



# The Fundamentals of Camera and Image Sensor Technology

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# Digital Cameras: Basic Course

- Light Basics + CCD/CMOS Imager Fundamentals
- Digital Camera Principals
- Interfaces
- Camera Types and When to Use



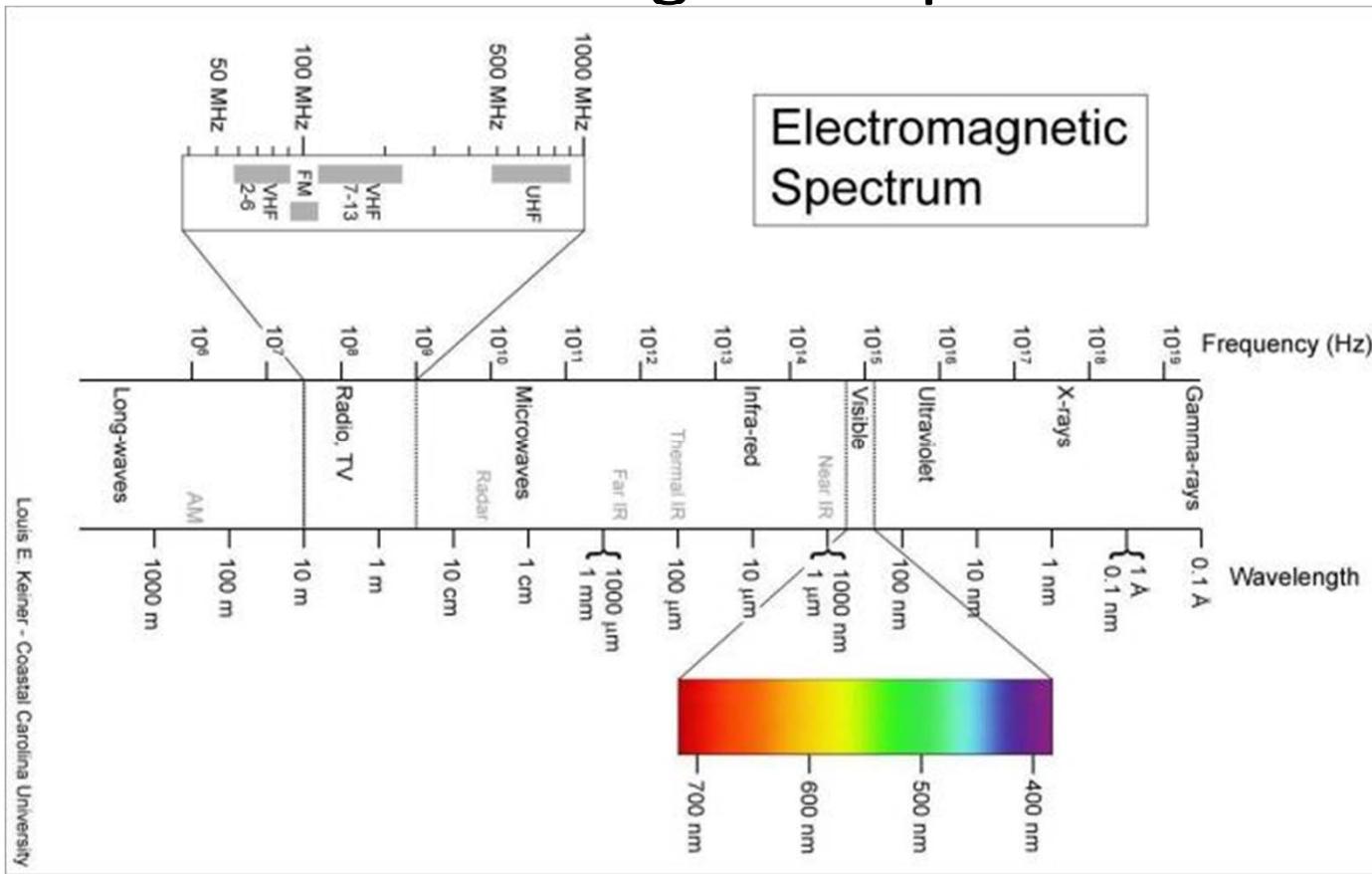
# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
  - Light Basics
  - CCD and CMOS Sensors
- Digital Camera Principles
- Camera Interface Standards
- Camera Types and When to Use



# Light Basics

## Electromagnetic Spectrum



Louis E. Keiner - Coastal Carolina University

Light is a very narrow band in the electromagnetic spectrum



# Light Basics

## Light Spectrum



We are primarily interested in wavelengths from **200–1100 nM**

- Visible Light: 400 – 750 nM
- NUV: 200 – 400 nM
- NIR: 750 – 1100 nM



# Light Basics

Light is represented as both  
a particle and an electromagnetic wave

- A light particle is called a photon.
- Photons have some energy. (UV - > IR)
- The amount of energy determines the wavelength.
- The wavelength corresponds to a color.
- Intensity of light = number of photons.
- Color of light = wavelength of photons.

$$E = \frac{hc}{\lambda}$$

E = Energy of Photon

h = Planck's constant

c = Speed of light

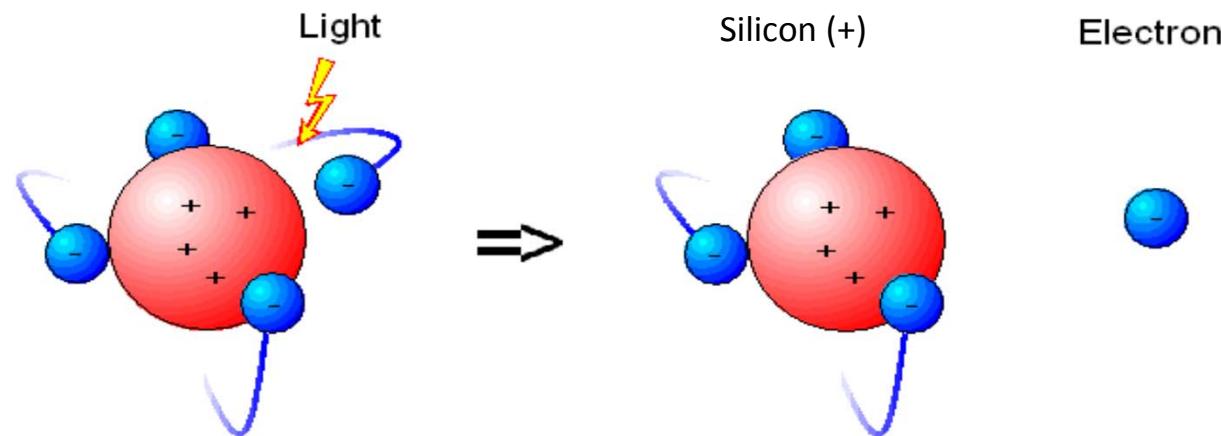
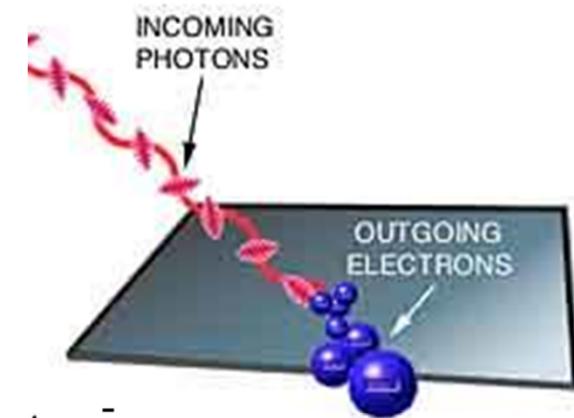
$\lambda$  = Wavelength of Light



# Light Basics

## Photoelectric Effect: Photons to Electrons

- Light photons hitting a Silicon surface will dislodge electrons
- Number of electrons released depends on intensity and wavelength

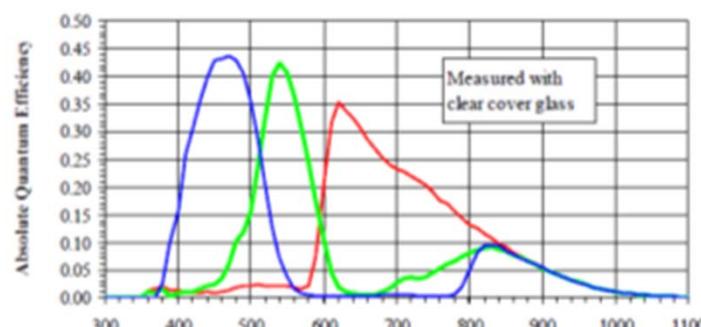


# Light Basics

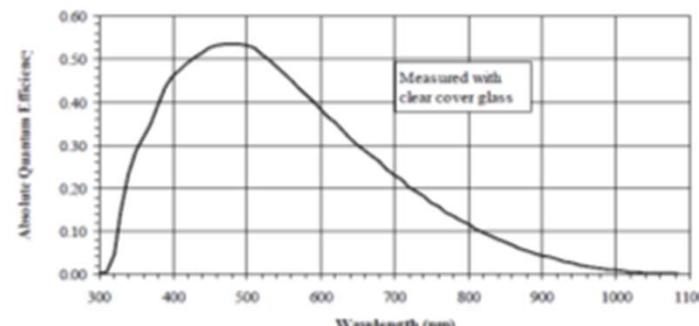
## Quantum Efficiency (QE):

The ratio of light that the sensor converts into charge.

Color with Microlens Quantum Efficiency



Monochrome with Microlens Quantum Efficiency

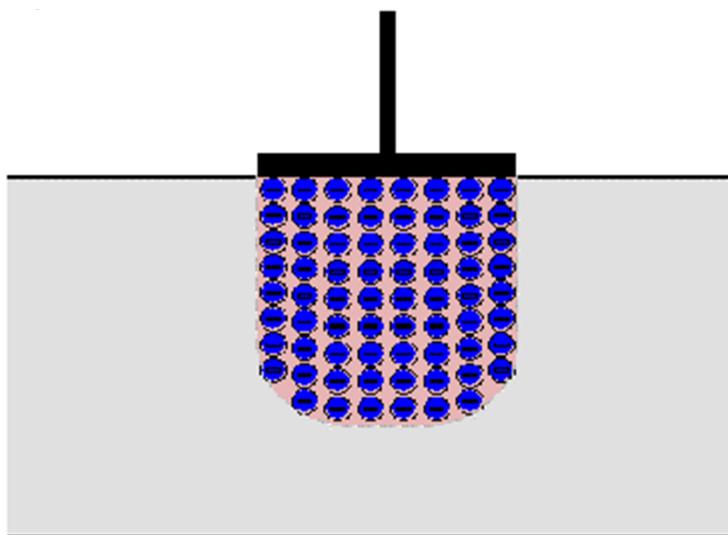


- **60% QE = For every 10 photons hitting a pixel, 6 electrons are released.**
- **QE response is sensor specific. Camera design does not affect the QE curve.**
- **QE is given in either absolute or relative terms. Relative QE is not good for comparison.**



# Light Basics

The **Full Well Capacity** is the maximum number of electrons that register a signal in a pixel. *Larger pixels have higher well capacity which also leads to higher sensitivity, better SNR, and increased*



## Full Well Capacity:

- 4,000 electrons – Small pixels
- 10,000 electrons – Medium pixels
- 50,000 electrons – Large pixels



# Digital Cameras: Basic Course

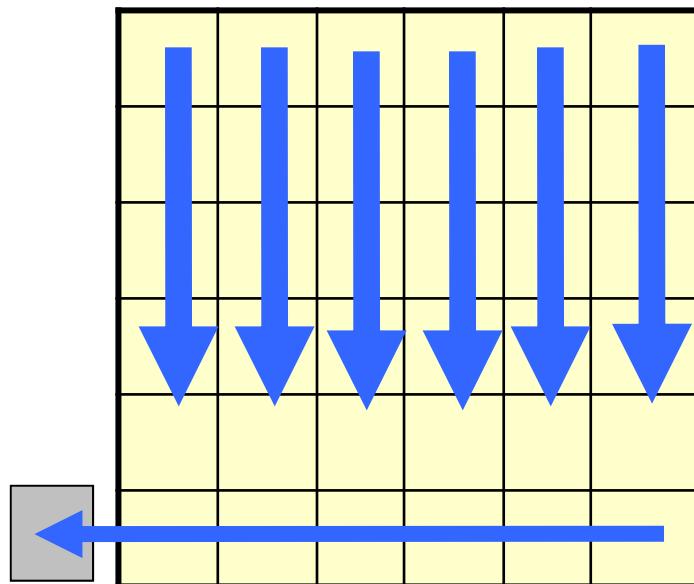
- **Light and CCD/CMOS Sensor Fundamentals**
  - Light Basics
  - **CCD and CMOS Sensors**
- Digital Camera Principles
- Interfaces
- Camera Types and When to Use



# CCD and CMOS Sensors

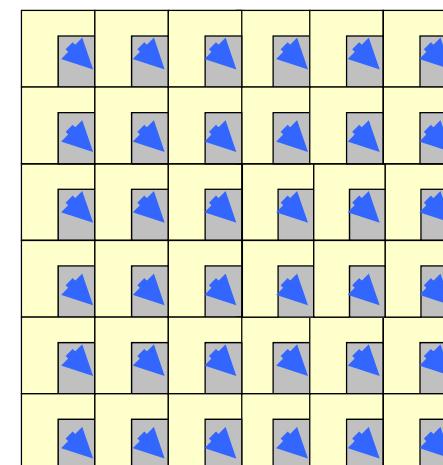
The main difference between CCD and CMOS is how they transfer the charge out of the pixel and into the camera's electronics "Read Out".

