2024 embedded VISION SUMMIT®

Seeing Through Machines: A Guide to Image Sensors for Edge AI Applications

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How Image Sensors Capture the World!
AI-Enhanced Vision-Based Applications…

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AI-Enhanced Vision Based Solution Success...

- AI models accuracy relies on its input quality

- Efficiency in data capture and processing in edge AI applications

- Successful employment of AI-enhanced applications with high-quality sensors paired with the right optics and interfaces which provides **precise**, **detailed** and **efficient** visual data

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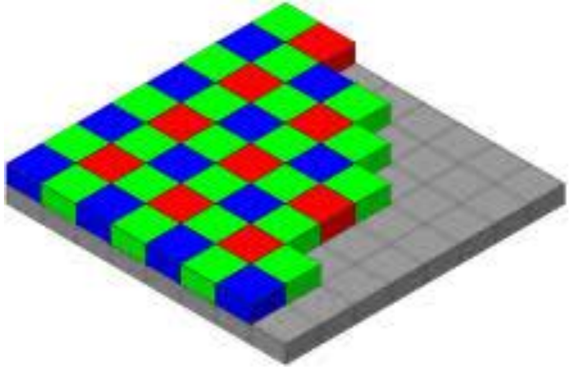
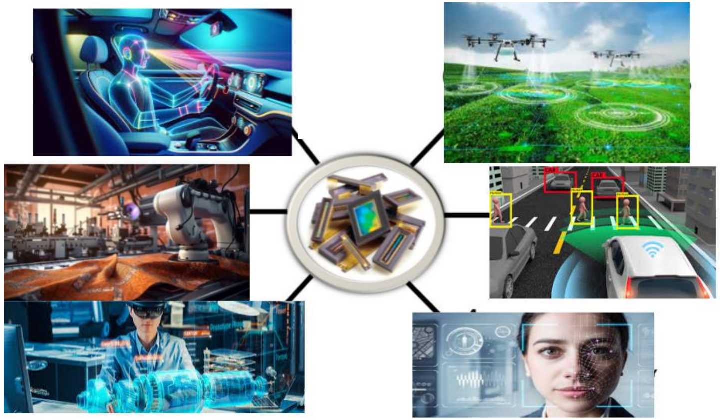
Outline

- How image sensors work, from light to bytes
- Overview of image sensor key terminologies
- Overview of image sensor key performance parameters (e.g., resolution, aspect ratio, dynamic Range, SNR, QE, MTF…)
- Achieving optimal performance in your edge AI or AI-enhanced solutions by choosing the “right” sensor





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Basics: How Image Sensors Work…

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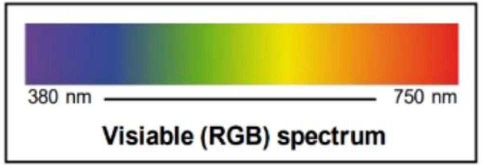
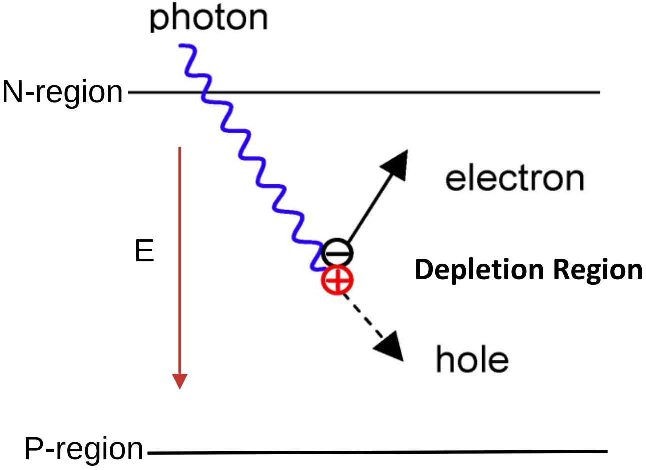
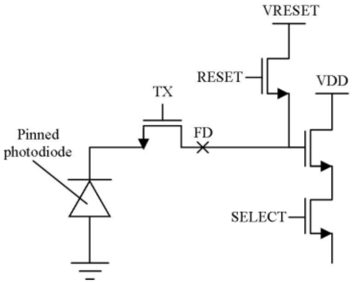
Photoelectronic Effect: Light Detection and Conversion





- The PN junction of photodiode hit by photons excites electrons, causing them to flow
- The electrical field guides charges to the collection point, a capacitor within the pixel structure
- The accumulated increase in charge (Q) leads to a proportional increased in the voltage (V)
- Photogenerated charges are proportional to the intensity of the light received

