Super Resolution through Optical Image Translation

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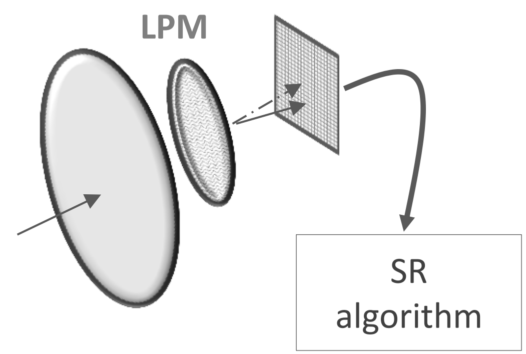
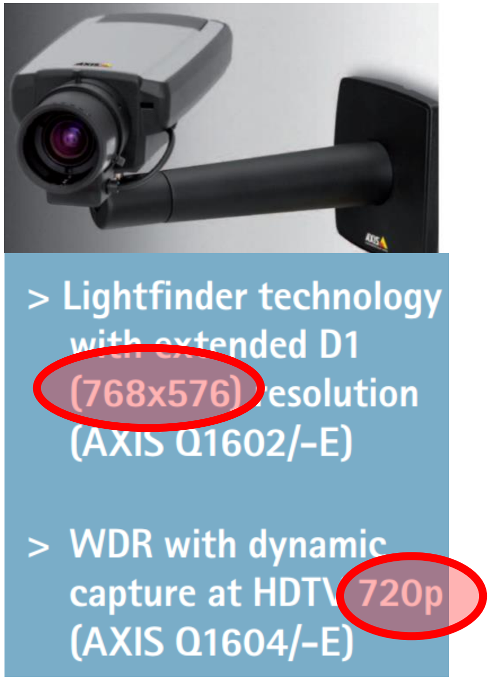


Super Resolution Imaging

- **What?**
  - Super resolution imaging generates images with more resolution than offered by image sensor
  - Unlike up-sampling/interpolation, which creates “fake pixels” to increase pixel count, super resolution truly resolves fine details not detected by sensor
- **Why?**
  - Image quality improves with higher true pixel count
  - Especially important for low light cameras, which sacrifice resolution for improved sensitivity by using sensors with large pixel size and low pixel count
- **How?**
  - Super resolution imaging processes multiple dissimilar low-resolution images to generate a high resolution image
  - Computationally intensive methods, such as dictionary learning, predict a high resolution image from a single low-resolution image



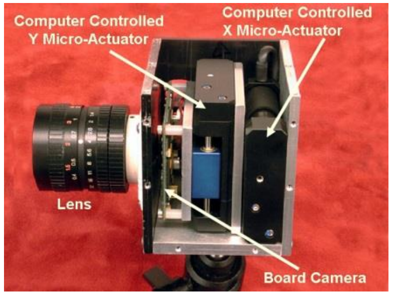
Low Light *implies* Low Resolution

Problem
Conventional Super Resolution Imaging is Complex

- Conventional methods
  - Multi Camera
    - Requires multiple lenses and sensors
  - Moving Camera
    - Requires precise shifting of whole camera
  - Jitter Camera
    - Requires precise shifting of sensor
  - Dictionary Learning
    - Requires extensive computational power

Multi camera

Jitter camera



- Conventional methods are impractical for surveillance cameras

Invention

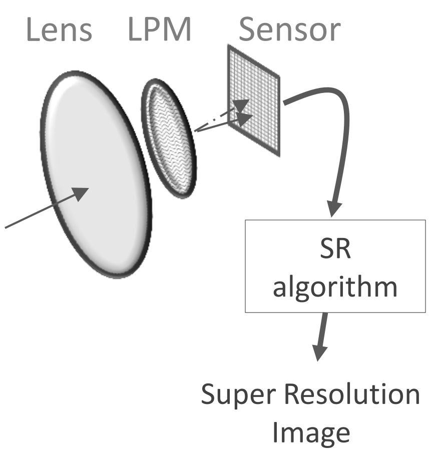
Super Resolution through Optical Image Translation

1. Optical radiation from lens is translated on sensor using a time-varying linear phase mask (LPM)

2. LPM is designed to introduce time-varying lateral shifts to the optical radiation

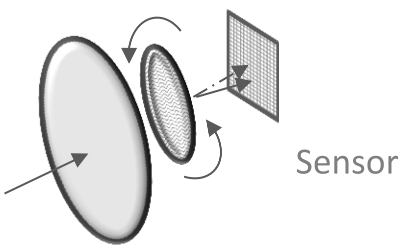
3. Successive images detected by sensor exhibit dissimilar shifts introduced by LPM

4. Multiple dissimilar images from sensor are combined with a super resolution (SR) algorithm to generate a high resolution image (with more "true pixels" than sensor)



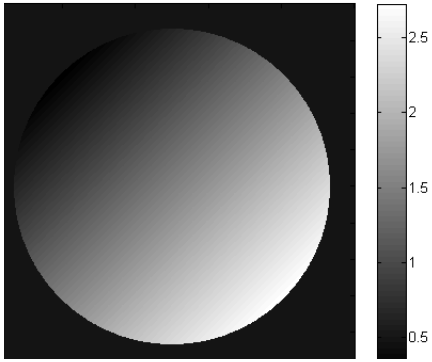
Linear Phase Mask (LPM)

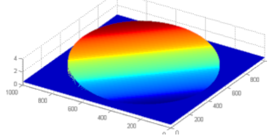
- Characteristics
  - LPM generates a linear phase shift in a plane close to the lens
  - Since the Fourier Transform of a linear phase shift is a translational shift, LPM results in a translational shift of the optical radiation on image sensor
  - The direction of orientation of LPM corresponds to the direction of the translational shift



- LPM Implementation
  - Option 1: Passive LPM
    - Glass or plastic with linearly increasing thickness
    - Rotating optical element either embedded in lens module or positioned between lens and sensor
  - Option 2: Active LPM
    - Liquid crystal optical element electrically controlled to generate time-varying phase shifts