CCD



Current

CMOS



Voltage  
Sample

Pixel:



Read Out Circuitry:



# CCD and CMOS Sensors

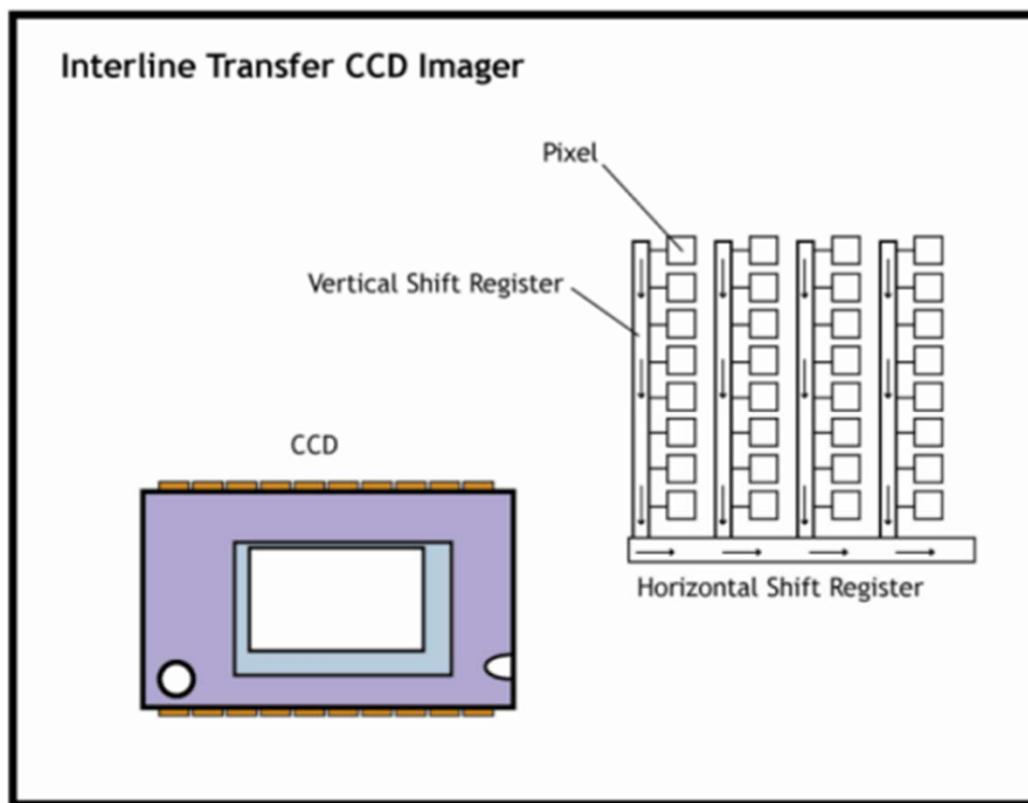
## CCD Sensor

Think “Bucket Brigade!”



# CCD and CMOS Sensors

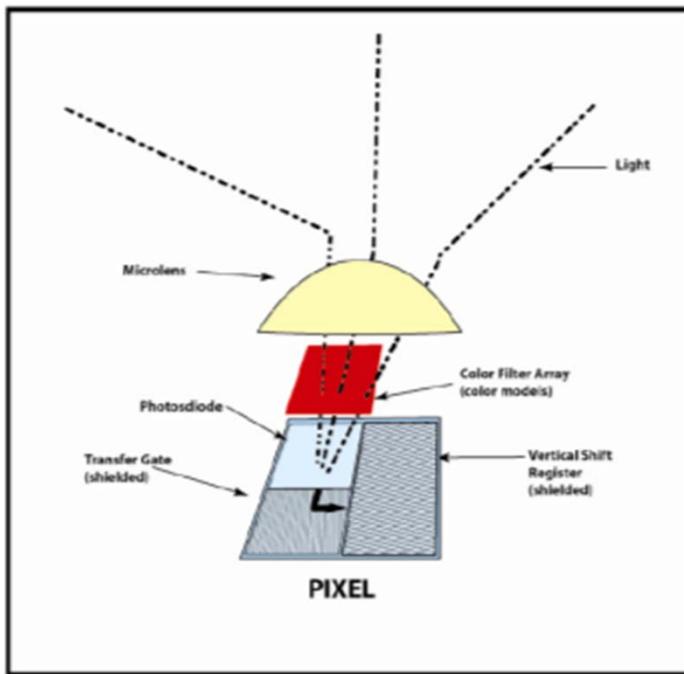
## CCD Sensor



- “Charge-Coupled Device”
- CCD imagers are **Current Driven Devices**
- Charge is collected in pixels
- The charge is then physically shifted on the imager surface to the output for sampling
- The CCD output is an *analog pulse* where the charge is proportional to the light intensity



# CCD Sensor



CCD Pixel with microlens

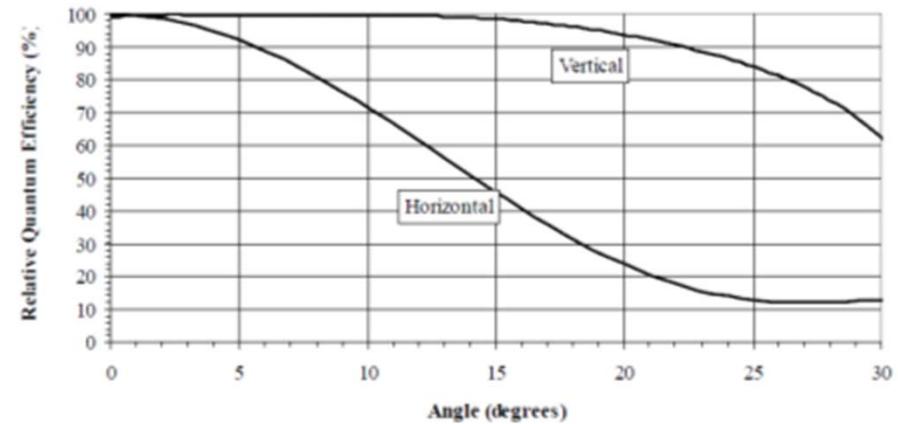
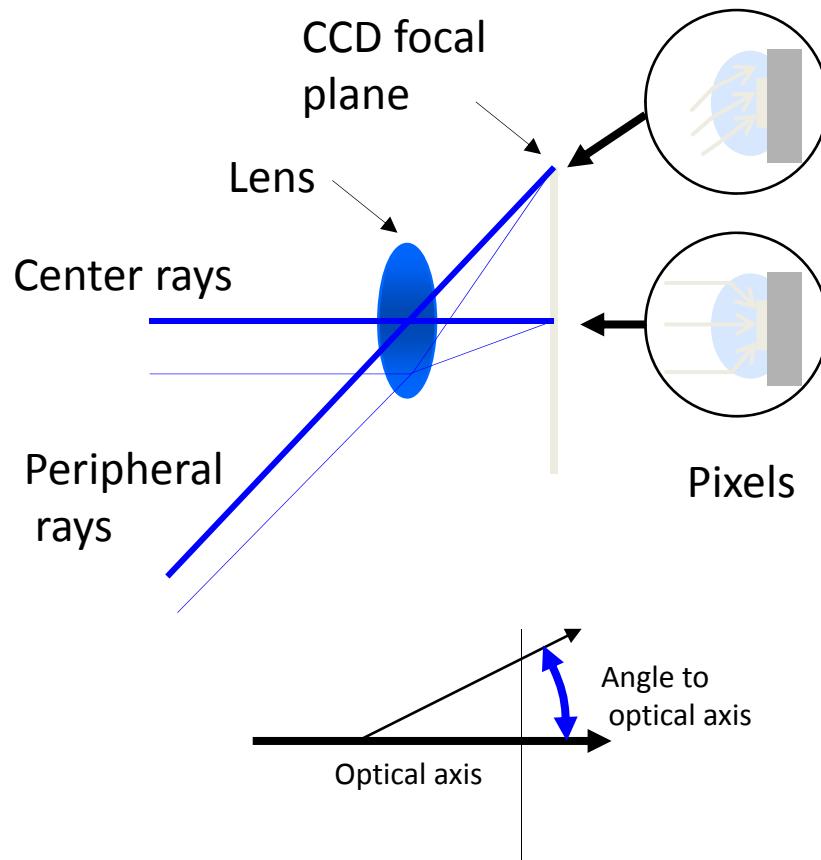
## Microlens

- Microlenses increase the photon collection area of the pixel and focus the photons into the photosensitive area
- Almost all modern CCD designs use microlenses (Bayer-Mono)
- **PRO** - Effectively increases the quantum efficiency of the pixel
- **CON** – Creates angular sensitivity to the incident light ray



# CCD and CMOS Sensors

**Microlenses decrease sensitivity to angular rays**



Angular QE data for Kodak KAI 0340 CCD

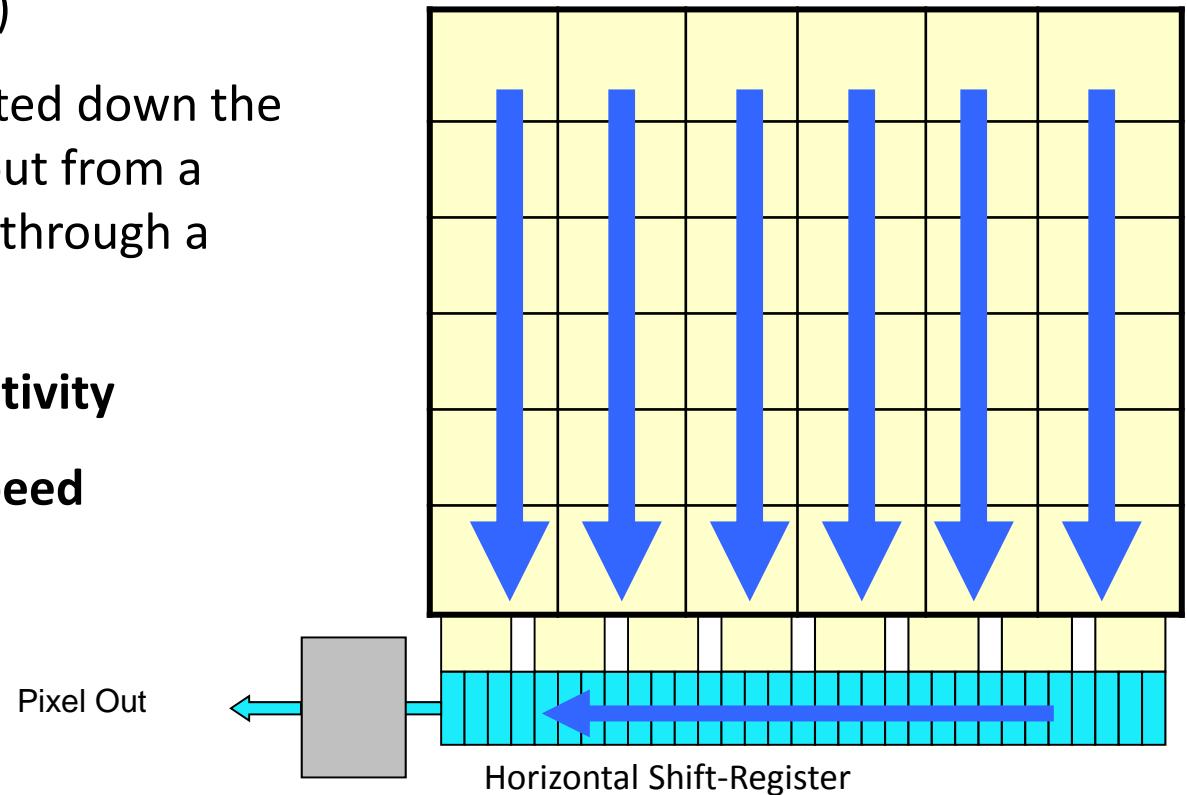
Varies due to the photosensitive area  
not being square!



# CCD and CMOS Sensors

- Microlens increases pixel effective area (Good “Fill Factor”)
- Horizontal lines are shifted down the sensor. Pixels are read out from a horizontal shift register through a common circuit
- **Main Advantage :Sensitivity**
- **Main Disadvantage: Speed**

**CCD Imager**



\*CCD: Charge-Coupled Device



# CCD and CMOS Sensors

## CCD Issues: Blooming

- Blooming is known as the spread of charges to adjacent pixels due to over saturation of pixels.
- This makes some very bright spots in the image.



# CCD and CMOS Sensors

## CCD Issues: Smearing

- Smear is similar to blooming. It's caused by pixels becoming saturated, and light spilling over into the next column of pixels.



# CCD and CMOS Sensors

## CMOS Sensor



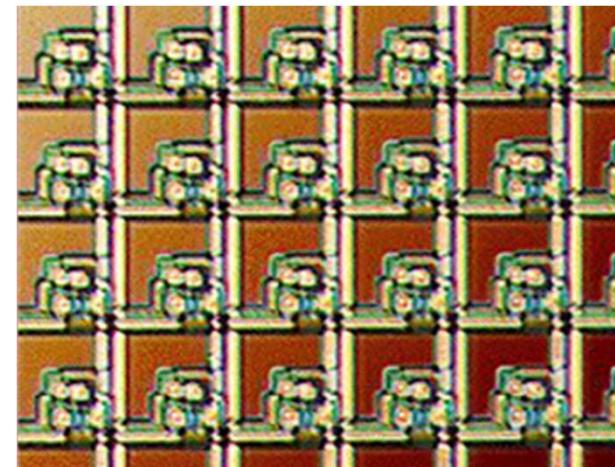
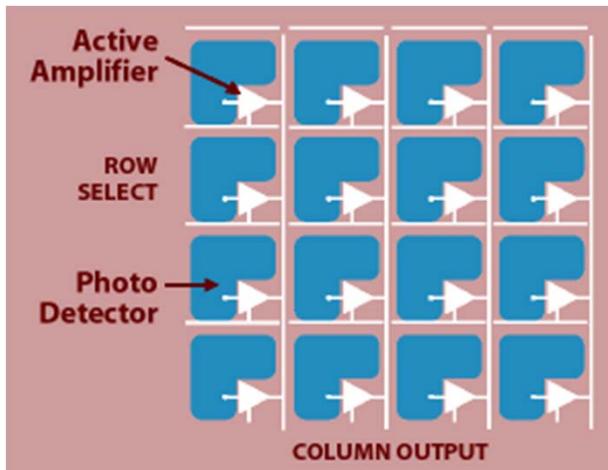
- “Complimentary Metal-Oxide Semiconductor”
- CMOS imagers are **Voltage Driven** Devices
- Light striking the pixel creates a voltage proportional to intensity
- The voltage is sampled directly at the pixel, digitized on the imager and cleared for the next frame
- The CMOS imager has a completely digital output



# CCD and CMOS Sensors

## CMOS Issues: Pattern Noise + Sensitivity

- CMOS layer stack up prevents using microlens and has lower charge conversion than CCD, usually resulting in lower sensitivity.
- Higher “Fixed Pattern Noise” due to unevenness between the individual Pixel cells and multiple A/D circuits in column readout.
- CMOS is more resistant to Smearing or Blooming than a CCD!