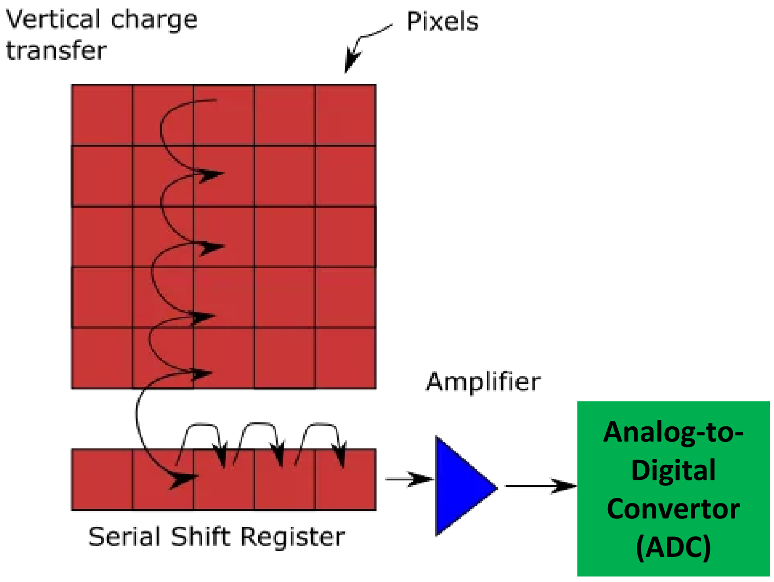
Q=CV



CMOS vs. CCD Image Sensors: Charge Coupled Device (CCD)

CCD sensors move charges pixel to pixel, convert it to voltage through an output node

- Key Features
  - Excellent light sensitivity, all pixels devoted to light capture (100% fill factor)
  - High image quality
  - Low noise images
- Specialized applications:
  - High-end professional photography
  - High-resolution scientific imaging (e.g., astronomy, spectroscopy)
  - Medical imaging



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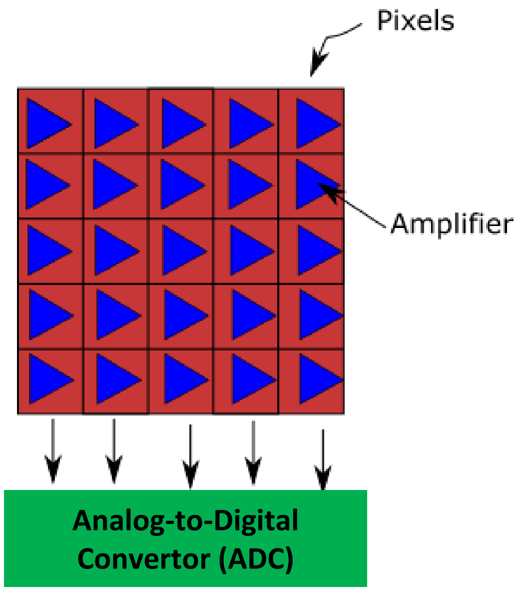
CMOS vs. CCD Image Sensors: Complementary Metal-Oxide-Semiconductor (CMOS)

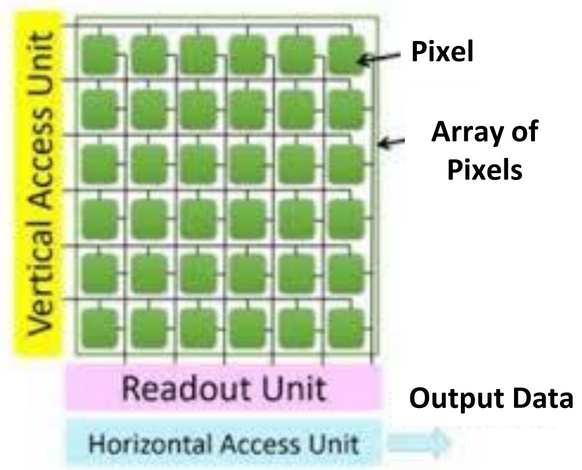
CMOS pixels integrate on-chip circuitry for conversion and amplification within each pixel

- Key Features
  - Faster parallel readout and speed
  - Lower cost and power consumption
  - On-chip processing capabilities
- Applications:
  - Consumer electronics
  - Industrial embedded vision/machine vision systems
  - Automotive (in-cabin and surround view sensing)



Building Blocks of a CMOS Image Sensors: Pixels

- Millions of pixels arranged in a grid form a pixel array
- Each pixel acts as a tiny photodiode, converting light into an electrical signal
- CMOS sensors includes amplifiers, ADC, noise-correction, and digitization circuits, so the chip outputs digital bit
- More pixels result in higher resolution image as a result more details



