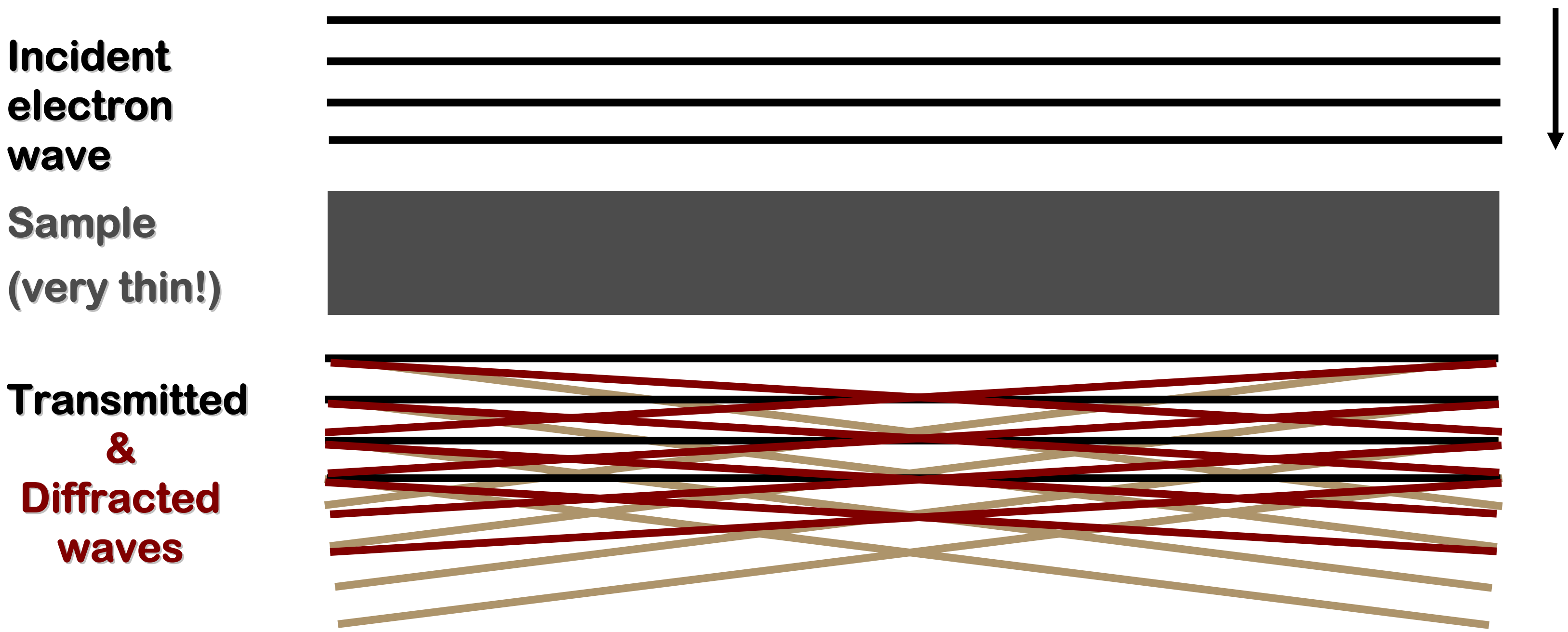

Returning to this picture

This means that the phases of the diffracted waves are changed by the objective lens focus