# CCD and CMOS Sensors

## CMOS Sensor

**Voltage sampling is faster than rolling charge in CCD.**

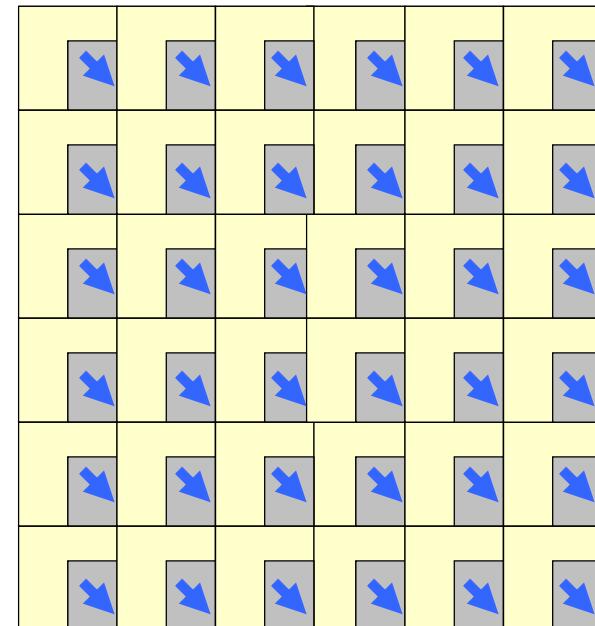
- This makes readout faster than CCD
- Less flow of charge = Less power

**Main Advantages:**

Speed + Power Consumption

**Main Disadvantages:**

Sensitivity + Pattern Noise



# CCD and CMOS Sensors

## CMOS Issues: Rolling Shutter

- An electronic shutter (CCD) or **global shutter** (CMOS) allow exposure of the whole frame at the same time.
- A **rolling shutter** will expose the frame line after line. The number of exposures equals the number of lines in the frame.



Image taken with global shutter

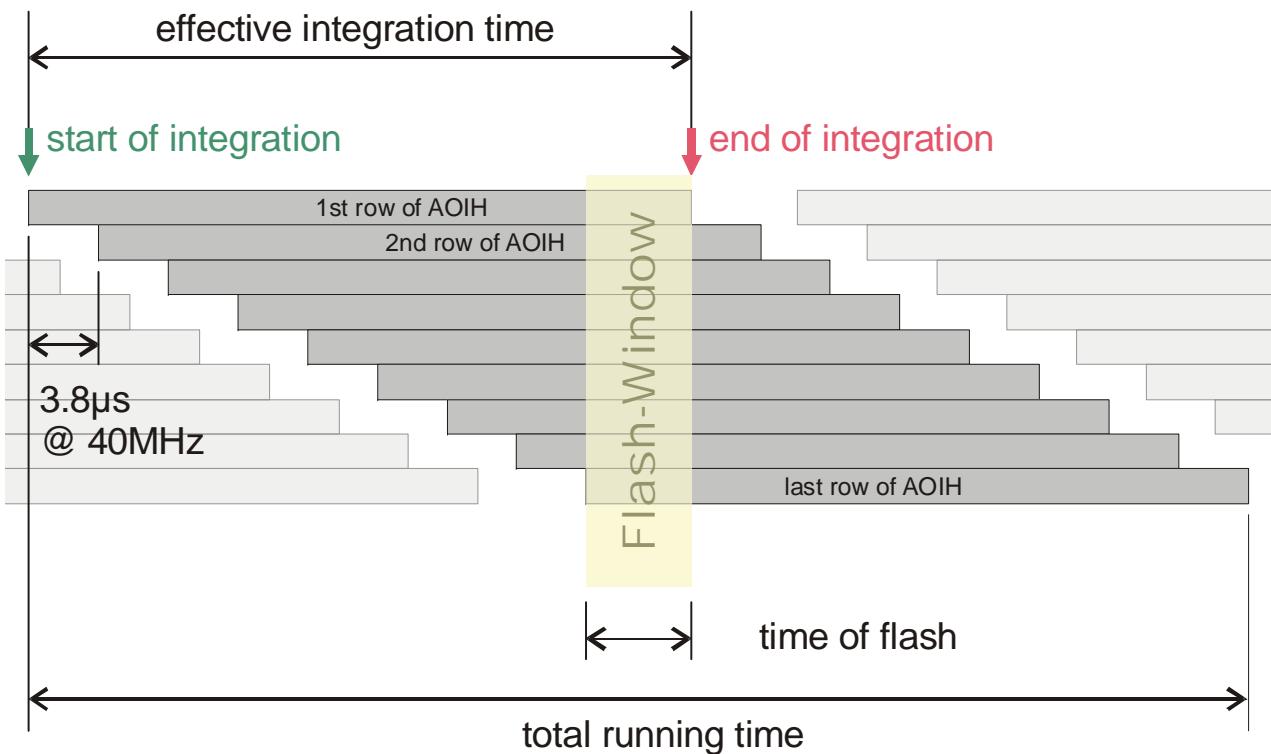


Image taken with rolling shutter



# CCD and CMOS Sensors

## CMOS Issues: Rolling Shutter



A strobe can be used to help freeze the motion and minimize rolling shutter effects



# CCD and CMOS Sensors

## CMOS Issues: Rolling Shutter

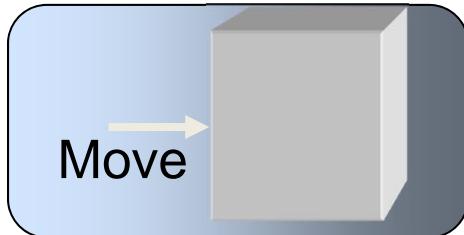


Image example with a moving object taken with global shutter.

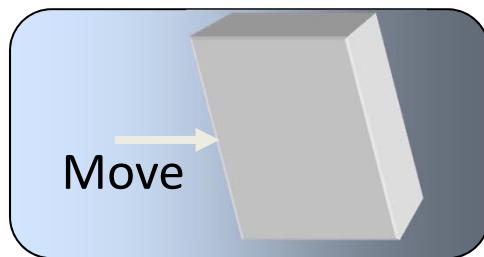
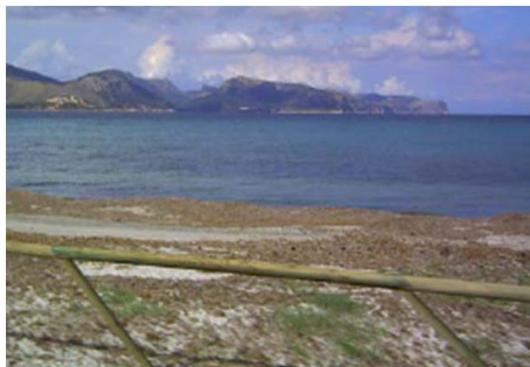


Image example showing distortion caused by a rolling shutter



Distortion caused by a rolling shutter

Picture taken from a moving car. The railing in front has vertical bars. Note that the vertical bars are shown distorted caused by the rolling shutter. The actual shutter setting is short enough to freeze the movement.



# CCD and CMOS Sensors

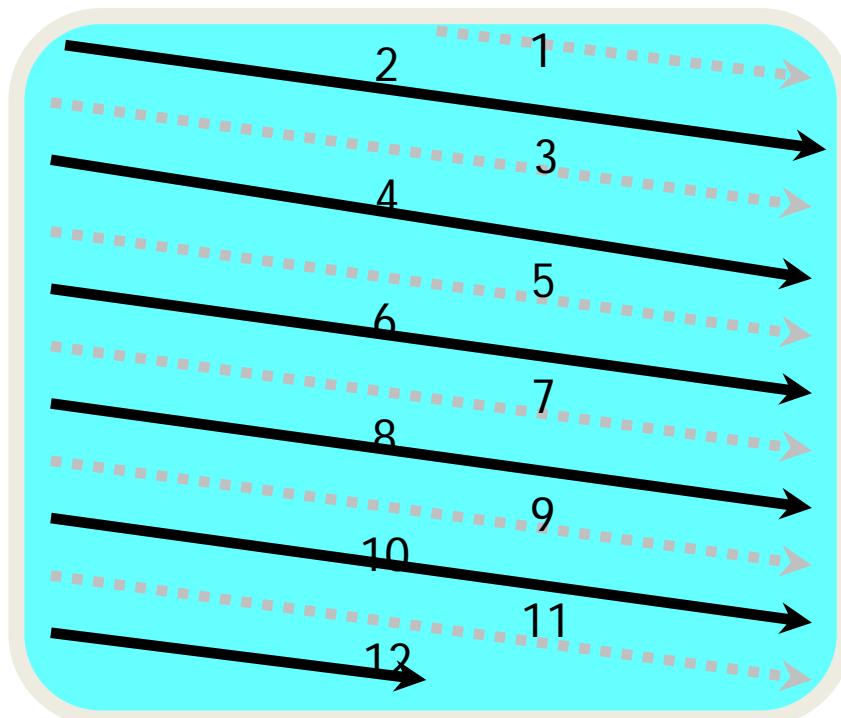
## Progressive and Interlaced Scanning

- Image from camera is formed by sequence of pixel lines scanned and displayed in one of two different ways.
- Progressive scanning :
  - Scanning of first line, second line, third line, etc... until the entire frame is scanned.
- Interlaced scanning :
  - Scanning of odd-numbered lines, then scanning of even-numbered lines. Both fields are then combined to form the entire frame.



# CCD and CMOS Sensors

Interlaced Scan (NTSC,RS-170,PAL,CCIR)  
1 Frame = 2 Fields



Field 2      Field 1c

Interlaced scan is used in normal TV systems. Odd lines (1-3-5...) are scanned in first field. In second field, even lines (2-4-6...) are scanned. One full frame consist of 2 interlaced fields (2:1 interlacing).

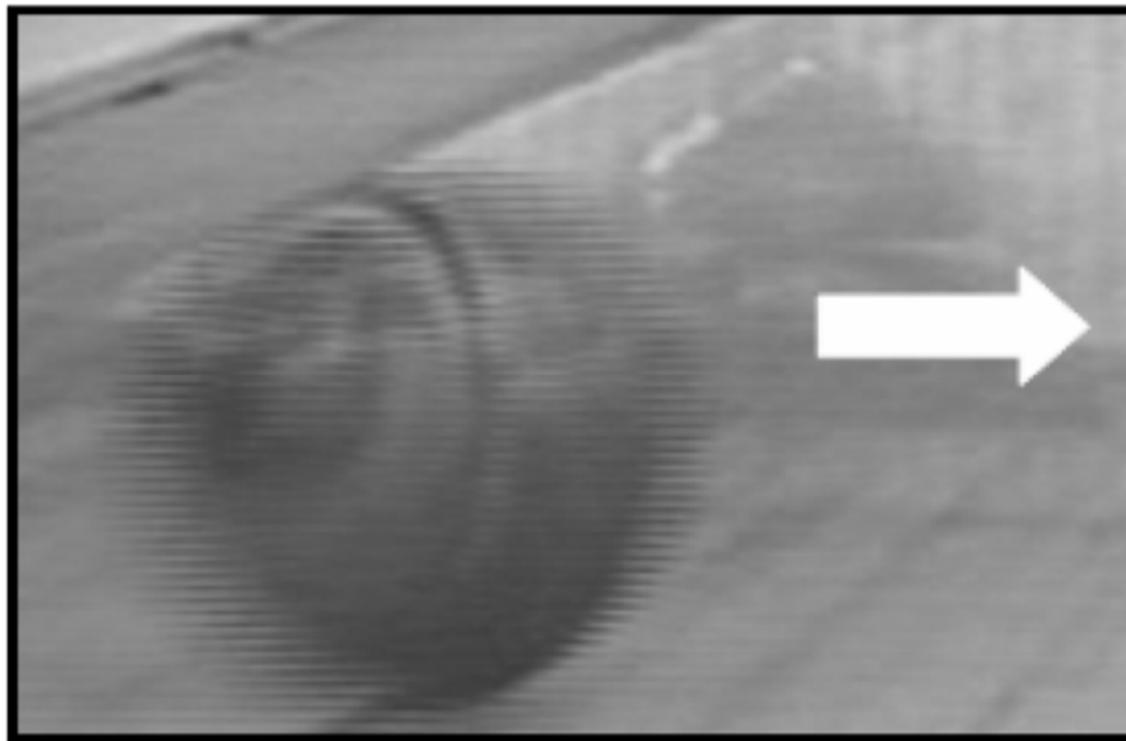
The benefit is smoother motion when displayed on a monitor.

The drawback is that each field has a separate exposure. The 2 exposures in one frame cause fast moving objects to blur; **interlace blurring**.