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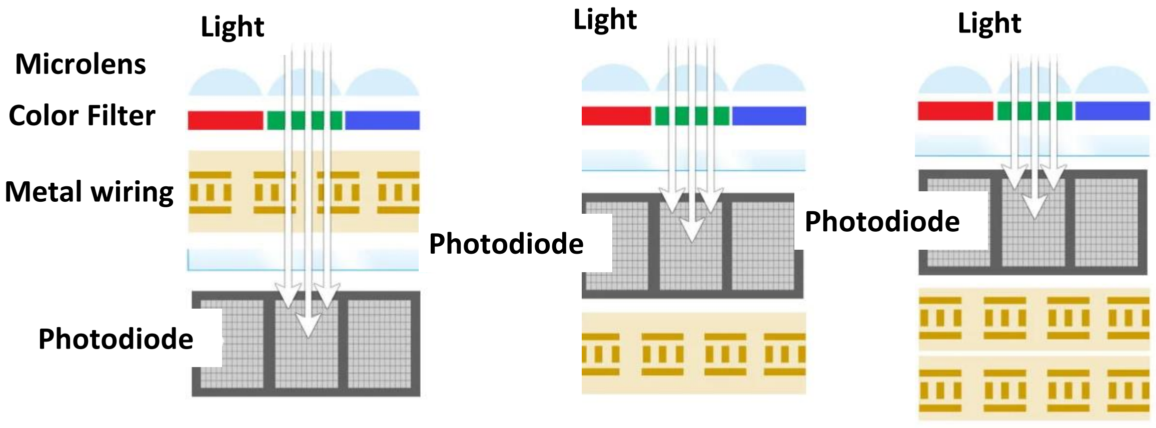
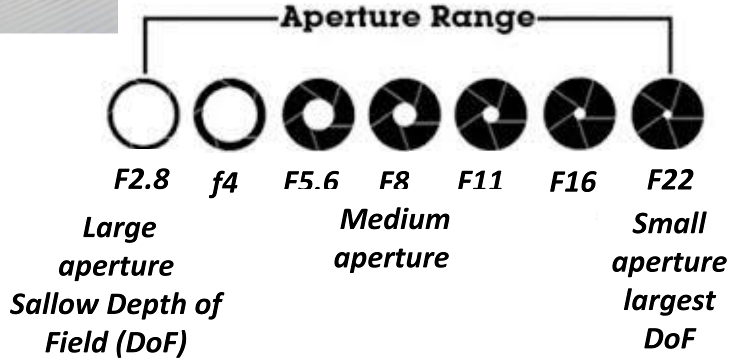
Improving Image Sensor Quantum Efficiency: Architectural Approach

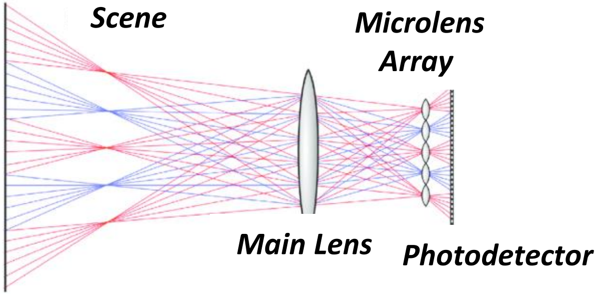


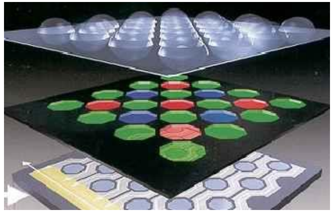
FSI (Front Side Illuminated)/basic CMOS	**BSI** (Back Side Illuminated) CMOS	**Stacked** CMOS
Is the conventional design Fabrication process is simpler Has limited low light performance	Fabrication process is more complex Improves light collection efficiency Has better image quality with improved light sensitivity and reduced noise	Improved fill factor by separating PD layers and circuitry layer Faster data transfer Advanced integration like enhanced on-chip image processing

Capturing the Light within: Optical Path

- Picking a right **lens** for your image sensor:
  - Define your application desired FoV and working distance
  - Calculate the focal length based on your FoV and your sensor size
  - Decide on an aperture that gives the necessary DoF considering the lighting condition
  - Fixed or autofocus lens will define your zoom capability
- **Microlenses** further concentrates light onto individual pixels