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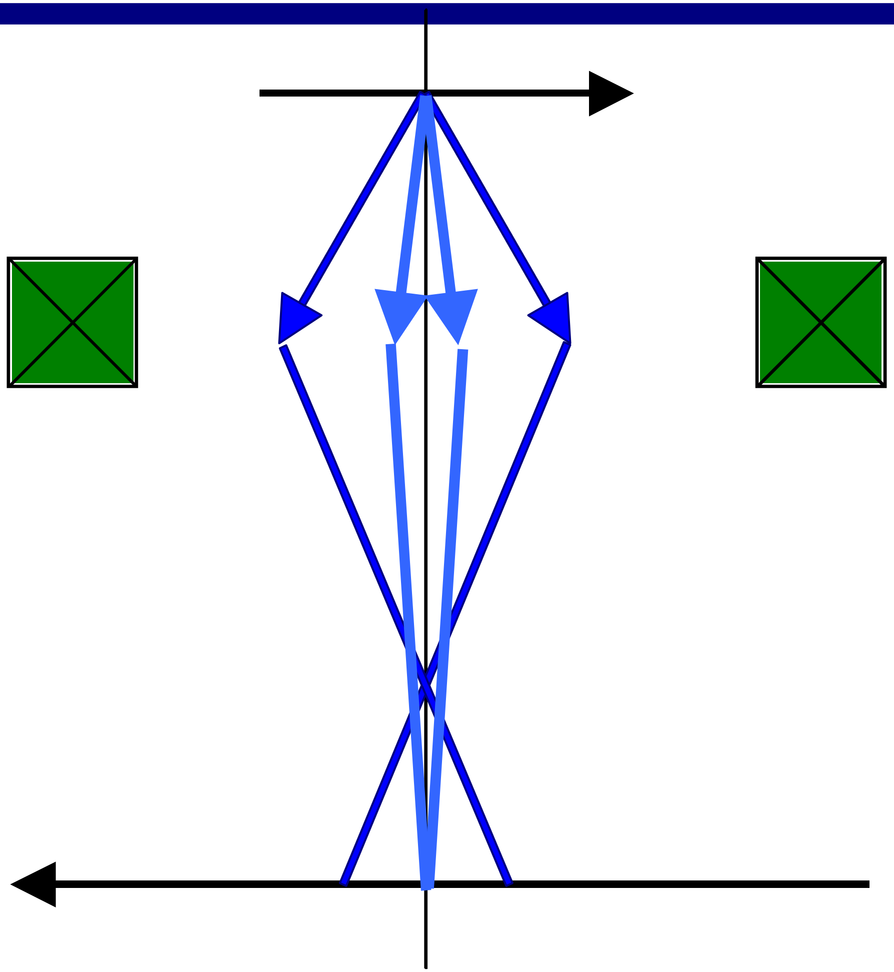