# CCD and CMOS Sensors

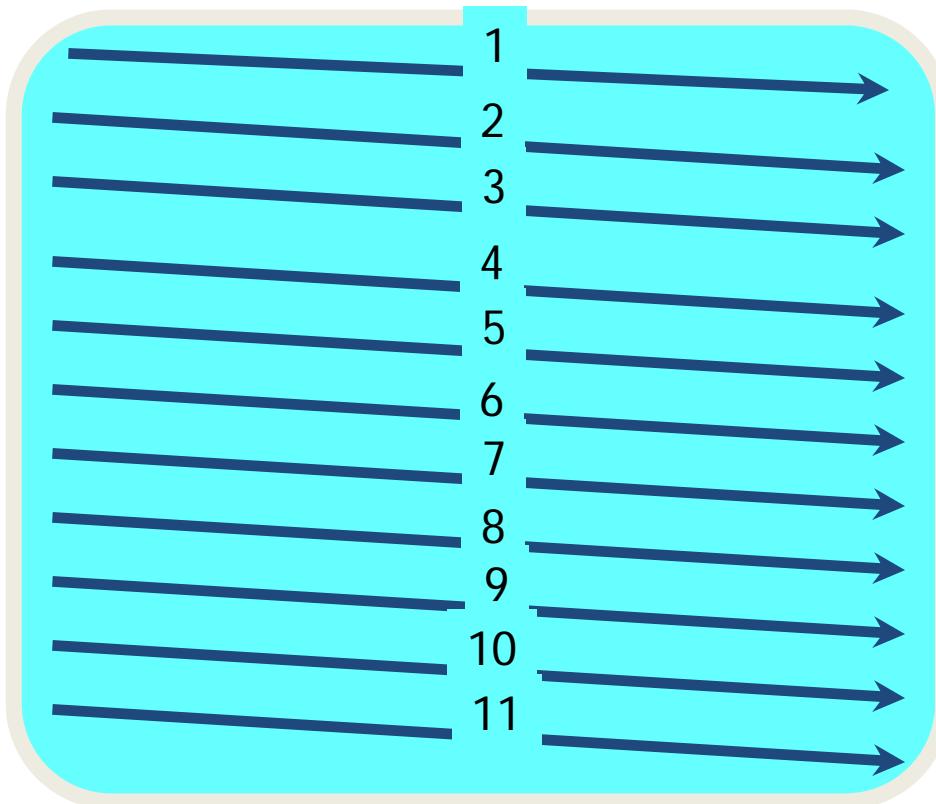
## Interlace Blurring



# CCD and CMOS Sensors

## Progressive Scan (Non-interlaced)

1 Frame = 1 Field



Non-interlaced scan or progressive scan is used in machine vision. The lines are scanned progressive from top to bottom in one full frame.

The scanning system is a non-standard. The video **can not be shown on a standard CCTV monitor.**

The benefit is that a full frame is available as the result of a single shutter event.



# CCD and CMOS Sensors

## Progressive and Interlaced scanning



Interlaced (odd lines)



Interlaced (even lines)



Progressive



# CCD and CMOS Sensors

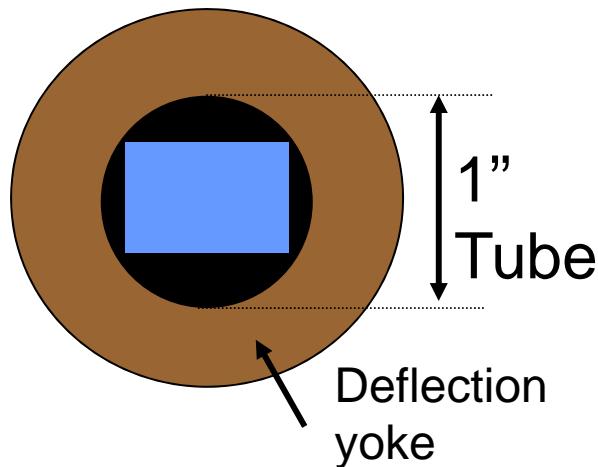
## Progressive and Interlaced scanning

- Interlaced scanning:
  - Spatial resolution is reduced but temporal resolution is improved. Twice as many 'full' images are presented per second.
- Progressive scanning:
  - Sharper images are formed.

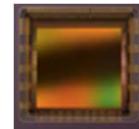
Note: With interlaced, you'll see smoother motion with *same frame rate*, but will also notice the interlaced lines in the image.



# CCD and CMOS Sensors

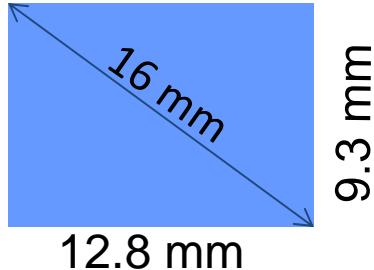
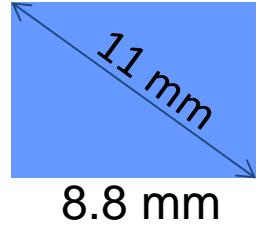
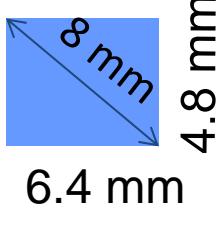


## Image Format



The image size in inches relates back to the tube camera. The image format of a tube which could be placed in a 1" deflection coil was called 1" format. The active image size is 16 mm in diagonal. It is the same as for a 16 mm film format.

BIPM (Bureau International des Poids & Mesures) recommend to use metric designation. Below is the most common image formats shown.

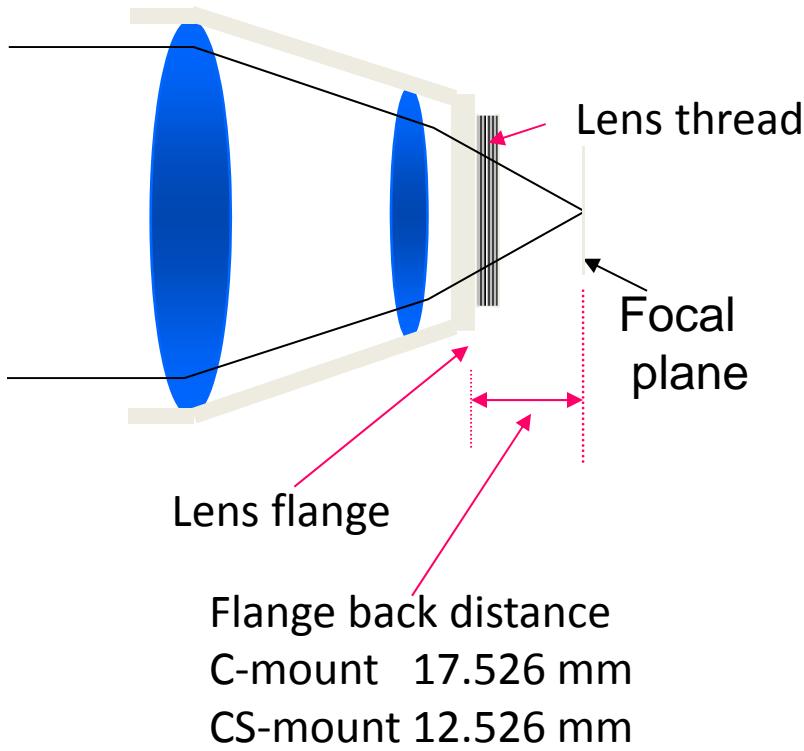
	1" format	2/3" format	1/2" format	1/3" format
Sony:	Type 1	Type 2/3	Type 1/2	Type 1/3
Diagonal:	16 mm	11 mm	8 mm	6 mm
Image size				

You MUST match formats to lenses!



# CCD and CMOS Sensors

## Lens Mount - C-mount and CS-mount



TIP - With a 5 mm adapter ring, a C-mount lens can be used on a CS-mount camera.

The most common lens for CCTV cameras are of the C-mount or CS-mount type.

The lens thread and the distance from the lens reference flange to the image plane is standard.

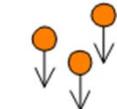
The lens thread is 1-32 UN-2A. Diameter is 1 inch.

The flange back distance in air is 17.526 mm for C-mount. For CS-mount it is 12.526 mm.

Glass filters or prism between lens and focal plane will increase the distance.



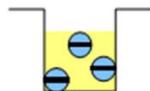
# Summary / Tips



A number of **photons** ...



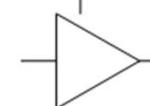
... hitting a **pixel** during **exposure time** .



... creates a number of **electrons** ...



... forming a **charge** that is converted by a **capacitor** to a **voltage** ...



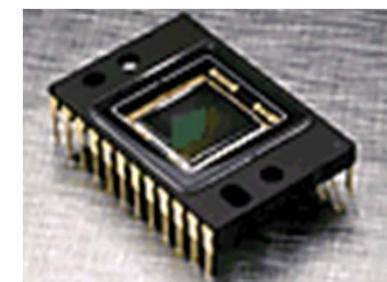
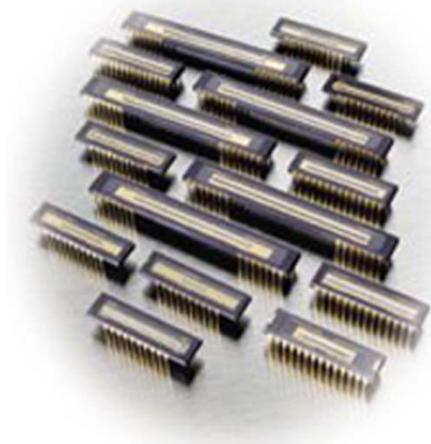
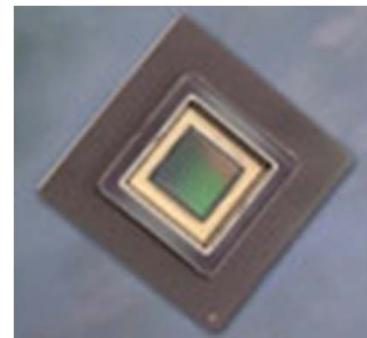
... and then **amplified** ...



... and **digitized** ...

42

... resulting in a **digital gray value**.



- **CCD: High image quality, lower speed.**
- **CMOS: High speed, lower image quality.**
- **Don't use Rolling shutter for motion.**



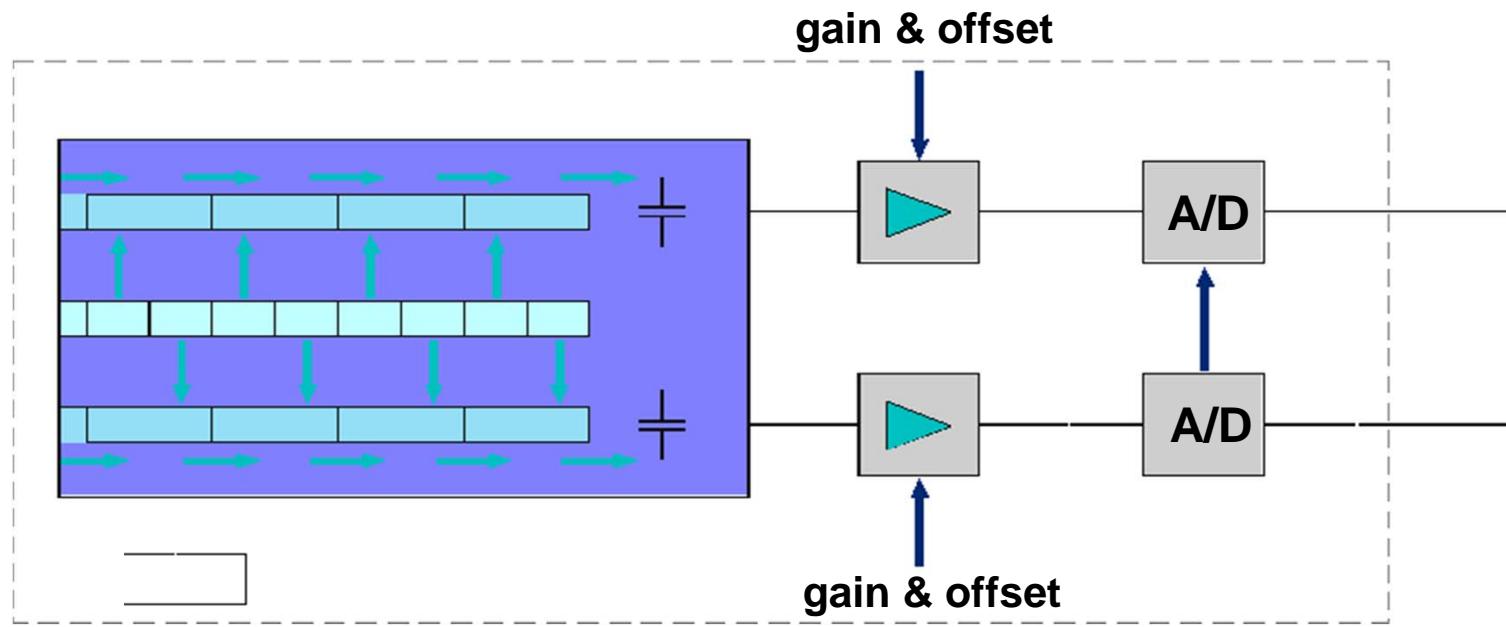
# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- **Concept of the Digital Camera**
  - **Analog and Digital Concepts in Imaging**
  - Digital Camera Benefits
  - Image Quality Basics
  - Camera Controls and Their Effects
- Interface Comparison
- Camera Types and When to Use



# Analog and Digital Concepts

- Charges from the pixels must be converted first to a voltage. This is done with a capacitor circuit
- Then the voltage levels must be measured and converted to a number. This is done with the analog to digital converter (ADC)
- Along the way, Gain and Offset can be adjusted before the conversion



# Analog and Digital Concepts

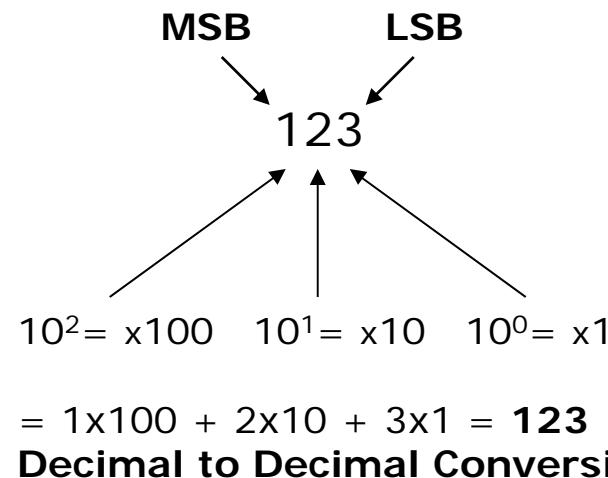
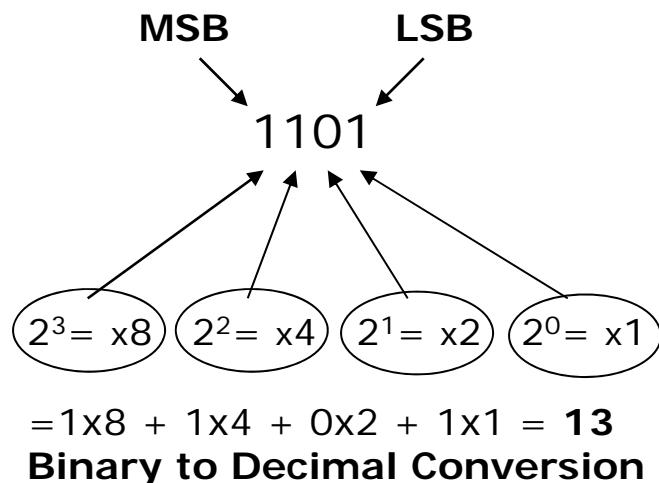
The ADC will represent voltage levels as Binary Numbers and convert to digital!