LPM glass thickness profile





Passive LPM design

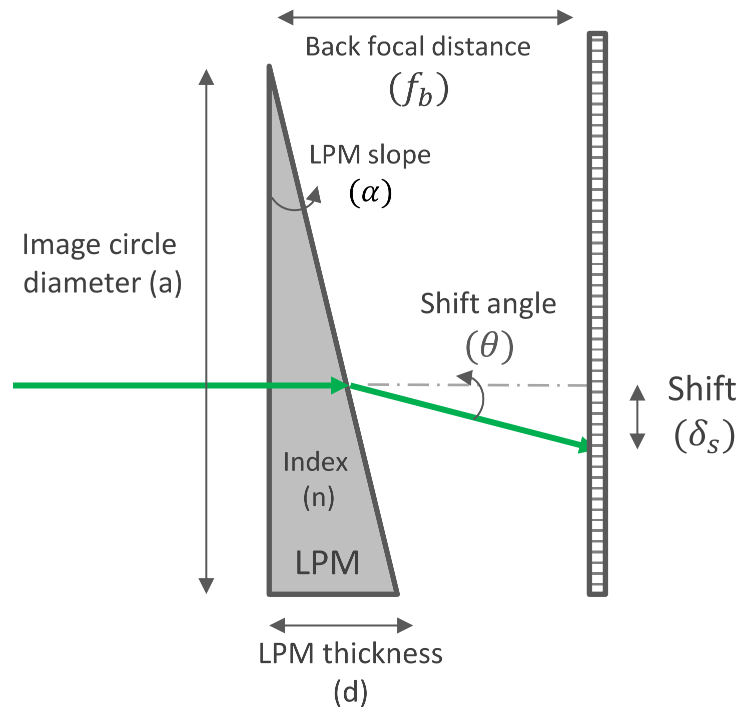
- LPM slope angle

$$\alpha = tan^{-1}\left[\frac{\sin(\theta)}{n - \cos(\theta)}\right] \text{ where,}$$

$$\theta = tan^{-1}\left(\frac{\delta_s}{f_b}\right)$$

- LPM thickness

$$d = \frac{a\ sin(\theta)}{n - cos(\theta)}$$



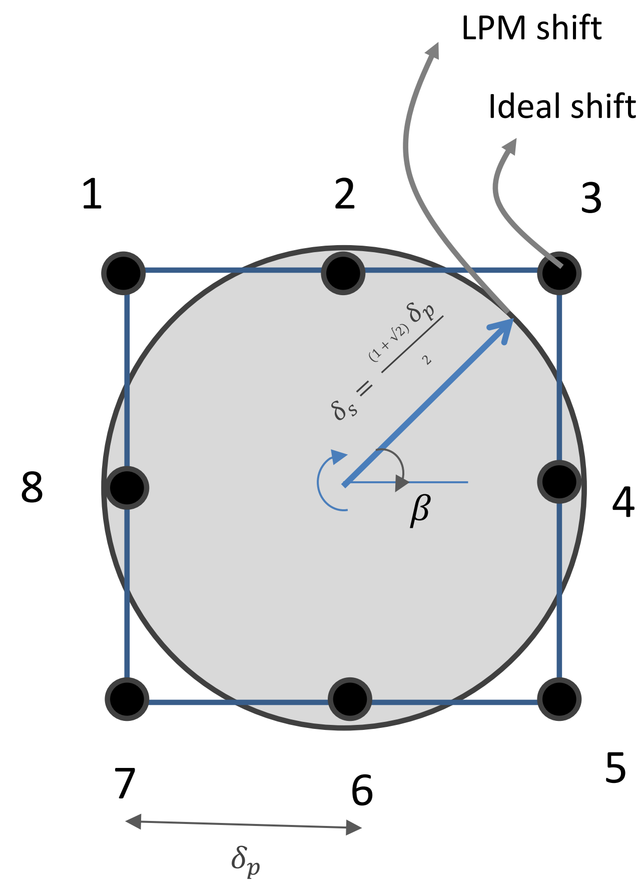
- Example
  - For n = 1.5 (glass), p = 3.75um, δ_s= 0.8 *p, f_b = 4mm, a = 6.71mm
  - α = 0.09^o, d = 10.1um, θ = 0.04^o

Optimal LPM shift

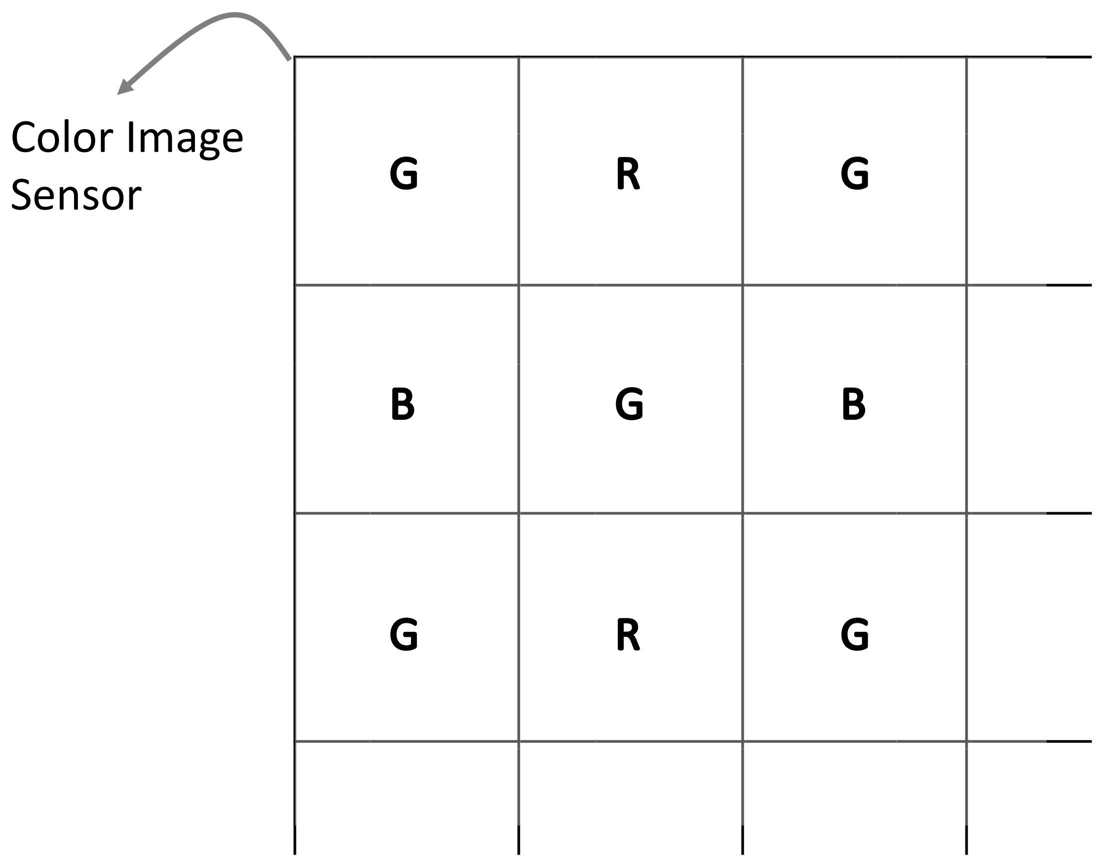
- Acquisition with 8 LPM orientations (β) provides 8 dissimilarly translated images
- Rotational motion of LPM constrains the shifts to lie on the contour of a circle on sensor plane
- However, commercial sensor pixels are arranged on a rectilinear grid, leading to a mismatch between ideal and achievable shifts
- An optimal value for shift (δ_s) is determined as

$$\delta_s = \frac{(1+\sqrt{2})\ \delta_p}{2}$$

where δ_p is the desired ideal pixel shift and δ_s is the most optimal achievable pixel shift achievable by LPM