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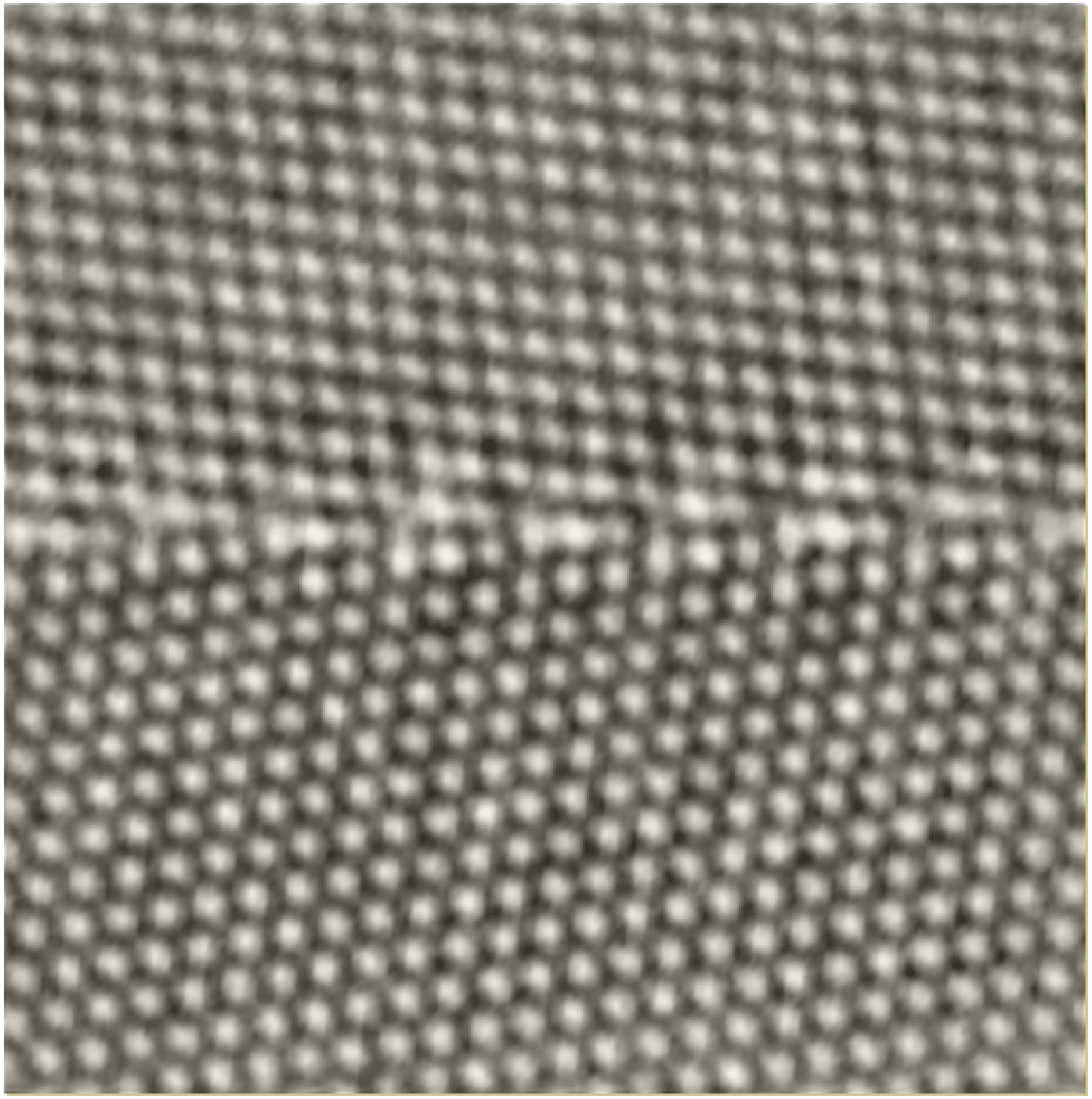

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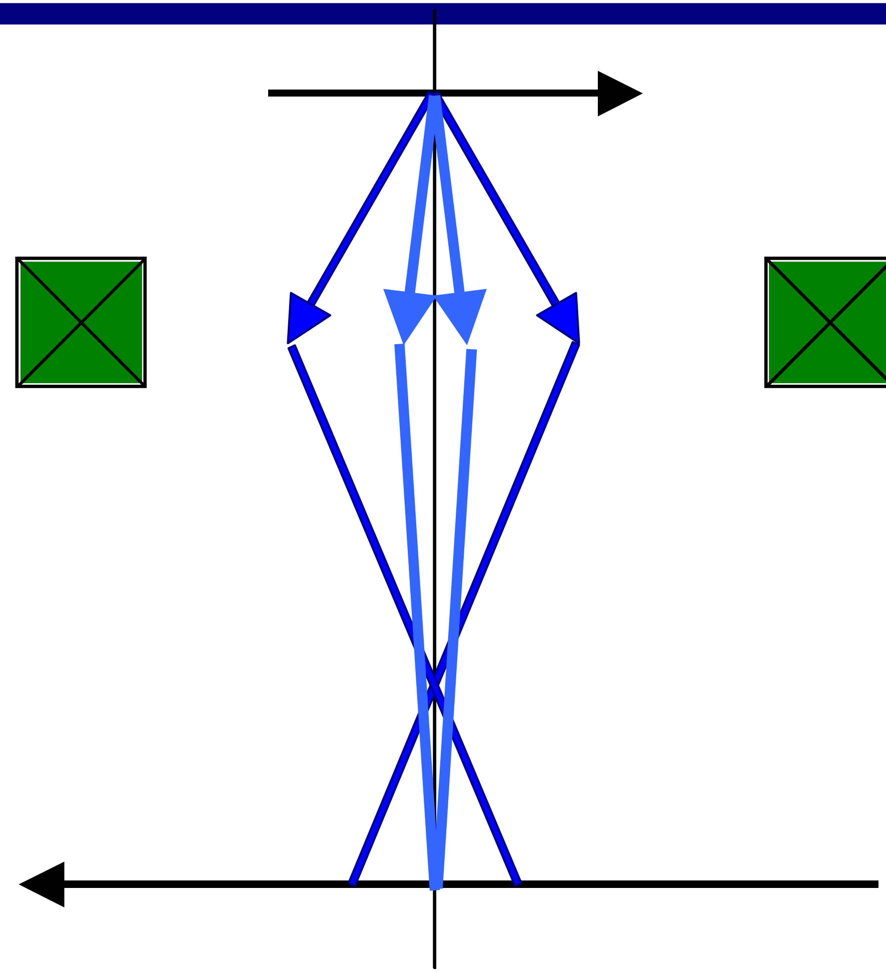