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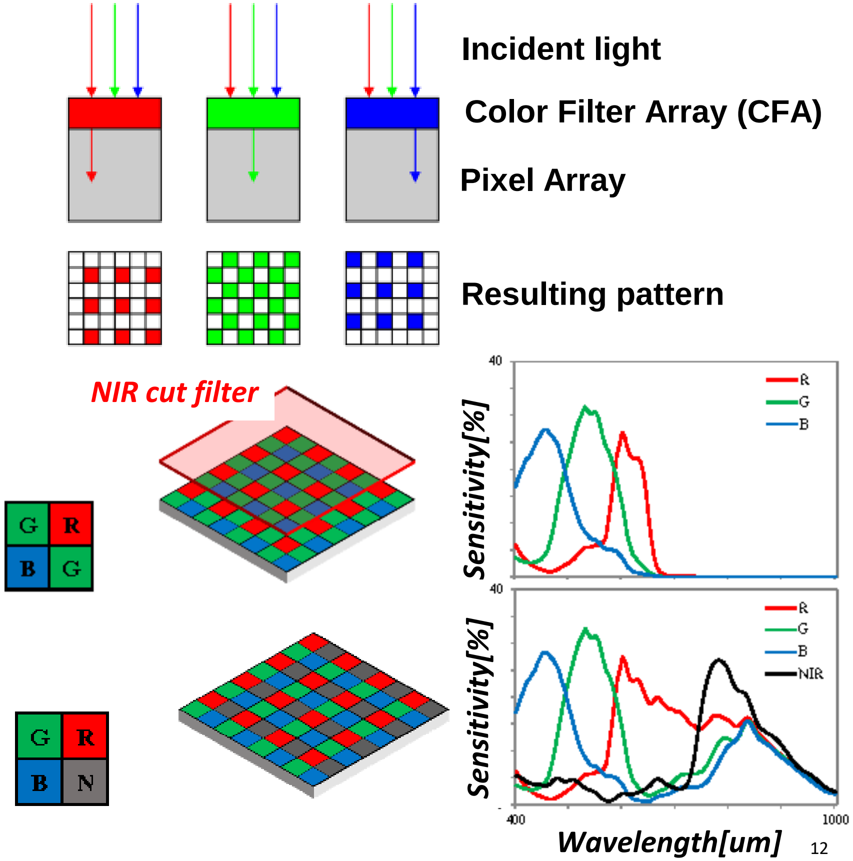
Unveiling Colors: Color Filter Arrays (CFA)

- Color Filter Array sits above the pixel array
- Each pixel records light filtered by its color filter
- Common CFA pattern: Bayer (RGGB)-
  Red, Green, Green, Blue
- CFA patterns like RGBIR used for specialized applications like security cameras or in-cabin sensing/monitoring
- Mono color filters (e.g., infrared) used for specialized applications like FaceID



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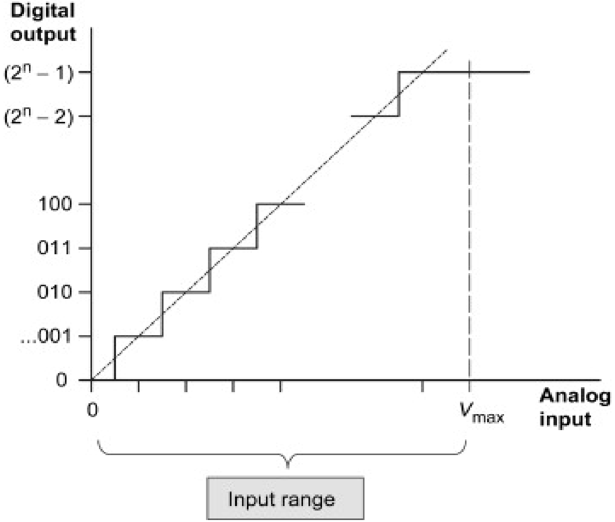
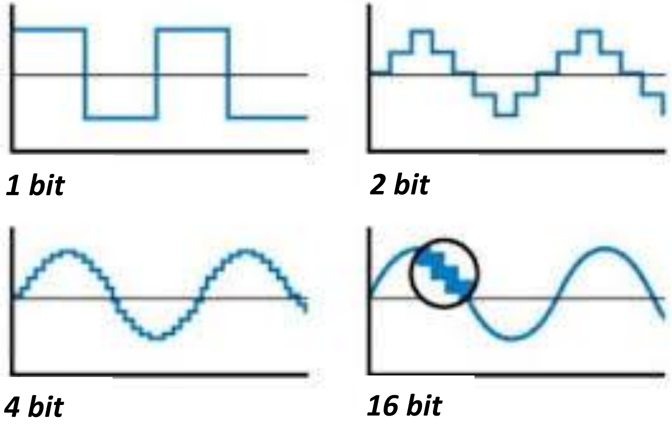
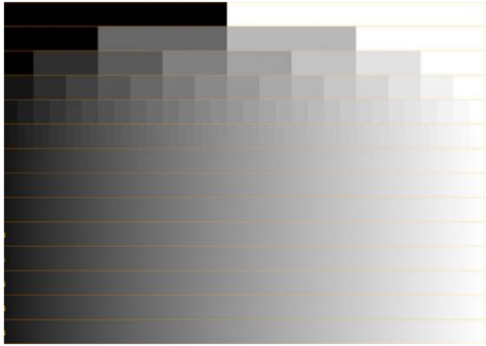
Electrical Signal Conversion to Bytes: Analog-to-Digital Conversion (ADC)

- ADC converts analog signals into digital data for processing
- The resolution of the digital image is determined by the ADC bit depth
- 8-bit ADC is 256 grayscale levels, 10-bit ADC is 1024 grayscale levels
- Higher bit-depth typically results in longer conversion and larger ADC