## Binary counting vs. Decimal:

- A pixel is given a number value based on amount of light it receives
- Cameras use binary numbers to represent this (bits)
- Humans use decimal numbers (DN) which represents a grey scale

The more bits you use, the higher you can count!

Binary	=	Decimal
0000	=	0
0001	=	1
0010	=	2
0011	=	3
0100	=	4



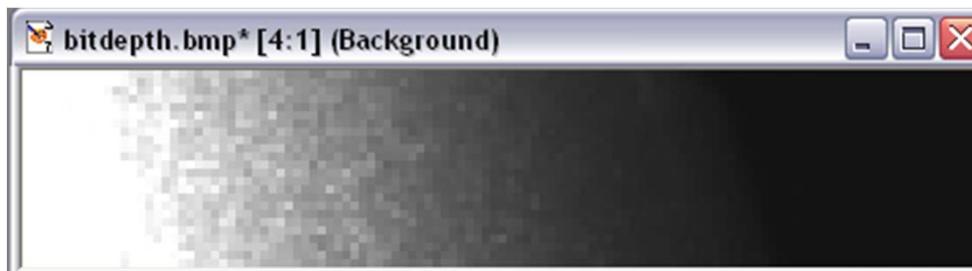
Converting from  
Binary to decimal is  
based on the position  
of the bit.



# Analog and Digital Concepts

So with more bits, you have more values to represent the light intensity from black to white.  
This is called “Bit Depth.” ( $2^8=256$ )

**8 bit image**



**256 pixel  
values  
available**

**4 bit image**



**16 pixel  
values  
available**

**1 bit image**



**2 pixel values  
available**



# Analog and Digital Concepts

## High Bit Depth Considerations

- With more bits, you get a more accurate measurement of the light. (8, 10, 12 bits = 256, 1024, 4096 grey scales)
- With more bits, you also have more data to transfer, process, store (12 bit = 50% more data than 8 bit).



# Digital Cameras: Basic Course

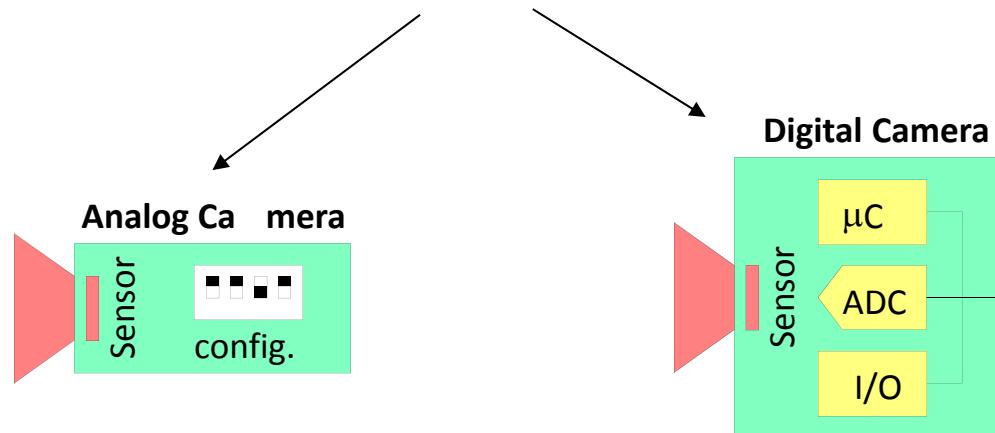
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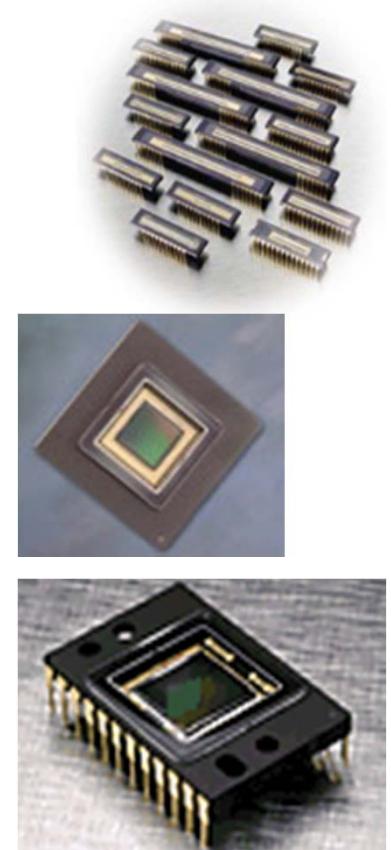
# Digital Camera Benefits

## Goal of Digital Cameras: To Replace Analog Cameras

Digital cameras use the same sensors as analog cameras

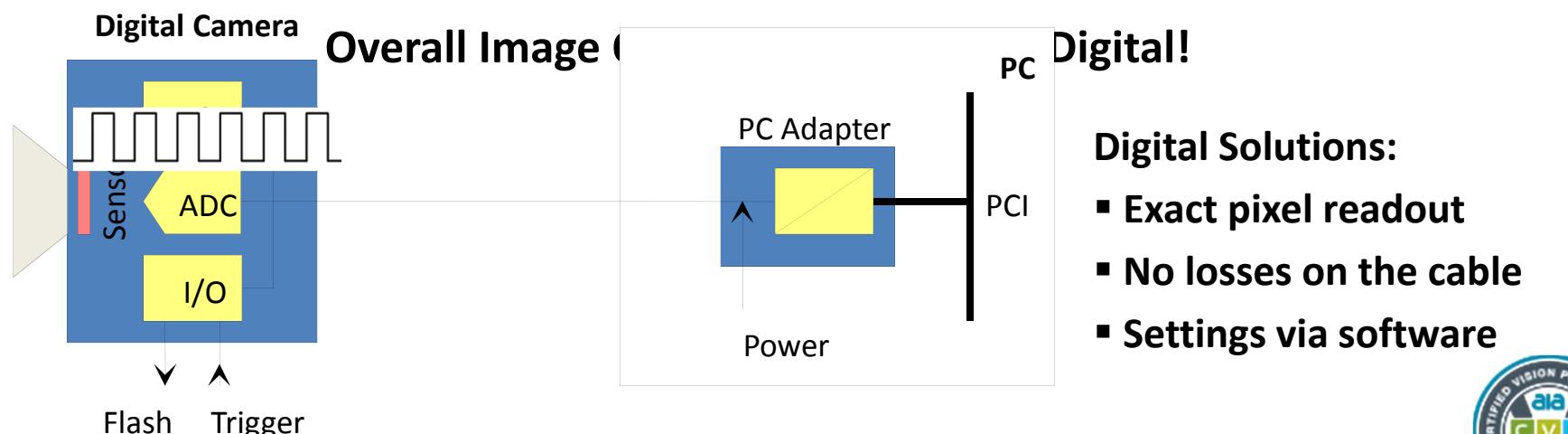
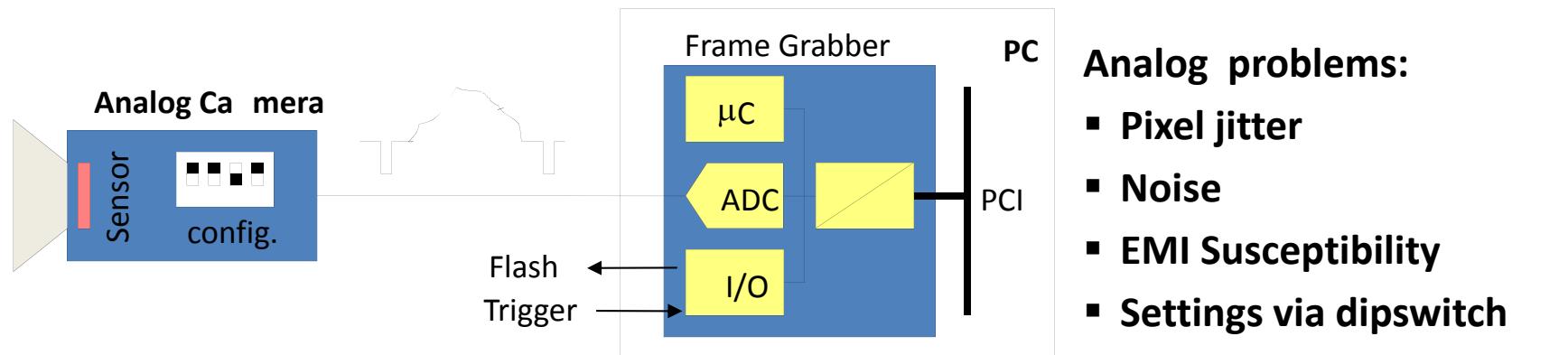


→ So, there is no difference in image quality at the sensor level, BUT...



# Digital Camera Benefits

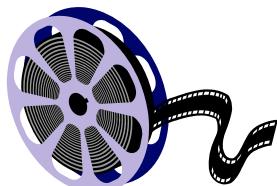
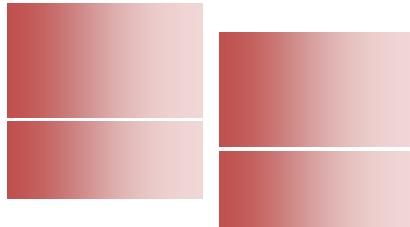
No Frame Grabber required with Digital!



# Digital Camera Benefits

## Analog

- CCIR / PAL → 624 lines, 25 fps
- EIA / NTSC → 525 lines, 30 fps
- Proprietary → more lines
- Interlaced / progressive scan



## Digital

- VGA @ 15 fps, 30 fps, 60 fps
- SVGA @ 15 fps, 30 fps, 60 fps
- XVGA @ 15 fps, 30 fps, 60 fps
- Or choose your own resolution!
- And choose your own frame rate!
- Progressive scan typically

Sensor Type	Sensor	Resolution [px]	Pixel Size [ $\mu\text{m}$ ]	Full Frames [fps]	GigE Vision*
1/4" CCD	SONY ICX618	656 × 490	5.6 × 5.6	160	
1/3" CMOS	CMOSIS CMV300	640 × 480	7.4 × 7.4	373	
1/3" CCD	SONY ICX445	1288 × 960	3.75 × 3.75	42	
1/1.8" CCD	SONY ICX274	1624 × 1228	4.4 × 4.4	27	
2/3" CMOS	CMOSIS CMV2000	2044 × 1084	5.5 × 5.5	55	
1"	CMOS	CMOSIS CMV4000	2044 × 2044	5.5 × 5.5	29

### Why Digital?

- ➔ Much more flexible
- ➔ Natural choice for high resolutions



# Digital Camera Benefits

## Analog

- Composite → 1 wire - cross talk
- S-VHS → 2 signal wires
- RGB → 3 or 4 signal wires

## Digital



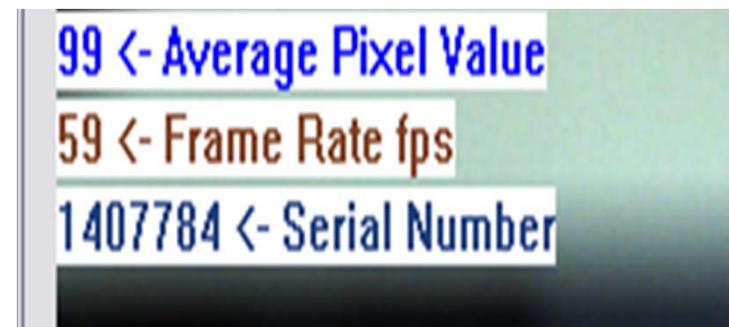
- RGB
- YUV 4:2:2
- Mono8 / Mono16
- Raw Bayer output
- Use your own interpolation



# Digital Camera Benefits

Digital cameras can provide advanced features

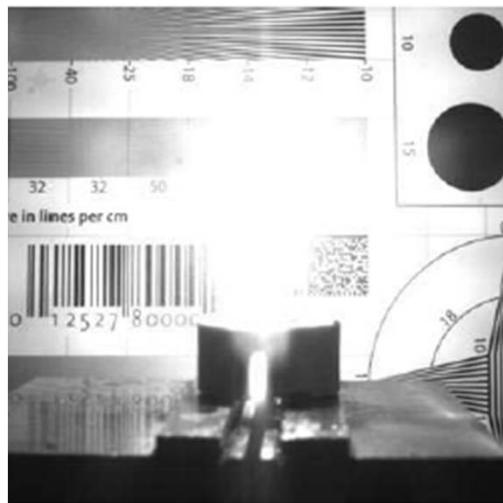
- Test Image
- Time Stamp
- Frame Counter
- IO Port Status
- Error Checking