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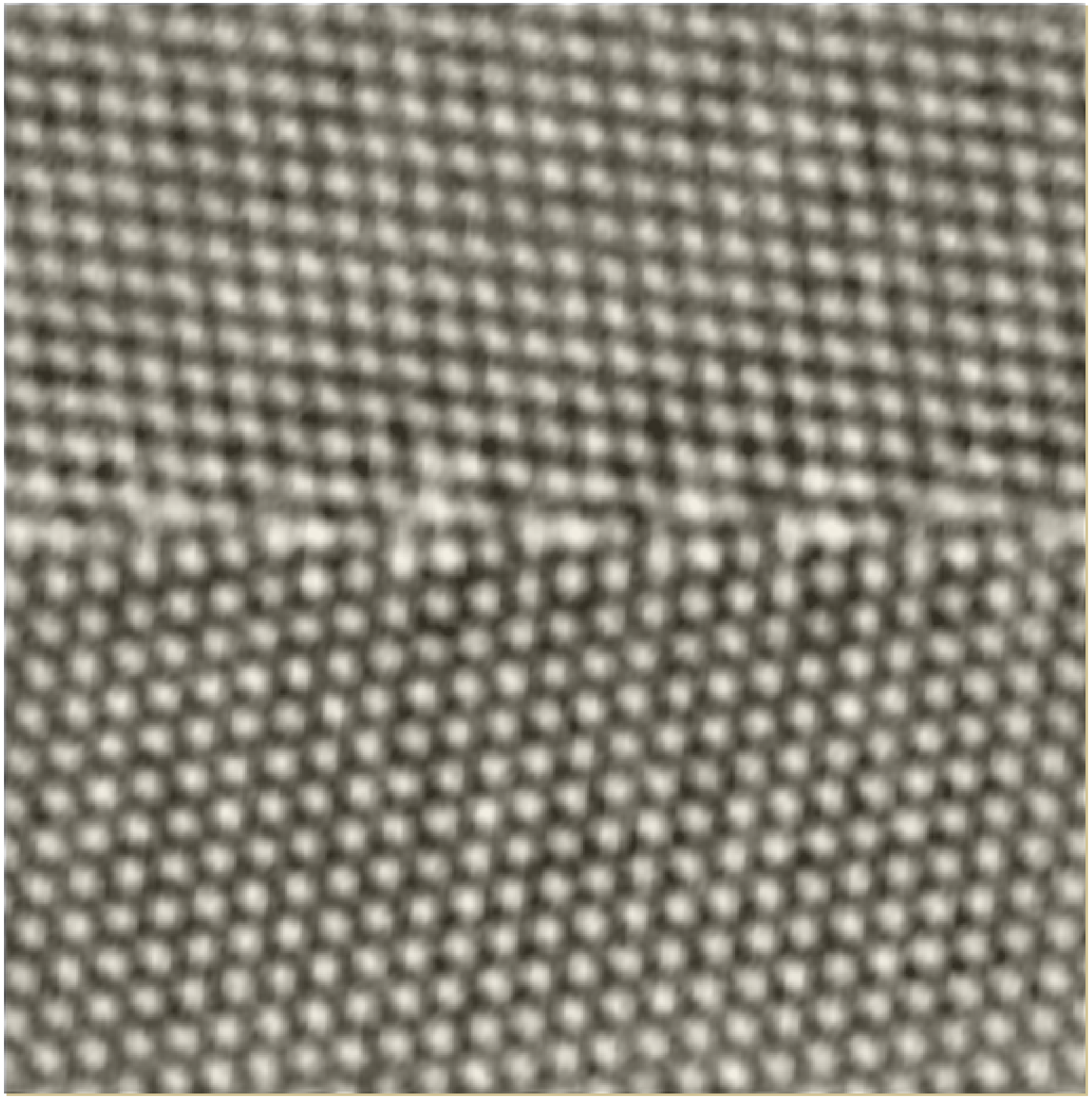