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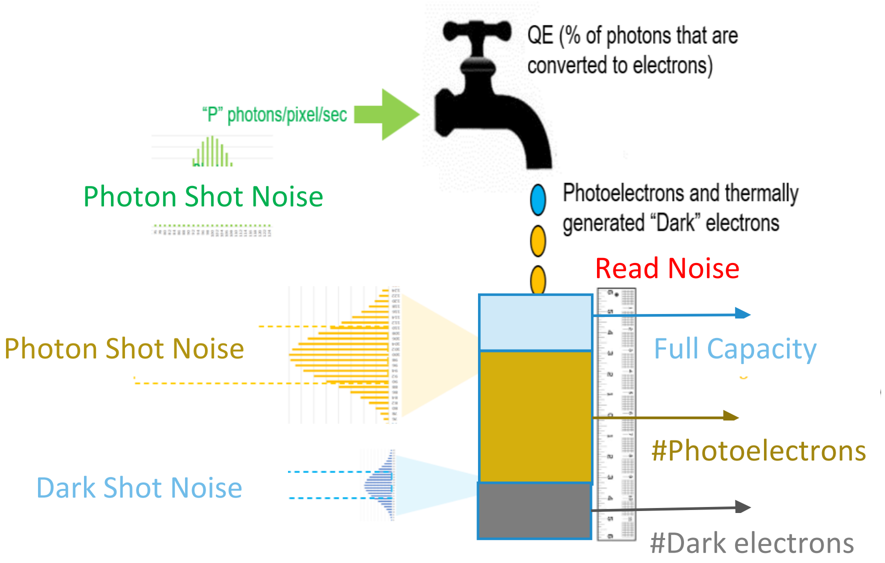
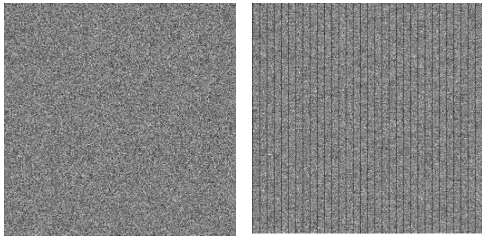
Main Sources of Noise in CIS

- **Photon shot noise:**
  - Random arrival of photons follows Poisson distribution
- **Dark current noise:**
  - Thermally-induced charges even when no light is present
- **Read out noise(including quantization noise):**
  - Random electrical noise from converting the captured light signal to a voltage value
- **Fixed pattern noise (FPN) has two components:**
  - DSNU: Dark Signal Non-Uniformity
  - PRNU: Photo Response Non-Uniformity





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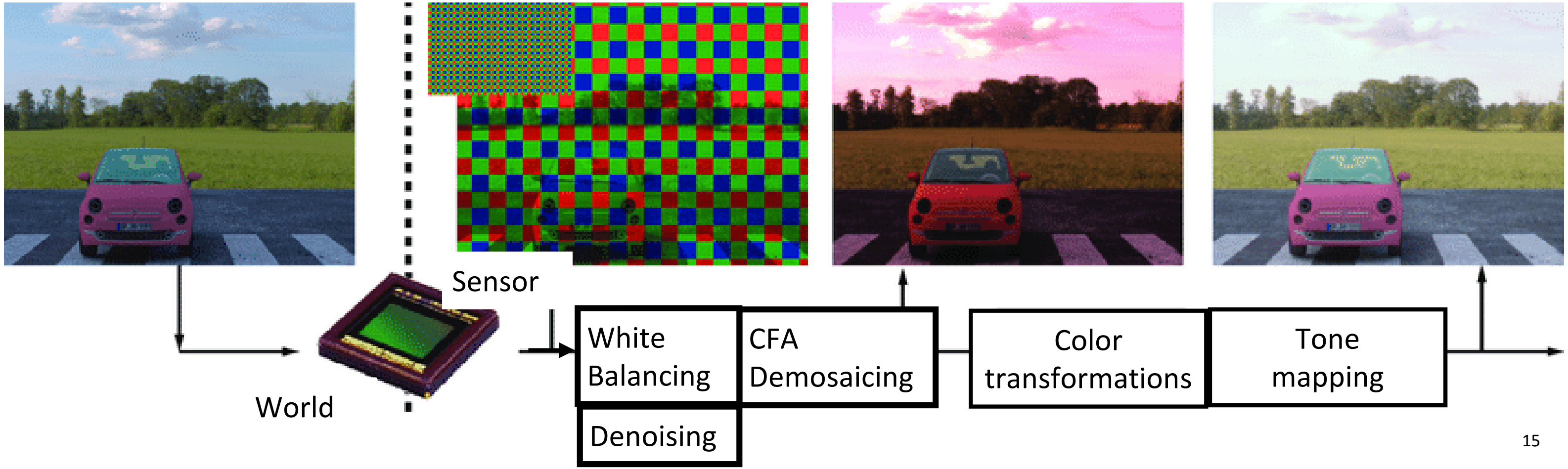
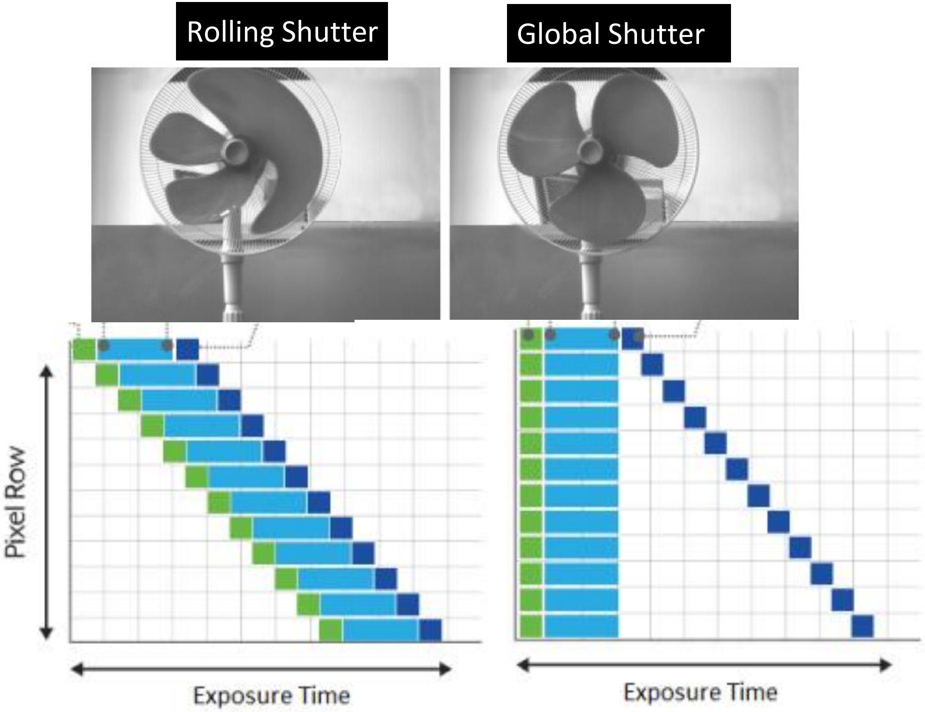
Beyond the Sensor: Image Processing Pipeline