Formation of Super Resolved Grid



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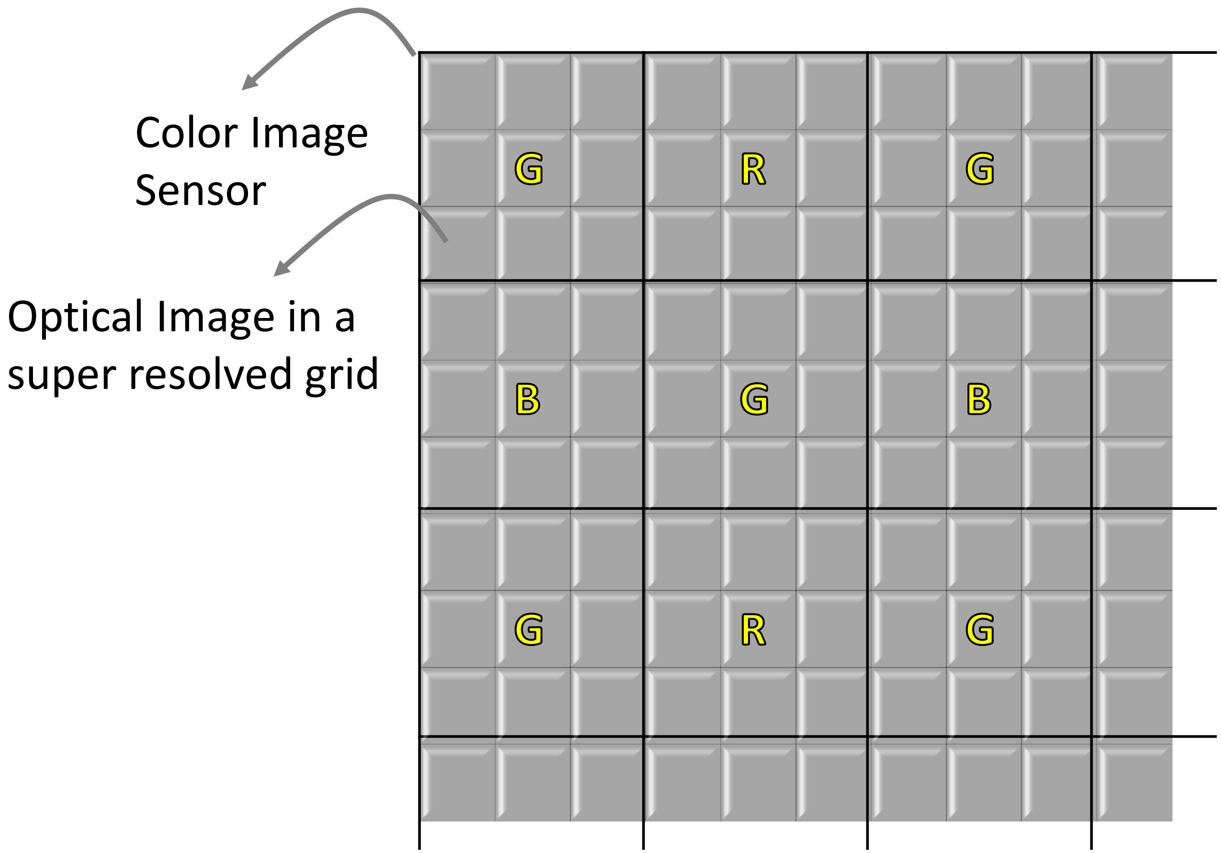