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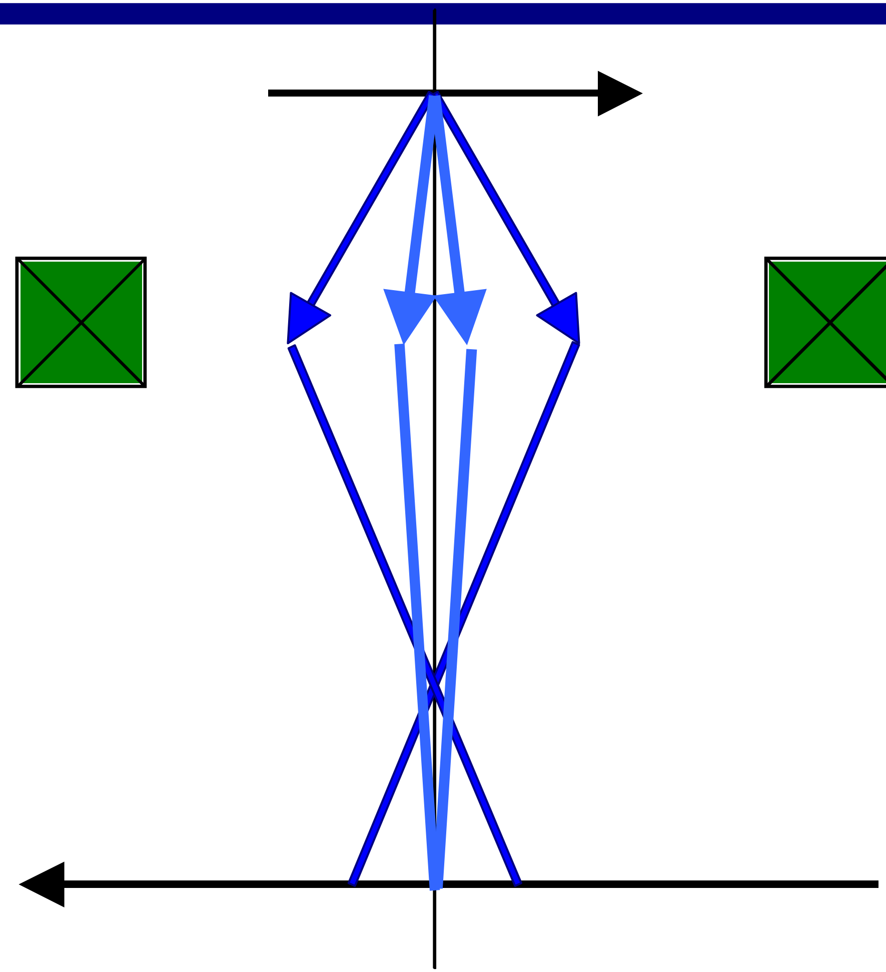