- Input of image processing pipeline is digital data, stream of numbers representing the brightness of each pixel
- Output of image processing pipeline is a high-quality digital image ready for storage, display, or further analysis by machine vision algorithm



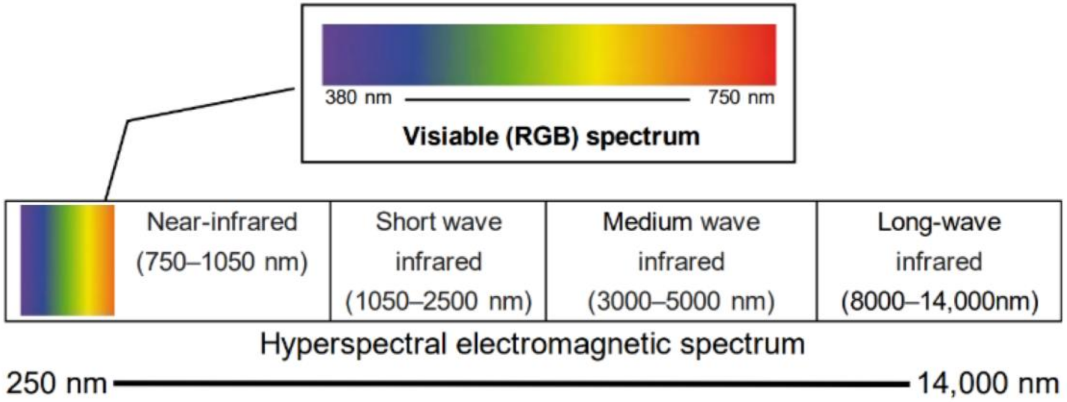
Global Shutter vs. Rolling Shutter Image Sensors

- **Rolling shutter sensor:** Exposes and reads out pixels row by row sequentially
- **Global shutter sensor:** Exposes all pixels at the same time, ensuring the uniform exposure
- **Motion artifacts:** Global shutter eliminate distortion in fast moving scenes



Specialized Sensors—Beyond the Visible Spectrum

- Depth Sensors (ToF, LiDAR): Measure distance to objects, enabling 3D imaging like object recognition and navigation
- Hyperspectral Sensors: Capture detailed spectral info beyond the visible spectrum, enabling material identification and environmental monitoring