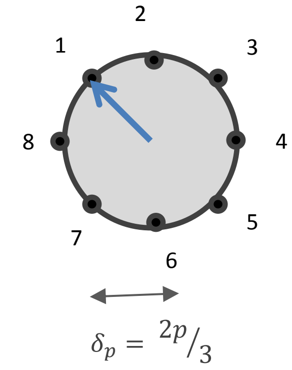

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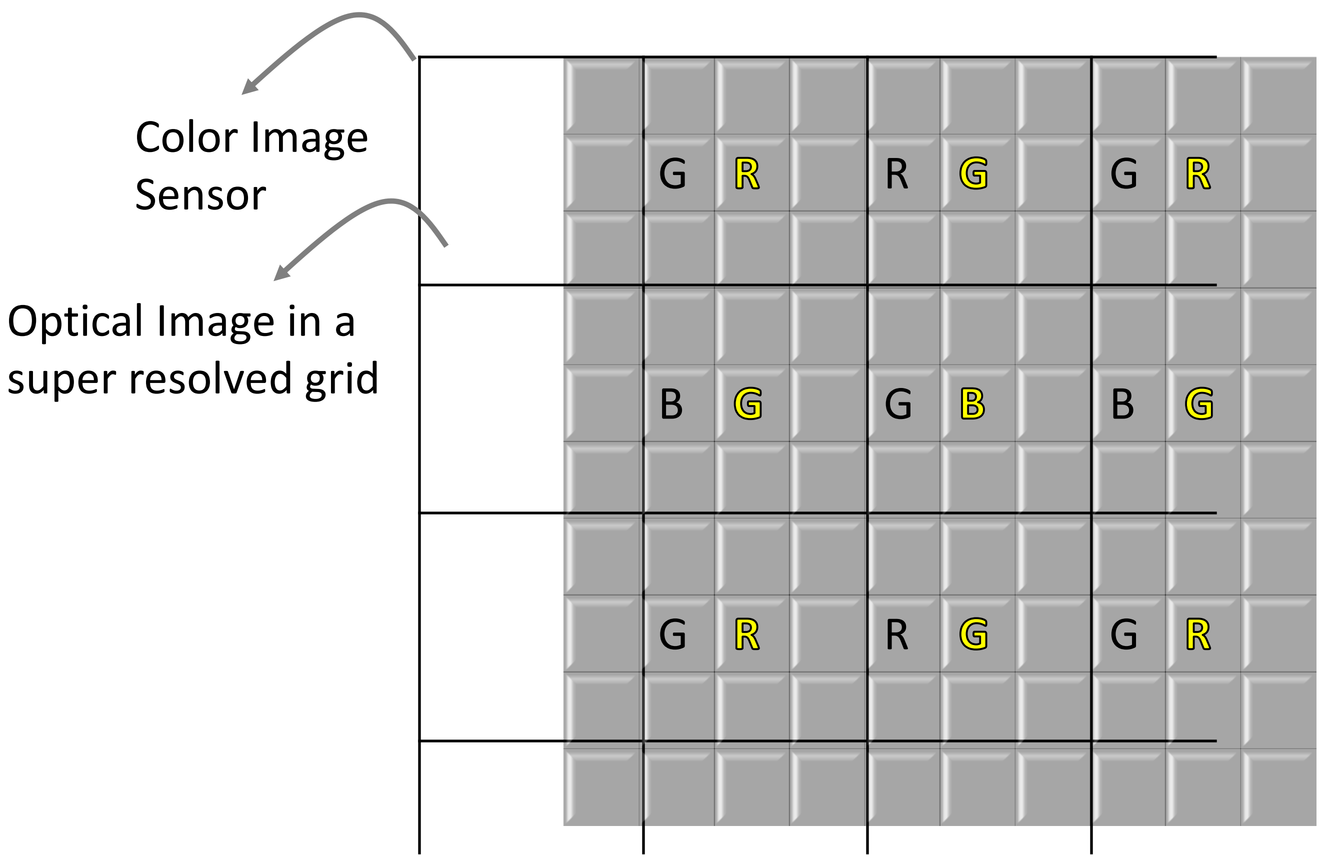
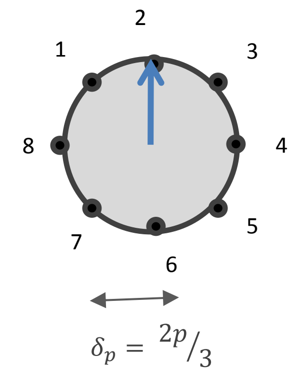
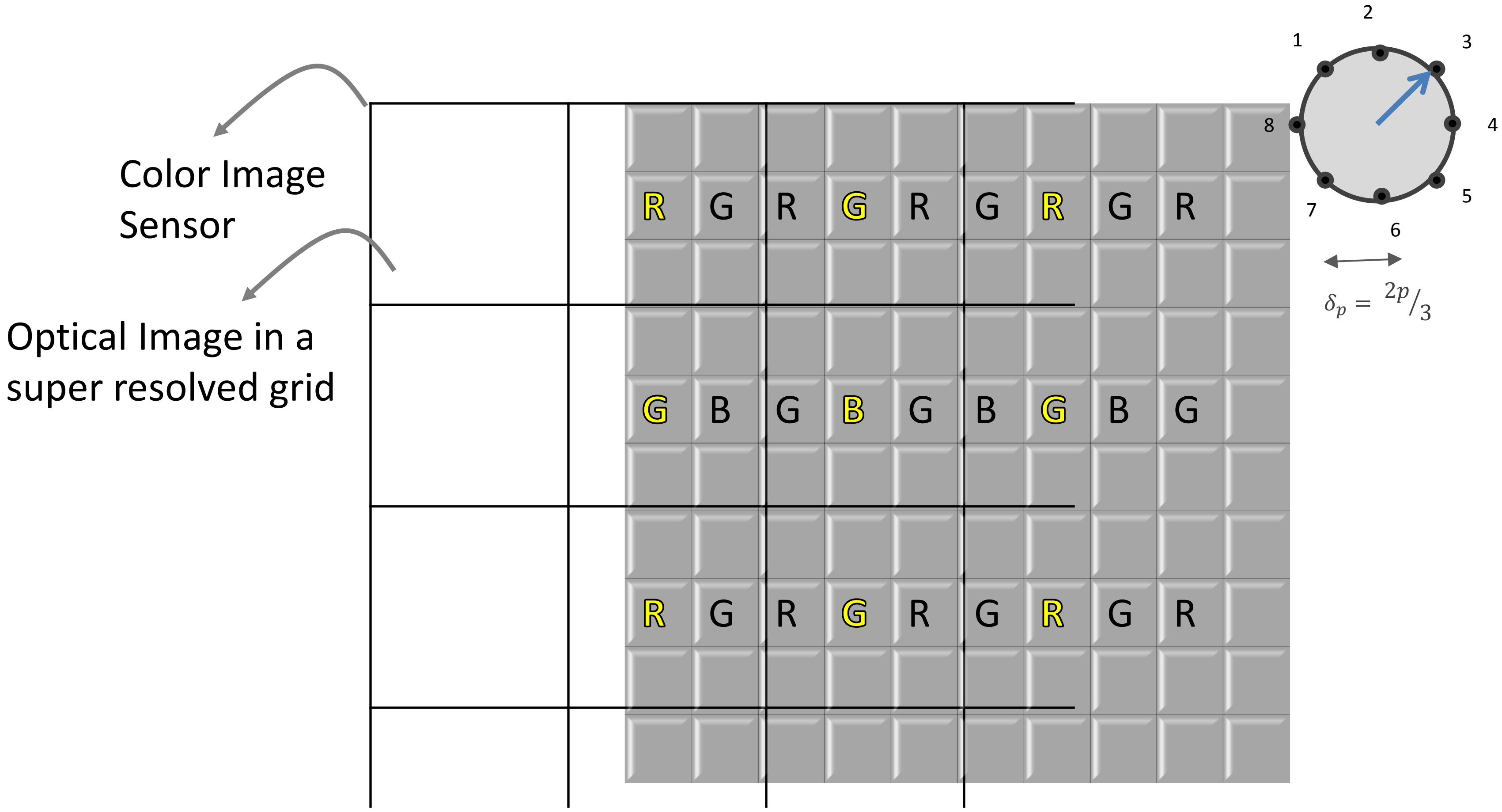