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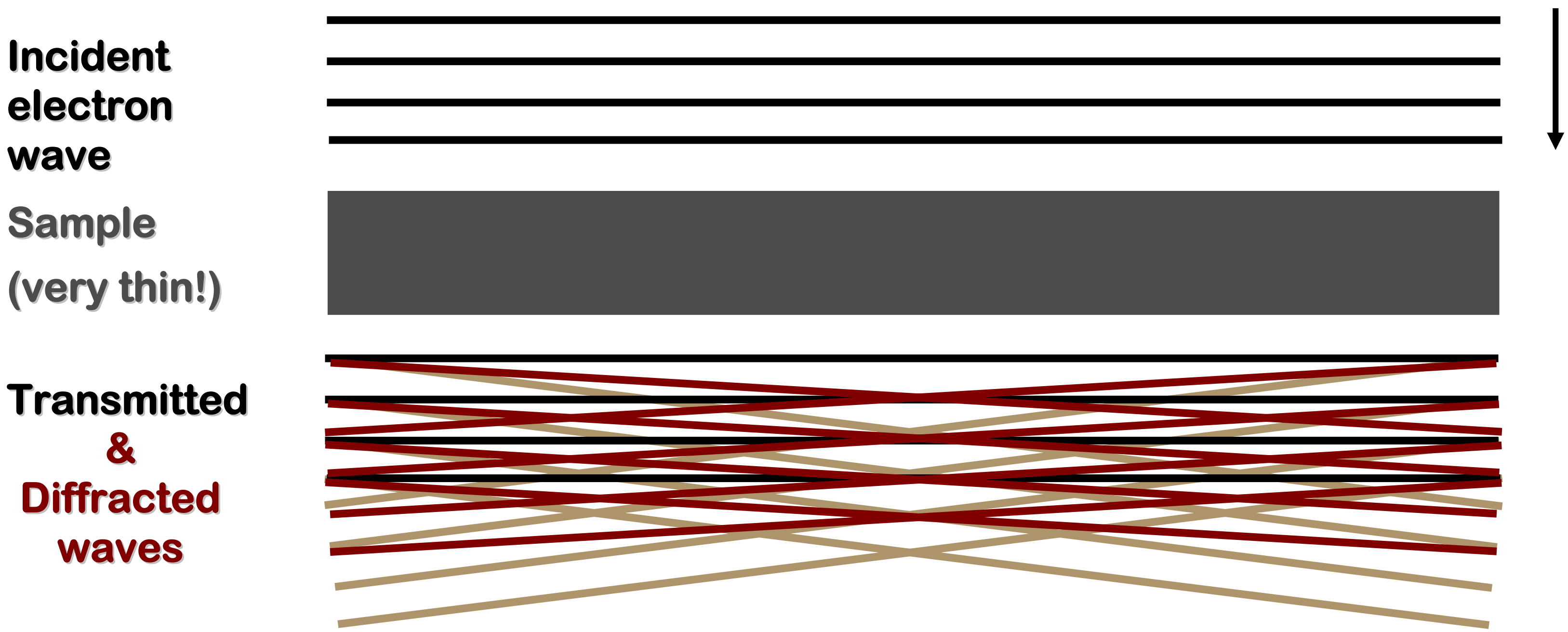