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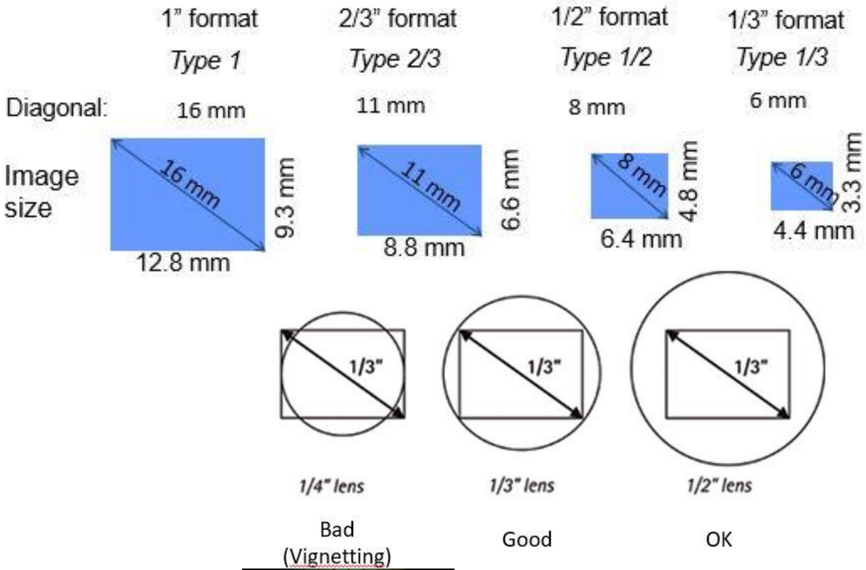
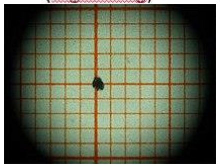
Overview of CMOS Image Sensor (CIS) Key Performance Parameters …

Key CIS Performance Parameters: Descriptions and Implications

- **Resolution (active pixel area size, pixel pitch)**:
  - Higher resolution captures finer details, but requires more processing power and storage
- **Sensor size and optical format or aspect ratio:**
  - A larger sensor captures more light, better low-light performance
  - Aspect ratio impacts compatibility with lenses and desired image format
- **Power consumption:**
  - Lower power sensors can extend battery life, improve efficiency for battery powered devices
- **Number of frames per second:**
  - Higher frame rates are essential for real-time fast-moving scenes like sports scenes capture





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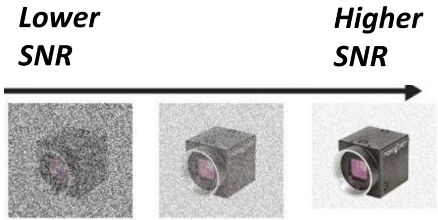
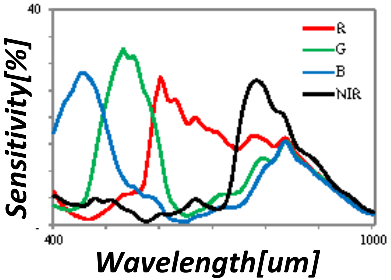
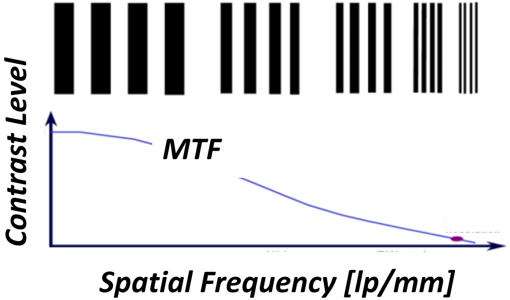
Key CIS Performance Parameters: Descriptions and Implications (Cont')

- **SNR (dB):**
  - The ratio of desired signal to unwanted noise
- **Quantum Efficiency (QE):**
  - Is % of photos converts to electrons translates to sensor's light sensitivity
- **Modulation Transfer Function (MTF):**
  - Assesses the sensor's ability to reproduce sharp details from the scene
- **Dynamic Range (ratio or dB):**
  - Measures the sensor's ability to capture details in both bright and dark areas of a scene
- **Modes**
  - HDR modes (multi-exposure)
  - Synchronization (master/slave mode)







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Impact of Selecting the "Right" Sensor for Your Edge AI Application…

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Image Sensor Selection Framework: Textile Manufacturing Line Quality Monitoring to Reduce Waste

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Sensor Perf Metrics Required	Textile Manufacturing Line Quality Monitoring
Sensor Size/Optical format	**Medium to Large** to balance between FoV and acceptable low-light performance
Sensor Resolution	**3-5 MP** to capture defects like mis-weave, tear or color inconsistencies
Color/Mono	**Color sensor** to capture color inconsistencies
Rolling vs. Global shutter	**Global Shutter to** capture fast scanning of the fabric
Frame Rate	**Moderate (30-60FPS) to** capture enough frames for defect analysis
Dynamic Range(DR)	**Moderate to High to** capture variation in high light and shadow
Signal to Noise Ratio(SNR)	**High to** ensure crisp and low-noise or noise-free image for effective analysis
…	…