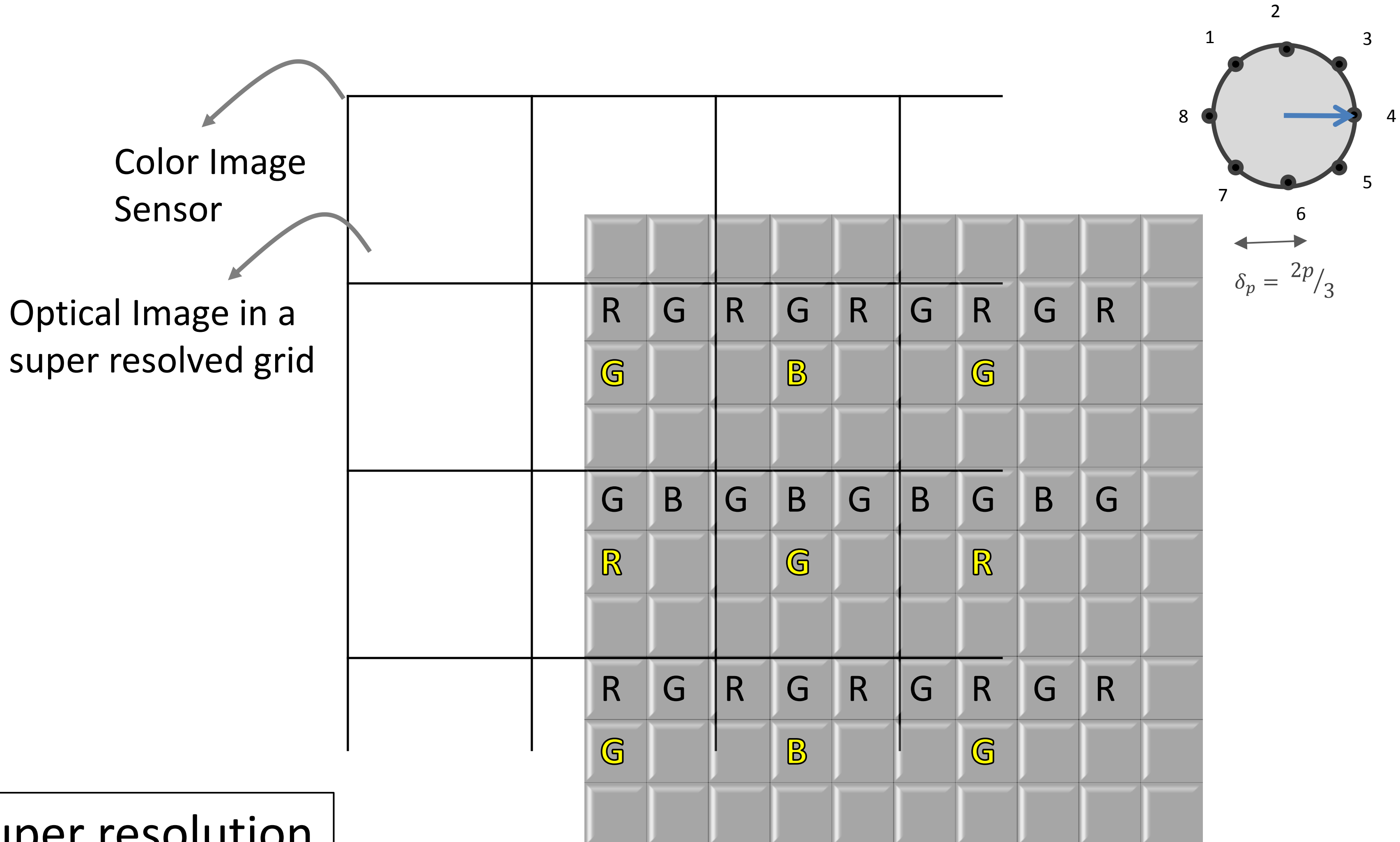
2x super resolution

Formation of Super Resolved Grid



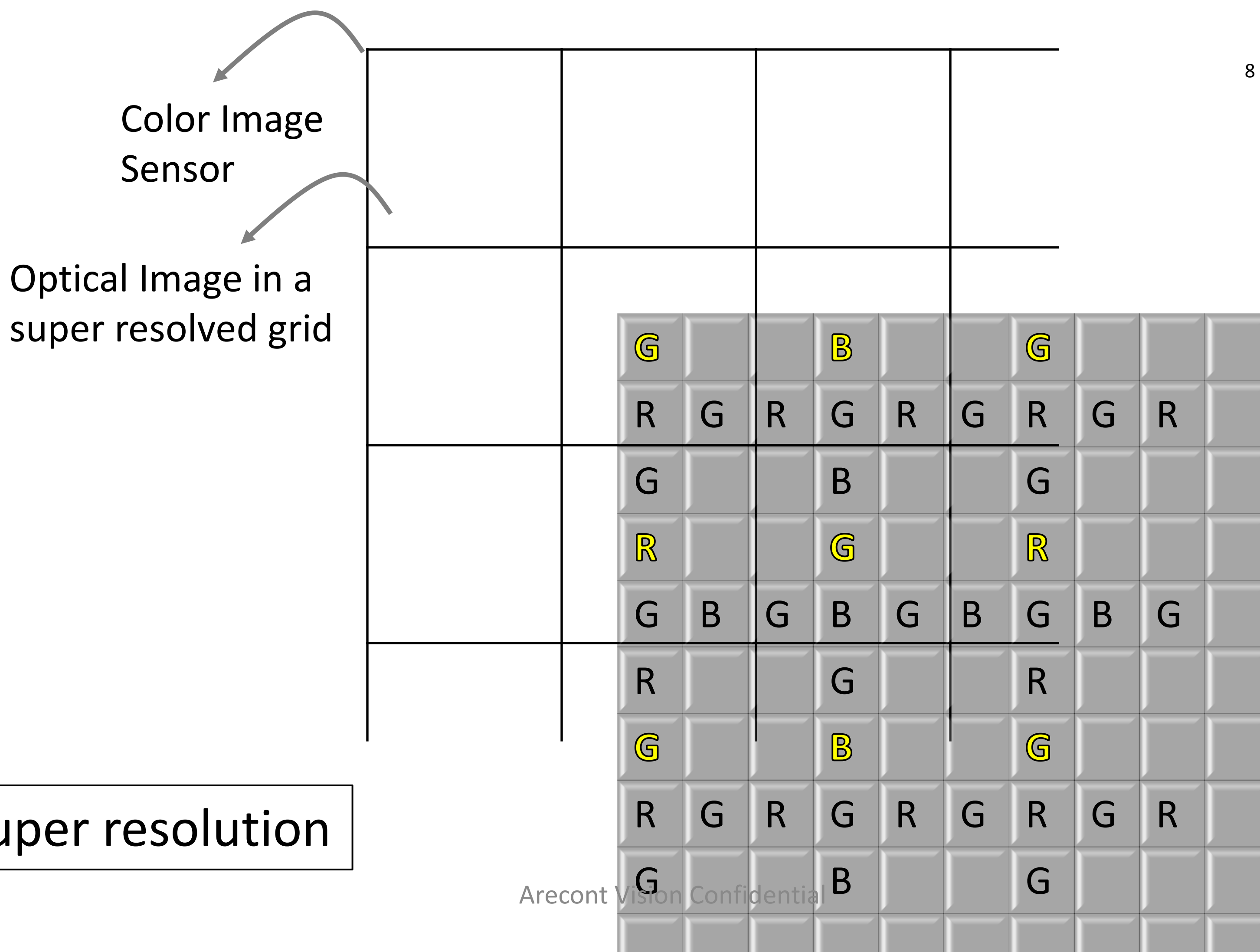
3x super resolution

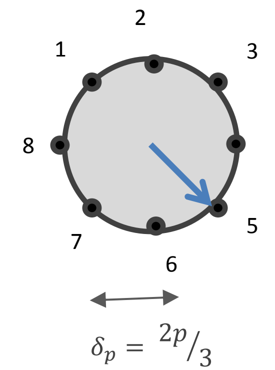
Formation of Super Resolved Grid



4x super resolution

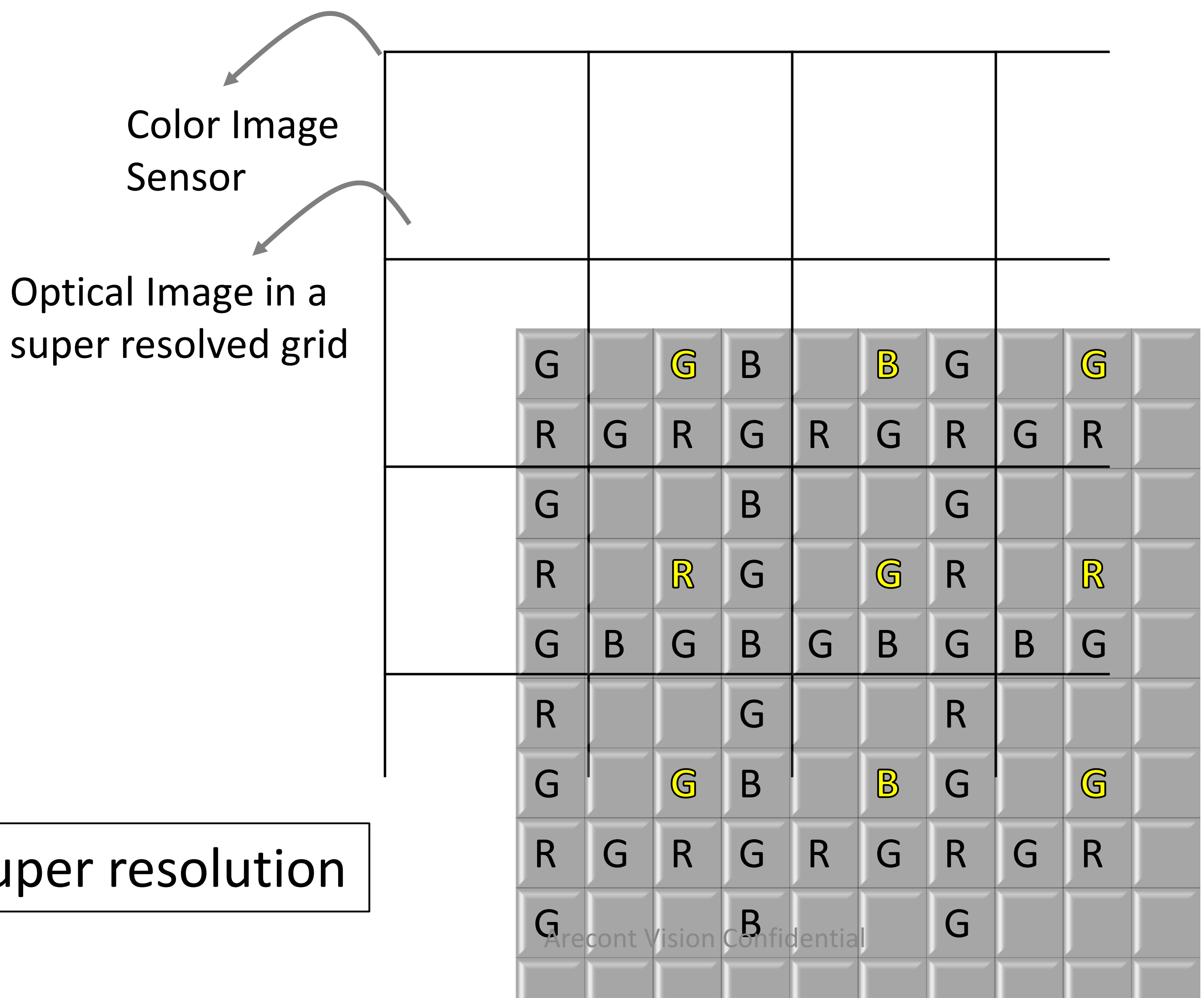
Formation of Super Resolved Grid

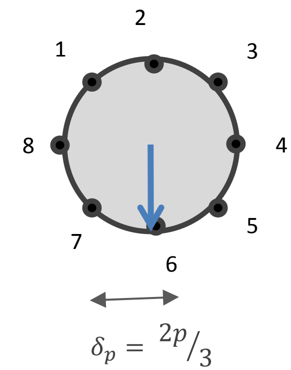




5x super resolution

Formation of Super Resolved Grid



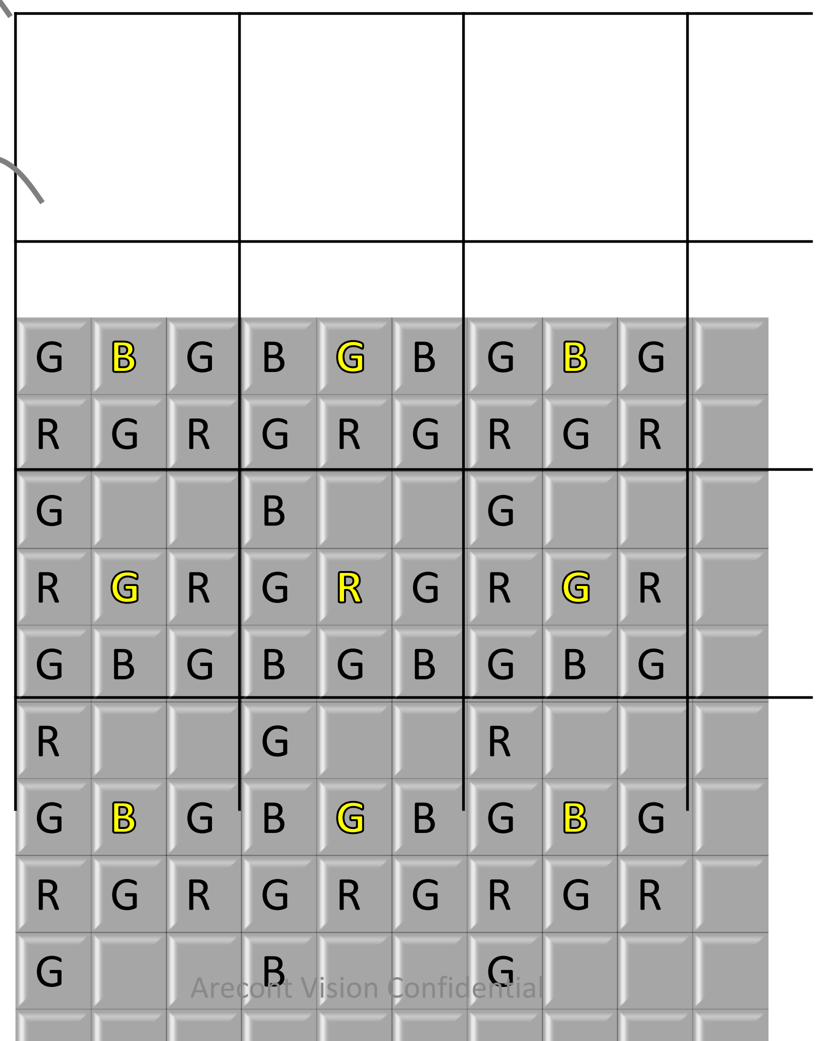