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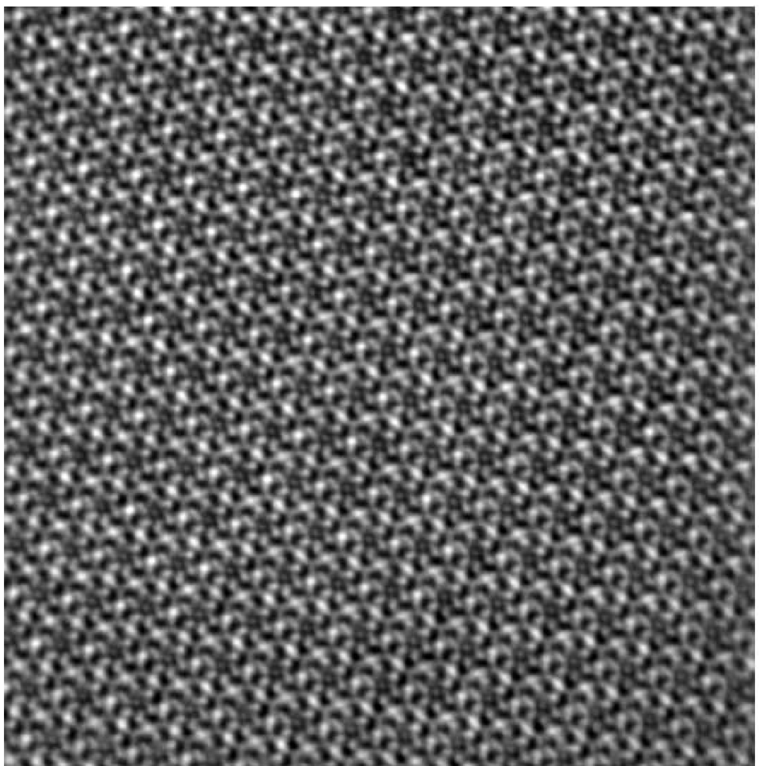
Thus, the image you get STRONGLY DEPENDS ON THE FOCUS CONDITION

A single HREM image



The 'unscrambled' exit wave

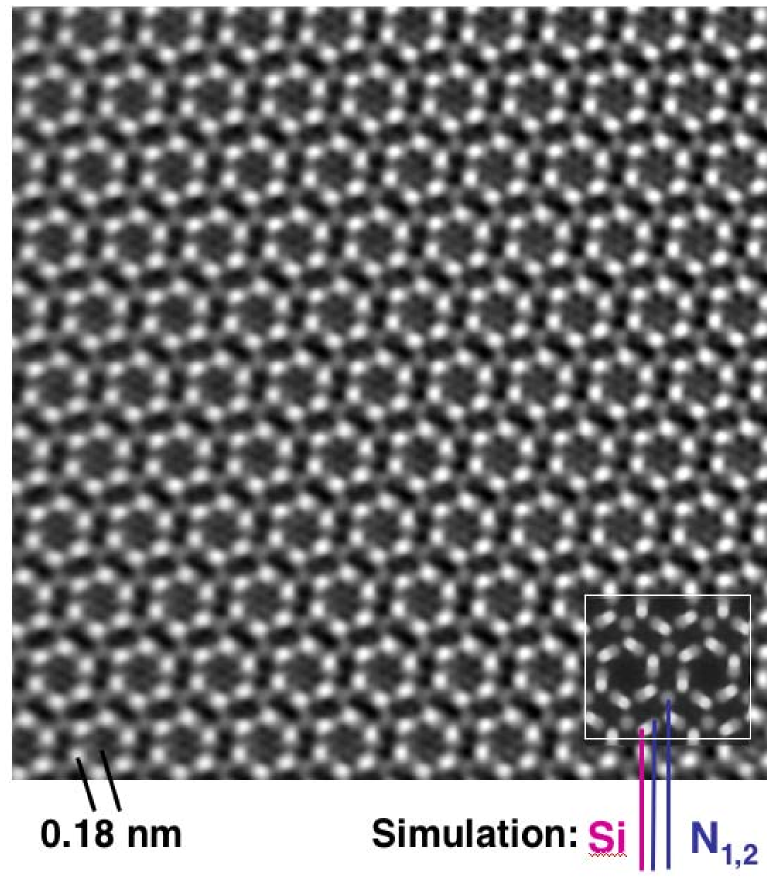


Image courtesy C. Kisielowski, NCEM, LBNL