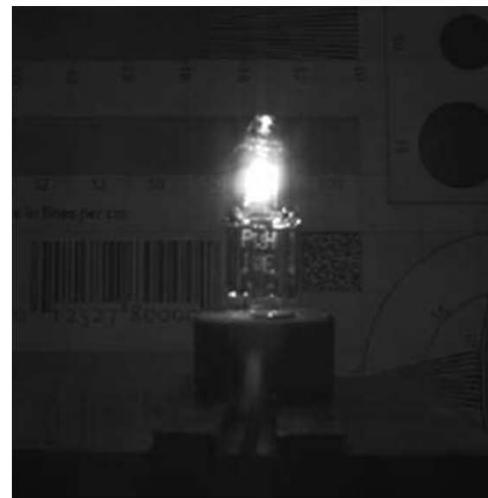
# Digital Camera Benefits

**Digital cameras can do on-board processing**

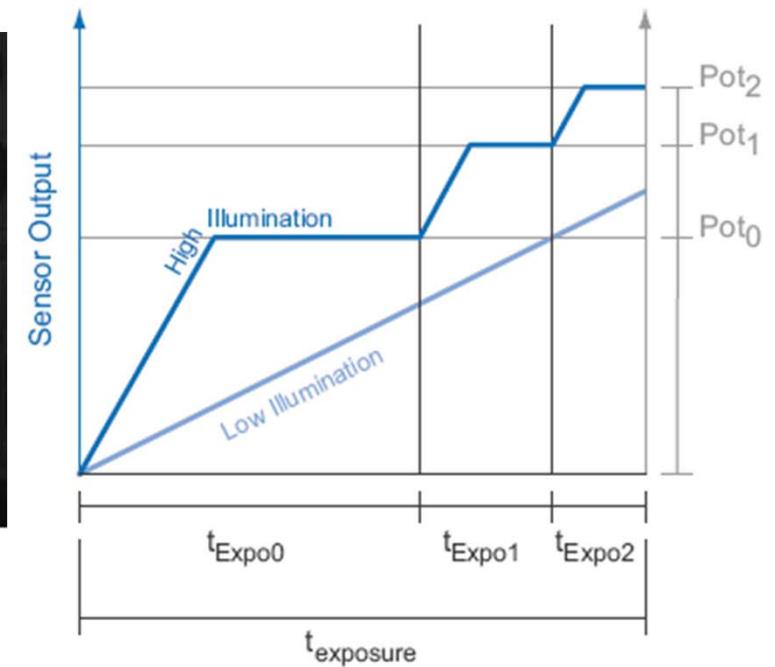
Example: High Dynamic Range Images (HDR)



HDR Off



HDR On



Other examples: Blemish Compensation, Flat Field Correction (FFC), Multi-ROI



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# Image Quality Basics

## Temporal Noise:

- Anything besides light that causes a pixel's value to change over time (temperature, ADC errors, etc.).  
This is measured by EMVA 1288.

## Spatial Noise:

- “Fixed Pattern Noise.” Constant non-uniformities in the image caused by bad sensor design, electrical noise, etc.



# Image Quality Basics

## Some Sources of Temporal Noise:

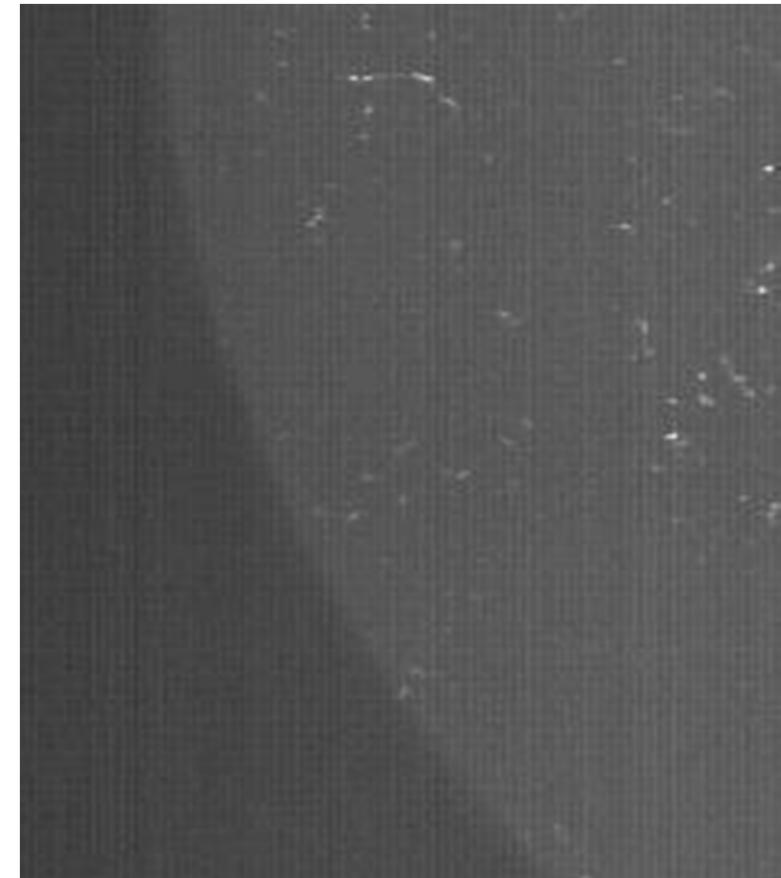
- **Shot Noise / Photon Noise:**  
Due to random fluctuations in the light.  
**[Brighter/Better Light = less shot noise]**
- **Dark Current Noise:**  
The rate at which electrons are produced due to thermal effects. Every  $8^{\circ}\text{C}$  = Dark noise doubles.  
**[cooler camera = less dark noise]**
- **Quantization Noise:**  
Errors coming from the A/D conversion process  
**[Use a better ADC = less quantization noise]**



# Image Quality Basics

## Some Sources of Spatial Noise (Fixed Pattern):

- Bad sensor design
- EMI



# Image Quality Basics

## Signal To Noise Ratio (SNR):

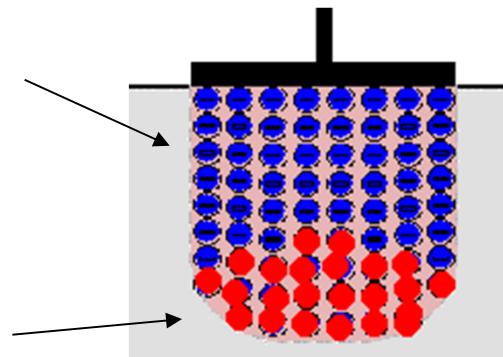
- The ratio of good signal caused by light to unwanted noise. The most important measurement of image quality for digital cameras.

## SNR Tips:

- High SNR achieved with large well depth (lots of signal to drown out the noise)
- Good camera design require less light to overcome

Signal electrons  
from light

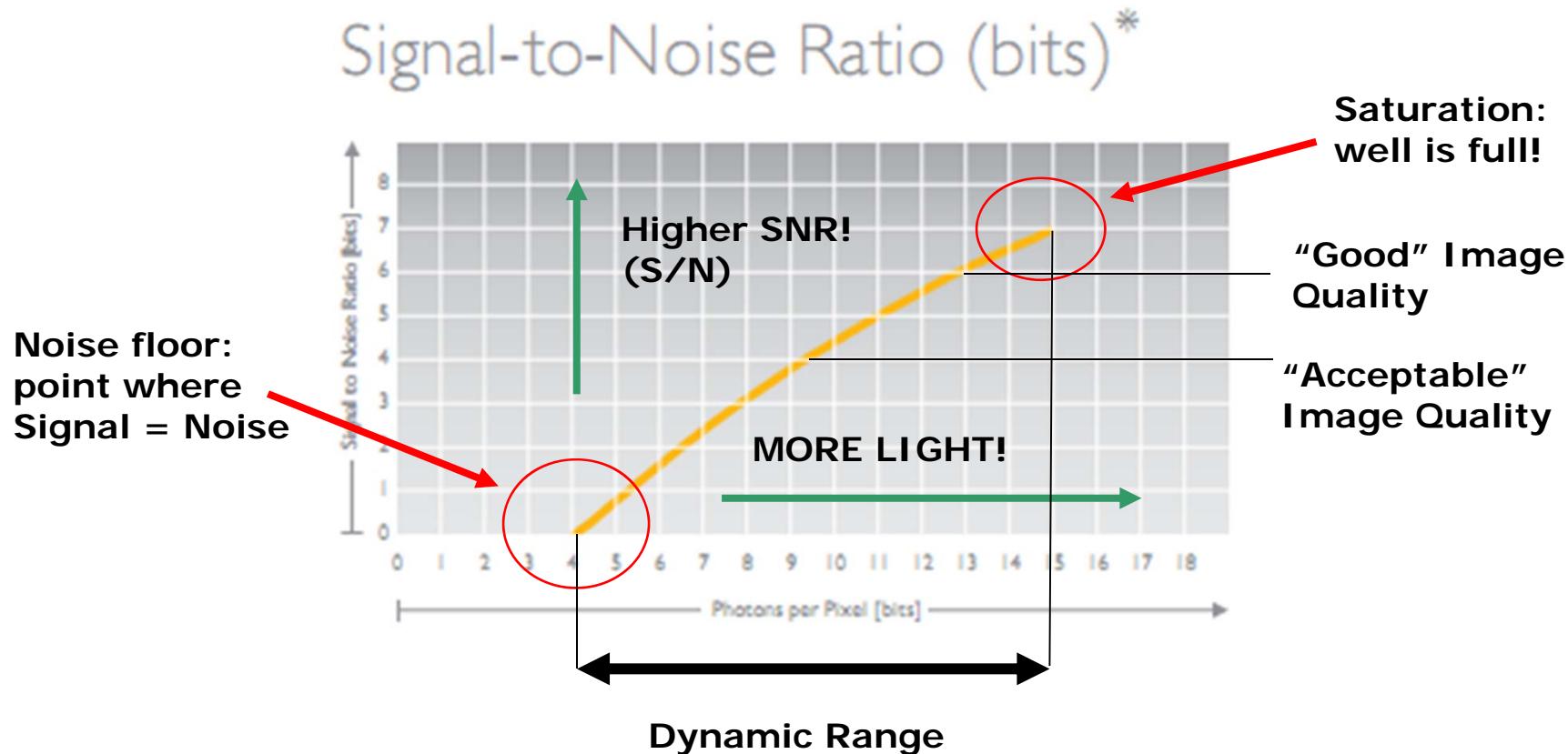
Noise electrons  
from heat, spatial,  
temporal, etc.



# Image Quality Basics

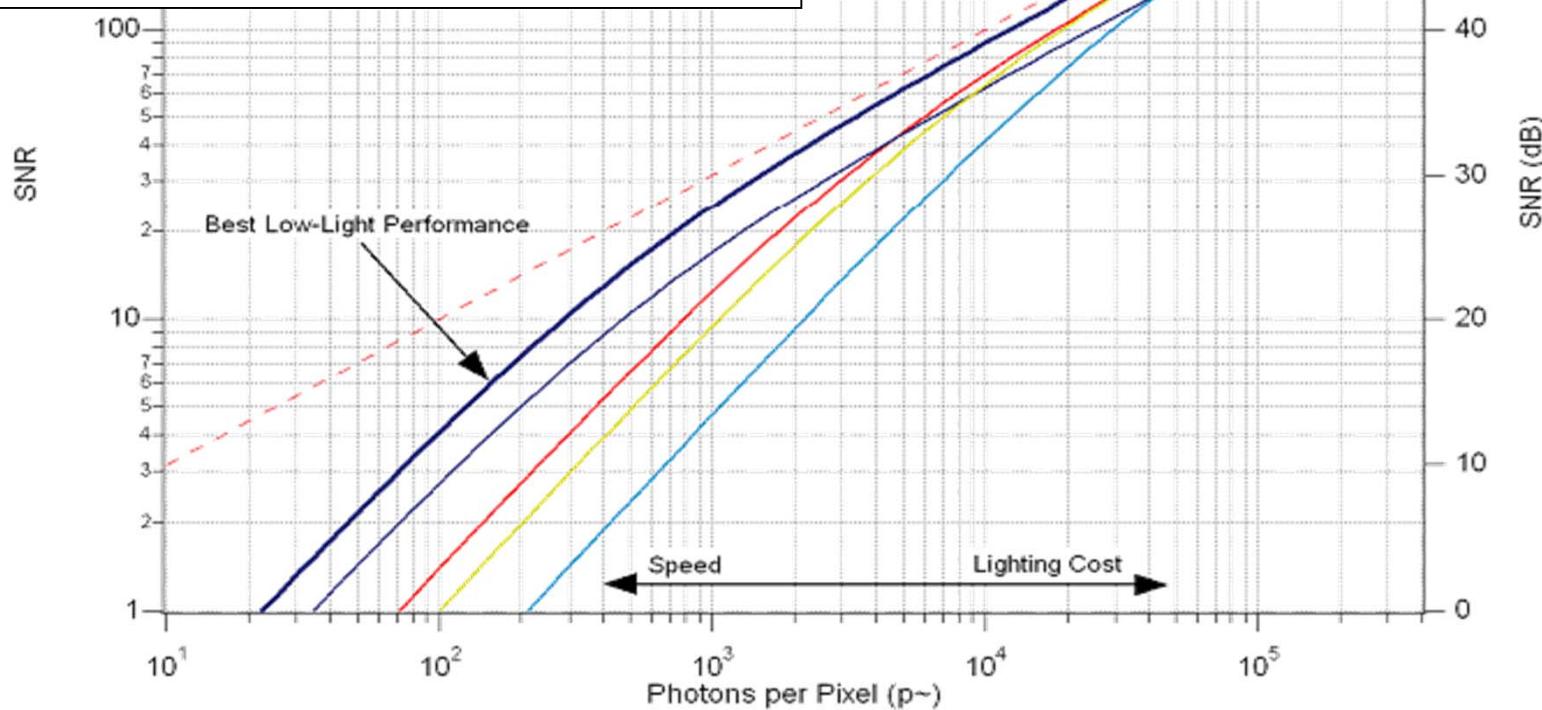
## Signal to Noise Ratio (SNR)

- **SNR Curve Characterization:** At-a-glance indicator of image quality and performance. Each camera has it's own and is unique.