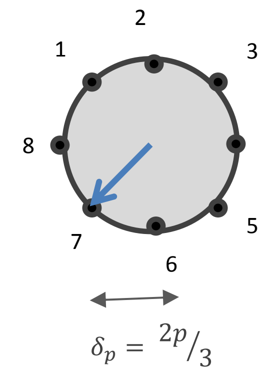
6x super resolution

Formation of Super Resolved Grid

Color Image Sensor

Optical Image in a super resolved grid



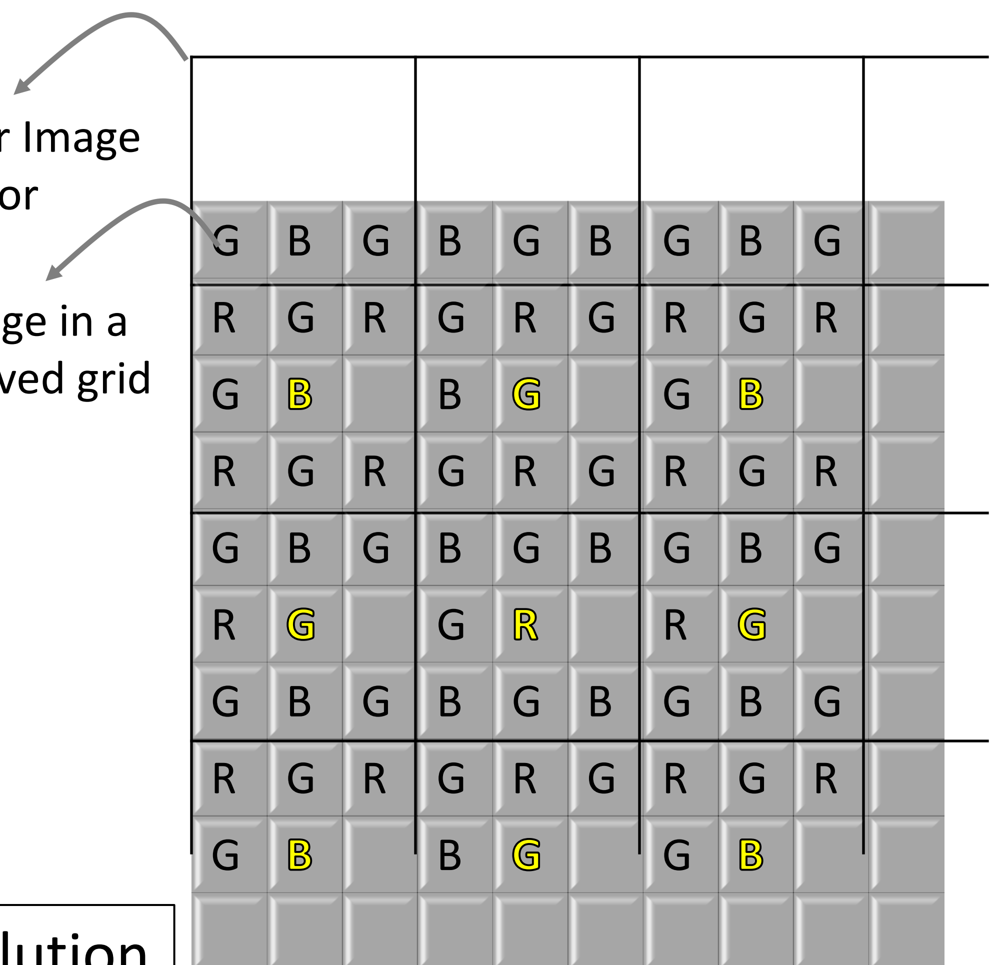


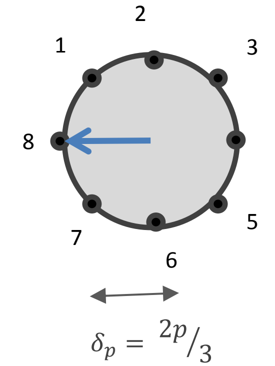
7x super resolution

Formation of Super Resolved Grid

Color Image Sensor

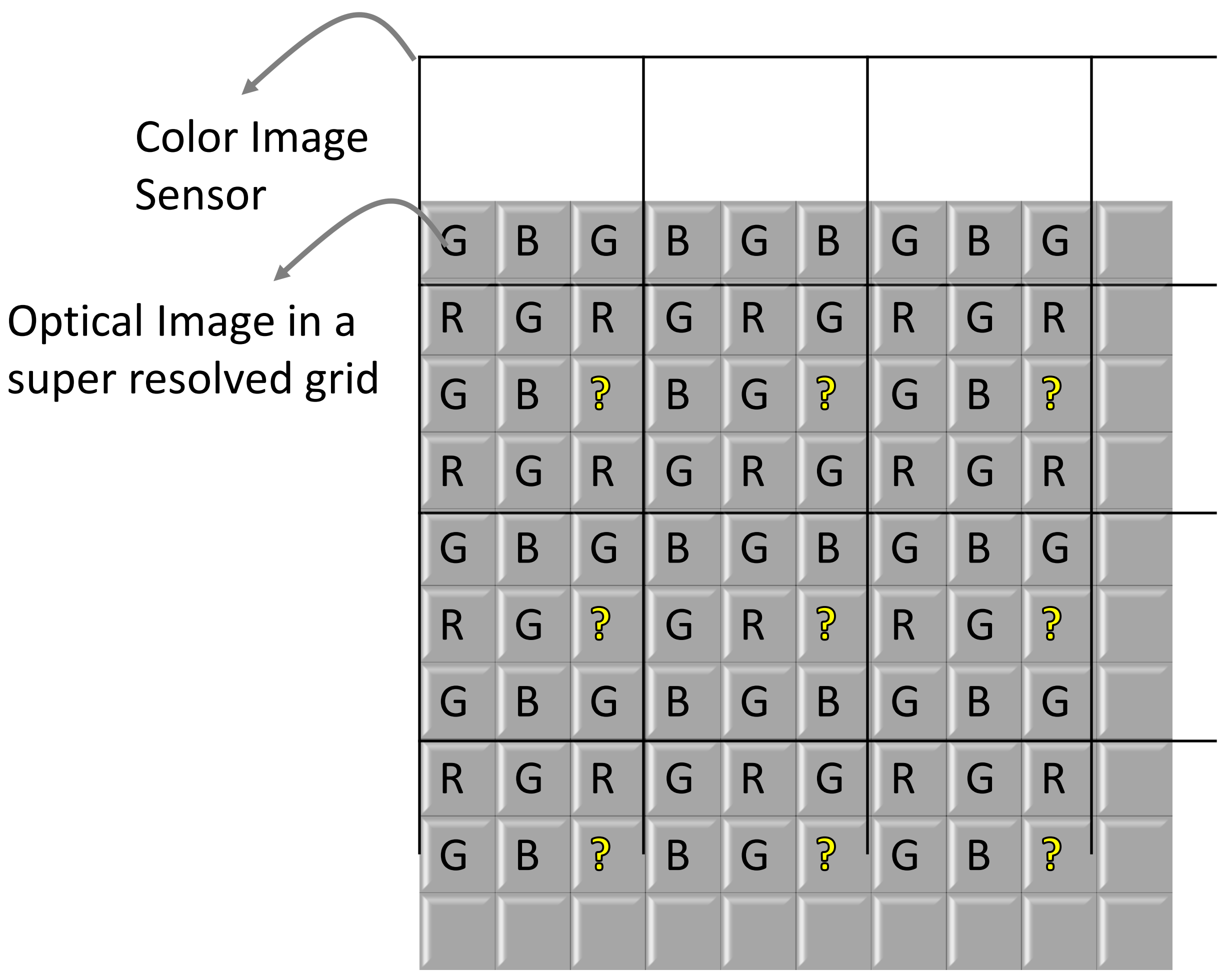
Optical Image in a super resolved grid





8x super resolution

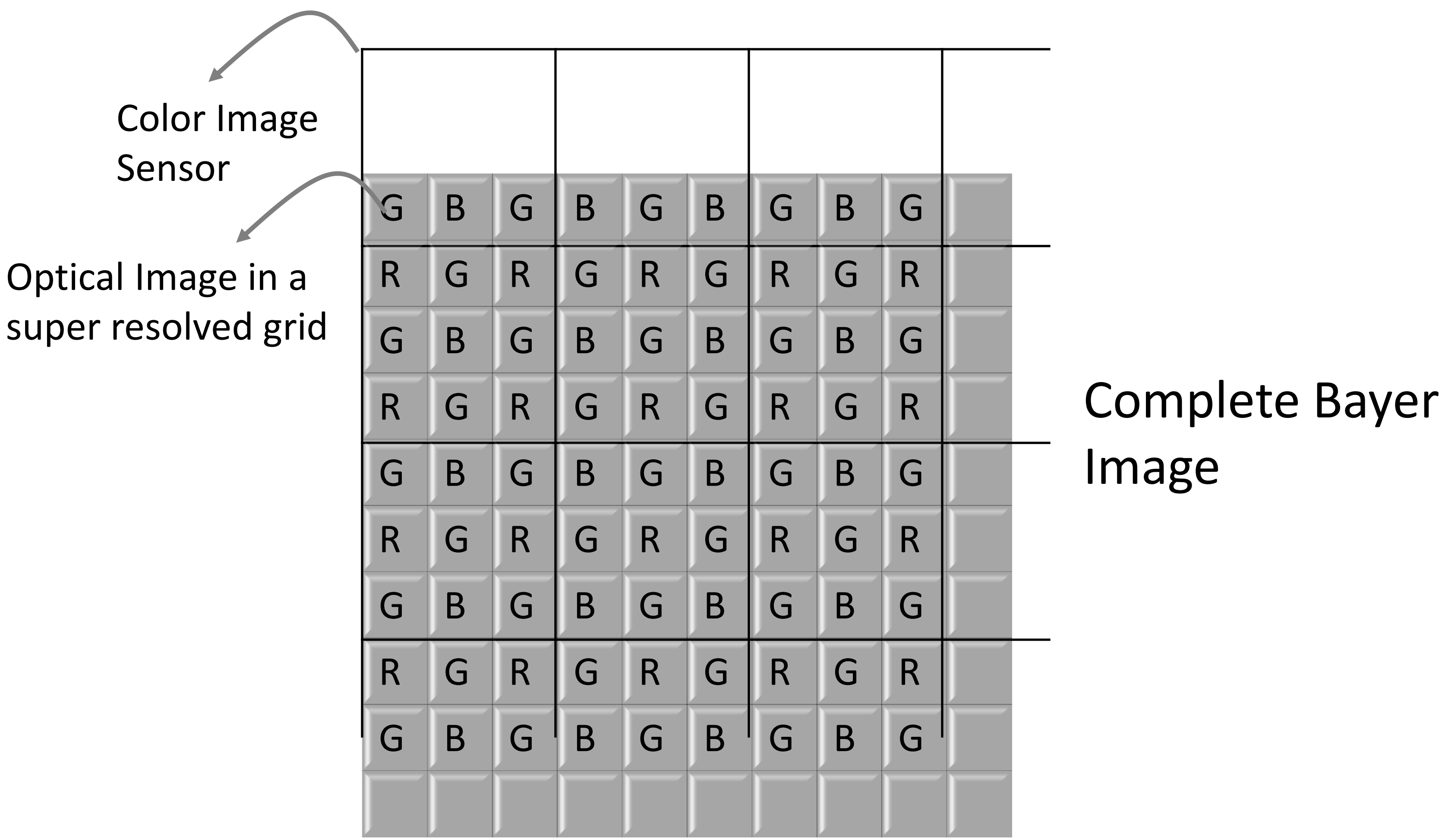
Missing Center Pixel Estimation



How to estimate center pixel?

- Replace LPM with a flat mask (possible with liquid crystal LPM implementation)
- Alternatively, estimate via interpolation

8x Super Resolved Bayer Image



Super Resolution (SR) Algorithm

1. Receive multiple low-resolution video frames, acquired with different LPM shifts, from sensor
2. Receive direction vectors corresponding to the received video low-resolution frames from LPM
3. Interleave low-resolution video frames using direction vectors to form an intermediate high-resolution video frame
4. Compute likelihood of pixel motion by comparing current video frame with a previous video frame
5. Compensate for motion by replacing high resolution pixels in the intermediate high resolution video frame with low-resolution pixels

Upper Bound of Super Resolution

(Maximum achievable resolution improvement)

- Maximum Super Resolution Factor (s_{max})

$$s_{max} = 4\left(\frac{p}{p - \varepsilon}\right)$$