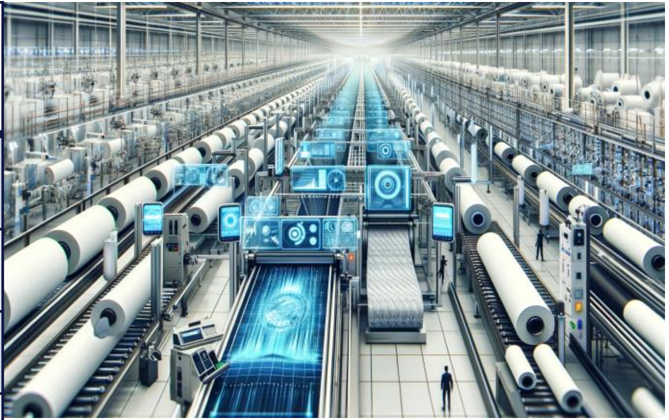

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Image Sensor Selection Framework: Drone Agricultural for Crop Monitoring

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Sensor Perf Metrics Required	Crop Monitoring with Drones
Sensor Size/Optical format	**Medium to Large** depending on #sensors to cover 360 view, lens design and acceptable low-light performance
Sensor Resolution	**5-20 MP** to capture crop details managing processing and storage limitations
Color/Mono	**Color sensor** to capture color crops
Rolling vs. Global shutter	**Global Shutter to** capture crop non- distorted images with drone moving
Frame Rate	**Slow to Moderate (15-60FPS) to** capture enough frames for crop analysis
Dynamic Range(DR)	**Moderate to High** for drone operated in carrying light condition
Signal to Noise Ratio(SNR)	**High to** ensure reliable clean images for effective crop yield or disease analysis
…	…

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Recap and Final Thoughts

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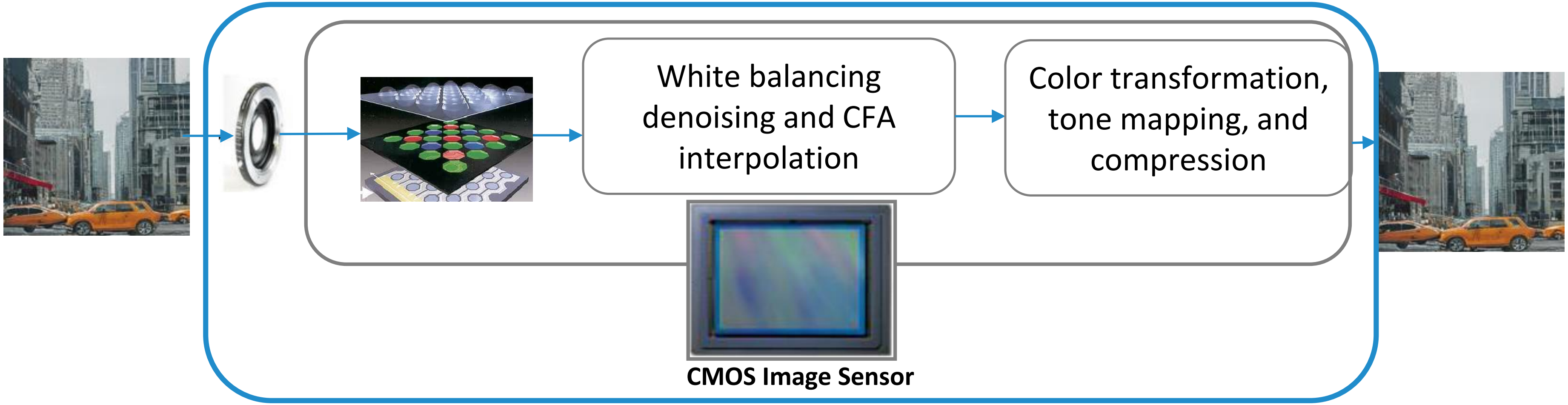
Key Takeaways



- Understanding image sensor mechanics and terminologies
- Selecting the right sensor to meet your specific application needs
- Selecting the appropriate sensor directly impacts your application effectiveness and AI model performance

Thank You!

Q&A

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References and Resources:

- Bayer arrangement of color filter array and the cross section
- RGB and RGB-NIR image acquisition and Quantum Effciency diagrams
- CCD vs. CMOS image sensor difference in exposure and readout
- Architectural differences between CMOS, BSI CMOS, and Stacked CMOS sensors
- Signal to noise ratio: high SNR and low SNR impact
- Photodiode to capacitor readout
- Rolling shutter vs. global shutter exposures and readouts ; moving fan motion artifacts with rolling shutter
- Lens characteristics like f-number, aperture and DoF
- Three stages of image processing pipeline: Demosaicing, color transformation and tone mapping
- Fixed patterned noise components: DSNU and PRNU
- ADC bit depth and impact on resolution
- Noise sources in image sensors and faucet and bucket analogy
- Stanford Image Sensor course