# Image Quality Basics

- Use the SNR Curves of various cameras to compare performance.
- A camera good in low light is not always the best in bright light!!
- Know before you buy!



# Image Quality Basics

**Dynamic Range:** The measure of how well a camera can represent details when both bright and dark areas are present.

## Capture Methods

- Sensor algorithms (clips)
- Multi-Exposure
- Higher bit depth



Low

High



# Image Quality Basics

**EMVA1288:** Industry standard for measuring image quality of digital cameras.

- Testing uses known set of conditions (light, lens, targets, etc.).
- Manufacturers' report data in agreed-upon format.
- Results for multiple cameras published to show level of consistency.
- Allows customer to compare apples to apples.
- <http://www.standard1288.org/>



# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- **Concept of the Digital Camera**
  - Analog and Digital Concepts in Imaging
  - Digital Camera Benefits
  - Image Quality Basics
  - **Camera Controls and Their Effects**
- Interface Comparison
- Camera Types and When to Use



# Camera Controls

What are some camera controls can we use to affect image quality?

- Gain
- Exposure
- Brightness (black level)
- Image Format
- Resolution (Array Size)



# Camera Controls

**Gain:** Amplifies analog signal from pixel before conversion.

- Pro: Higher Grey Scale level (Brighter)
- Con: Noise introduced (6db gain = 2X increase)

The camera's gain setting is adjustable. As shown in Figure 59, increasing the gain increases the slope of the response curve for the camera. This results in a higher gray value output from the camera for a given amount of output from the imaging sensor. Decreasing the gain decreases the slope of the response curve and results in a lower gray value for a given amount of sensor output.

Increasing the gain is useful when at your brightest exposure, a gray value lower than 255 (in modes that output 8 bits per pixel) or 4095 (in modes that output 12 bits per pixels) is reached. For example, if you found that at your brightest exposure the gray values output by the camera were no higher than 127 (in an 8 bit mode), you could increase the gain to 6 dB (an amplification factor of 2) and thus reach gray values of 254.

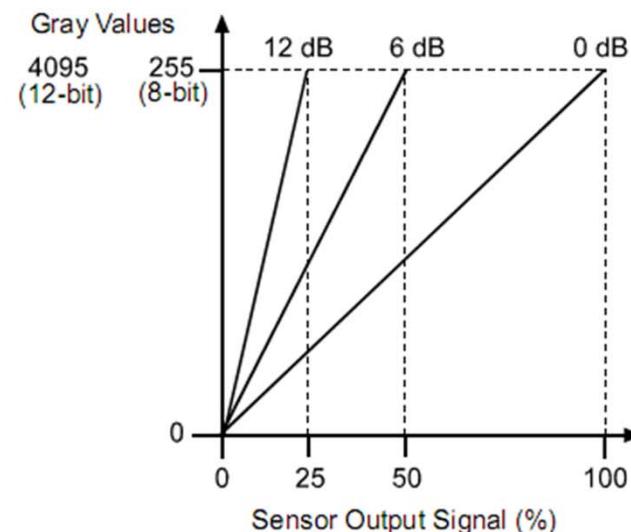


Fig. 59: Gain in dB



# Camera Controls

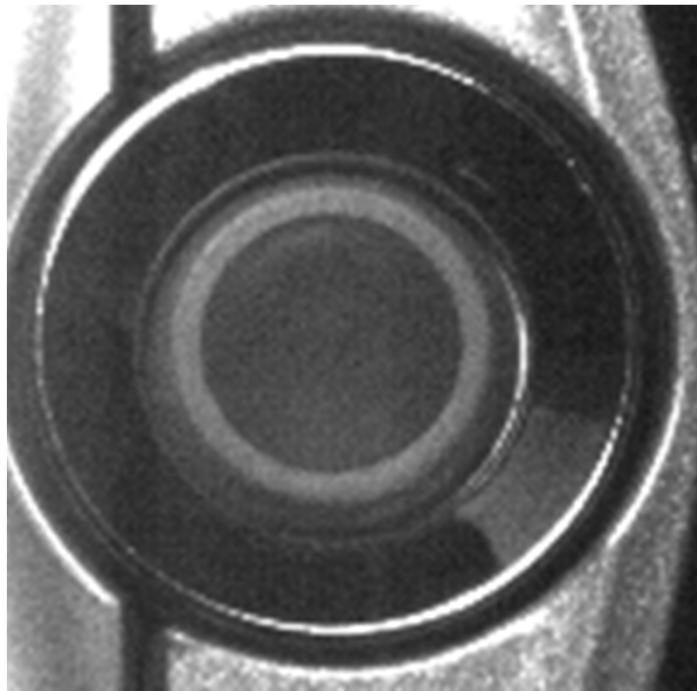
## Gain Considerations:

- Increasing gain will increase visibility of *both* signal and noise!
- Does not increase image quality!
- Use only as a last resort to increase brightness.
- Gain may be limited at higher bit depths.

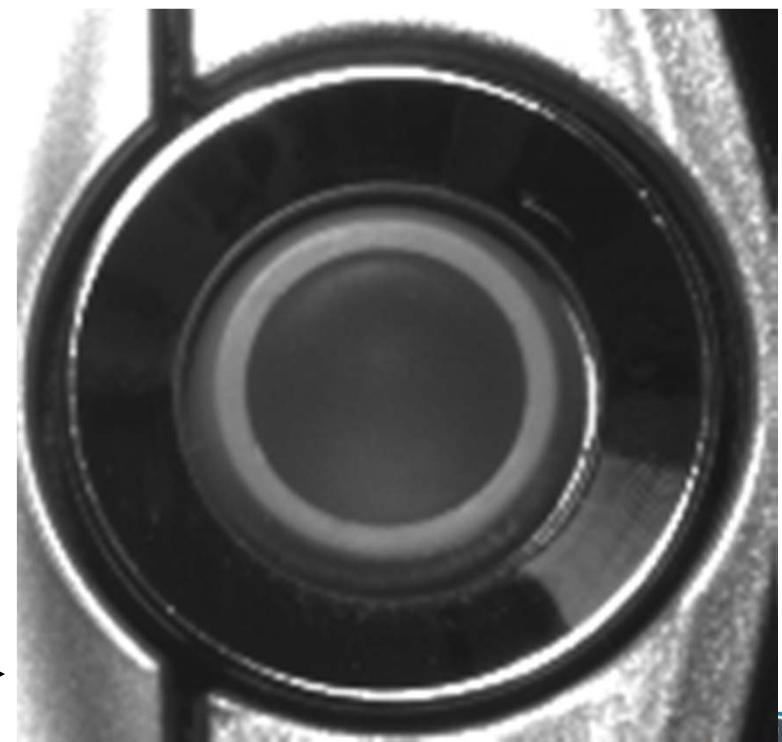


# Camera Controls

## Example Images of Gain Effects:



High Gain used to compensate for low light.  
Bright image, but noise is apparent



Low gain and good lighting is used. Light  
drowns out noise and makes clean image.



# Camera Controls

**Exposure Time:** The length of time that the sensor is open for collecting light. Also known as shutter speed and integration time.

## Exposure Time Considerations:

- Frame rate may be reduced with increase.
- Motion blur is greater with increase.
- SNR is greatly increased with more exposure (longer shutter time – filling pixel well)

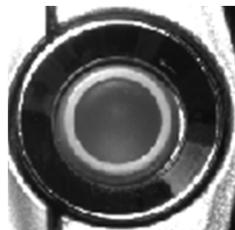


# Camera Controls

## Example Images of Exposure Effects:



Underexposed image: Detail lost in shadows



Good image: Detail is visible

Note that “Good” and “Better” are always a matter of opinion and application. Contrast is King!



Better image: Good detail and good contrast



Overexposed Image: Detail lost in highlights



# Camera Controls

**Black Level (Brightness):** Adds an offset to pixel values.

Adjusting the camera's black level will result in an offset to the pixel values output by the camera. Increasing the black level setting will result in a positive offset in the digital values output for the pixels. Decreasing the black level setting will result in a negative offset in the digital values output for the pixels.

- i.e. Black image emitting photons – adjust black level to capture or not

## Black Level Considerations:

- Proper use is to ensure camera accurately measures light when scene is darker.
- Side effect is that it can make the image brighter or darker, but not by much.



# Camera Controls

## Example Images of Black Level Effects:



Low Black Level used. Good Contrast, but some detail is lost in the darker regions (reduced grey level count)



High Black Level used. Contrast suffers, but detail is seen in darker regions (increased grey level count)



# Camera Controls

**Image Format:** The type of image sent from the camera. Usually specified by color or mono, and then by bit depth. (i.e. mono8)

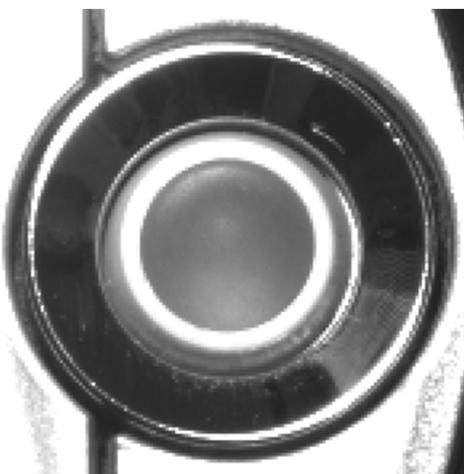
## **Image Format Considerations:**

- Higher bit depth = more data to transmit/process.
- Lower bit depth = loss of detail
- Be wary of anyone wishing to “view” a 12 bit image on a computer monitor. All monitors can *only* display 8 bits or less!
- Many people think they need 12 bits but don’t!

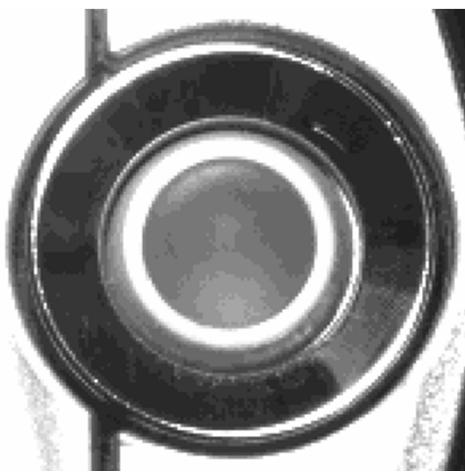


# Camera Controls

- Example Images of Image Format Effects:



8 bit  
88.2KB/image



4 bit  
44.2 KB/image



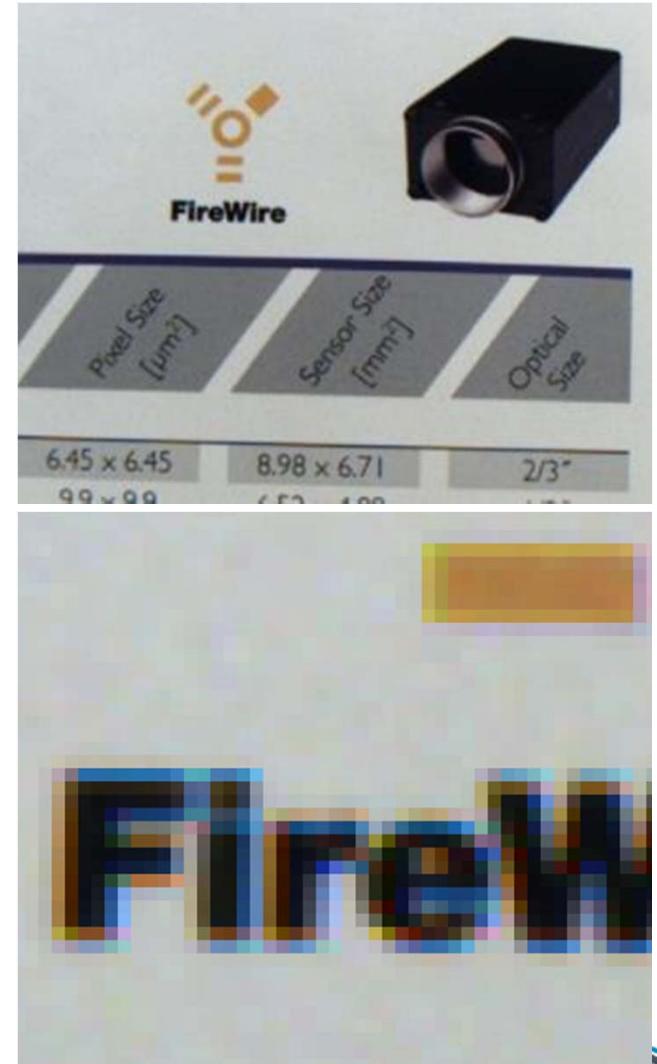
1 bit  
11.3KB/image



# Camera Controls

## Color Format Considerations

- Color cameras can be as little as \$50 more than mono cameras.
- But this is not always something you want.
- Color Images are nice, but usually not found in general machine vision.
- Color Interpolation does not work well when no colors are present (i.e. black text on white background).
- This will affect your image processing!
- More details later...



# Camera Controls

**Resolution (array size):** The number of pixels in the sensor,  
i.e., 640x480

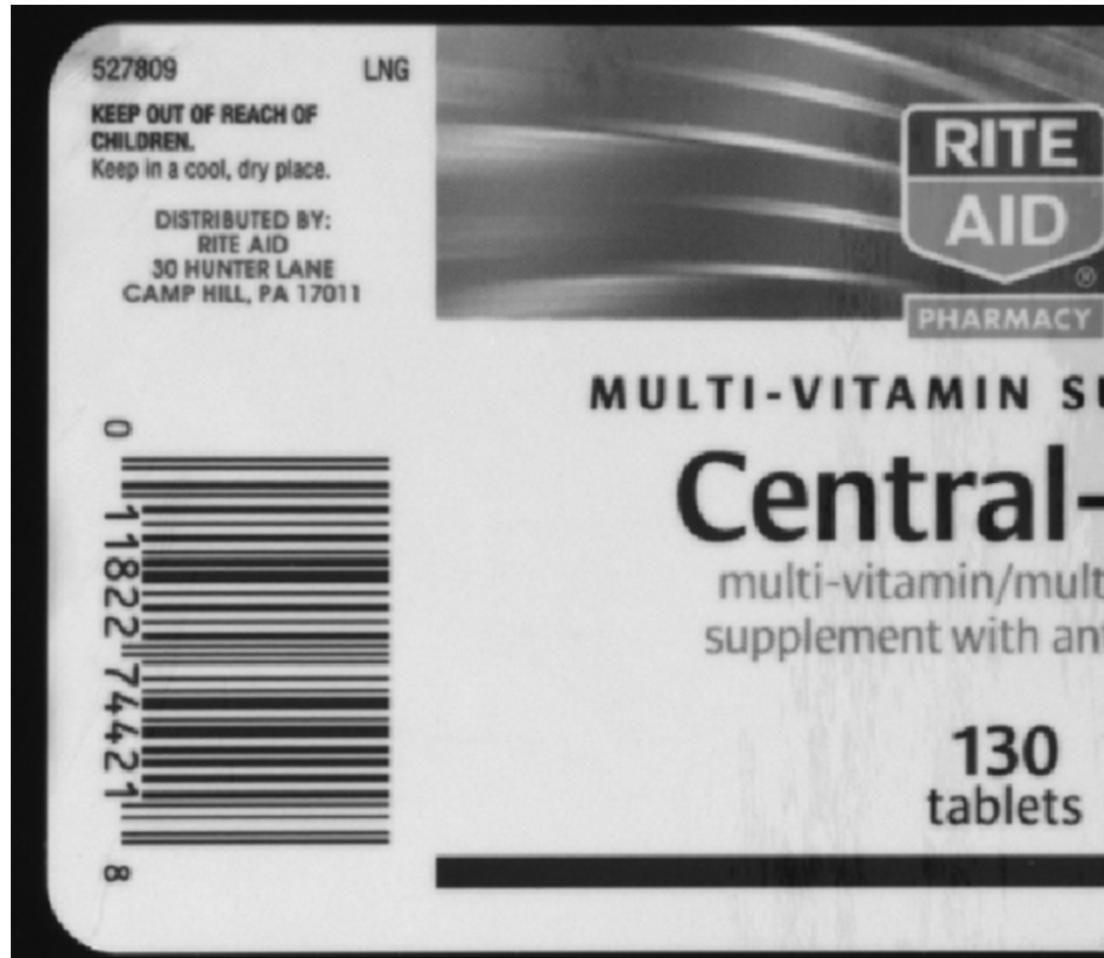
## Resolution Considerations:

- More pixels can achieve higher detail.
- But more pixels is not necessarily better!
- More pixels = small pixels = low SNR.
- Small pixels are hard for lenses to resolve.
- Always choose the lowest resolution possible for the application.
- High resolution = high price too



# Camera Controls

## Example Images of Resolution Effects:

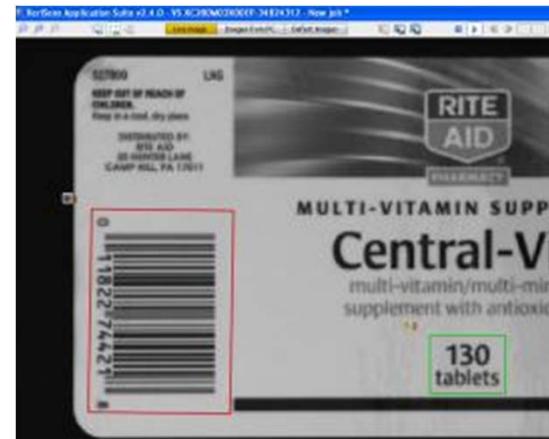


What if we need to inspect the **whole label** but also need to read the **barcode**?

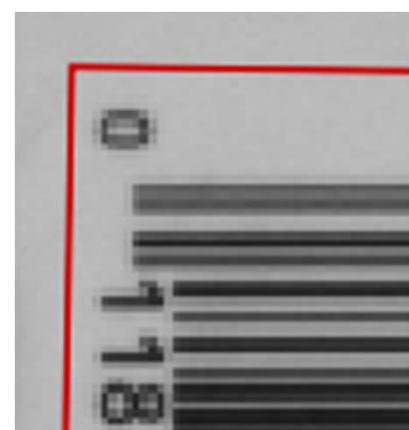
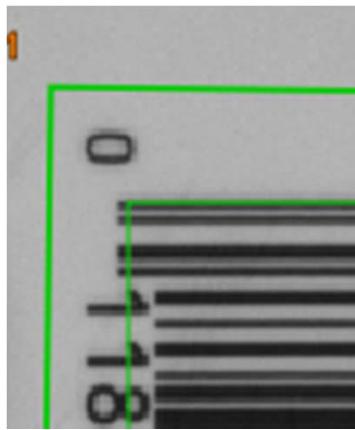


# Camera Controls

## Example Images of Resolution Effects:



High  
Resolution



Low  
Resolution

The resolution we choose to read the **barcode** determines the resolution we need to inspect the **whole label**.



# Summary / Tips

- Identify whether it is a low or high end application.
- Low end applications may only need frame rate, resolution, and a sample image to select a camera.
- High end applications will need deeper data. Get the EMVA1288 reports, manuals, sensor datasheets.
- Become familiar with the more common sensors: ICX285, ICX445, ICX414, KAI1020, etc.
- Digital cameras are packed with features. Many that customers would never think they need!
- Don't let bad settings misrepresent image quality.



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  - Camera Link HS (Framegrabber)
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  - GenICam (Software common to many standards)
  - Interface Comparison
- Camera Types and When to Use



# Digital Interface Standards

GLOBAL MACHINE VISION  
INTERFACE STANDARDS  
Understanding today's digital camera interface options



Host Org	Standard	Highlights
AIA	Camera Link*	<ul style="list-style-type: none"> <li>Version 2.0 released February 2012</li> <li>Version 2.1 in development for maintenance</li> <li>Industry leading standard for the past decade</li> </ul>
	Camera Link HS*	<ul style="list-style-type: none"> <li>Version 1.0 released May 2012</li> <li>Version 2.0 target release Q3 2014 with increases in speed to 5 &amp; 6 Gbits/s for C2, fiber connector, ROI support</li> <li>Copper and Fiber interfaces with an available core for quick development</li> </ul>
	GigE Vision*	<ul style="list-style-type: none"> <li>Version 2.0 released in November 2011</li> <li>Version 2.1 target release date is end of 2014 with mechanical spec's, improved testability, new pixel formats, support for 3D data</li> </ul>
	USB3 Vision*	<ul style="list-style-type: none"> <li>Version 1.0 released January 2013 for Superspeed USB 3.0</li> <li>Version 1.1 under research: high fps optimization, deterministic event transfers, multi-camera sync</li> </ul>
EMVA	GenICam**	<ul style="list-style-type: none"> <li>Version 2.4 was released in January 2014</li> <li>Version 3.0 target release date Q3 2014 with improved performance, reduced footprint</li> </ul>
JIIA	CoaXPress*	<ul style="list-style-type: none"> <li>Version 1.1 released in February 2013</li> <li>Version 2.0 target release Q3 2014 with increase in speed supporting 10 and 12.5 Gbits/s, error correction, multiple frame grabber support,</li> </ul>
	IIDC2**	<ul style="list-style-type: none"> <li>Version 1.0 released in Jan 2012</li> <li>Version 1.1 target release Q2 2014 with improved image format, trigger control</li> </ul>

\* Global standard available free for download (or will be upon release)

\*\* Software Standards



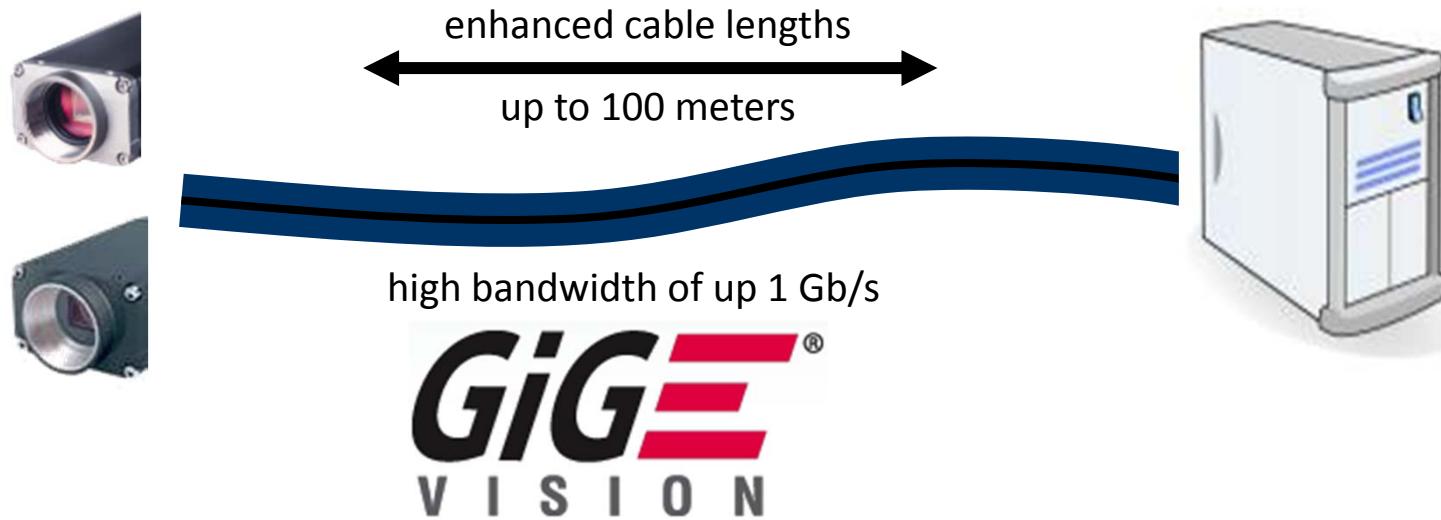
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# GigE Vision

## The Main Advantages of GigE Vision: Cable Length and Cost Effective Components



COTS accessories are reliable because networks are worldwide!



# GigE Vision

## GigE Vision Standard Background:

- Created to mold Gigabit Ethernet to the needs of Machine Vision.
- Designed to increase stability and determinism, while reducing CPU load.
- Built-in error checking and packet resend features:
- Contains two protocols:
  - **GVCP:** GigE Vision Control Protocol for establishing a constant link to camera for settings, configuration, etc.
  - **GVSP:** GigE Vision Streaming Protocol for streaming images.



# GigE Vision: What it is



*Open framework for transferring imaging data and control signals between cameras and PCs over standard Network connections:*

*GigE, 10 GigE, WiFi etc.*

- **Device Discovery**  
Defines how compliant devices obtain IP addresses and are identified on the network
- **GigE Vision Control Protocol (GVCP)**  
Defines how to specify stream channels and control and configure compliant devices
- **GigE Vision Stream Protocol (GVSP)**  
Defines how images are packetized and provides mechanisms for cameras to send image data and other information to host computers
- **XML Camera Description File**

Computer-readable datasheet of features in compliant devices  
Must be based on schema in EMVA's GenICam standard  
Seven mandatory features



**Four main elements**



# GigE Vision: What it is NOT



*No performance guarantee.  
Designed to allow vendors to  
differentiate products via features,  
performance levels*

Does not automatically deliver:

- Reliability
- Line rate throughput at camera or PC
  - Throughput is only guaranteed on the GigE link between them
- Deterministic real-time operation & low latency
- Recovery from packet loss
- Low CPU usage at the PC
- Real-time triggering and synchronization

Compliant products  
are still susceptible to  
native behavior of  
underlying GigE  
network and  
implementation

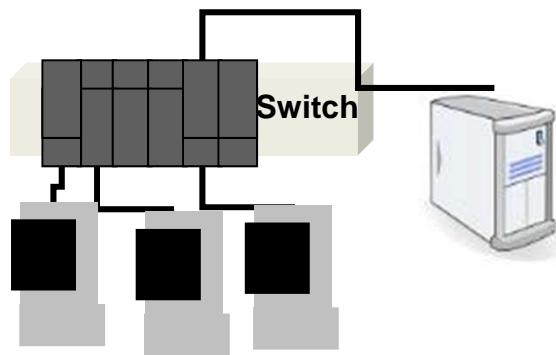
Good  
**IMPLEMENTATIONS** deliver ALL of this  
to a higher level



# GigE Vision

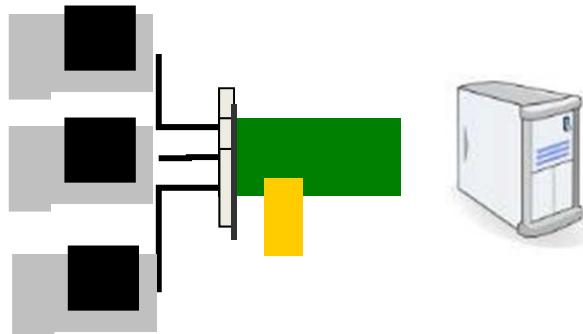
## GigE: Multi-Camera Applications by design

### Active network components



- GigE allows the usage of switches
- Multiple connections are possible
- Ideal setup for multiple cameras
- Save PCI-Slots

### Multiport GigE network cards



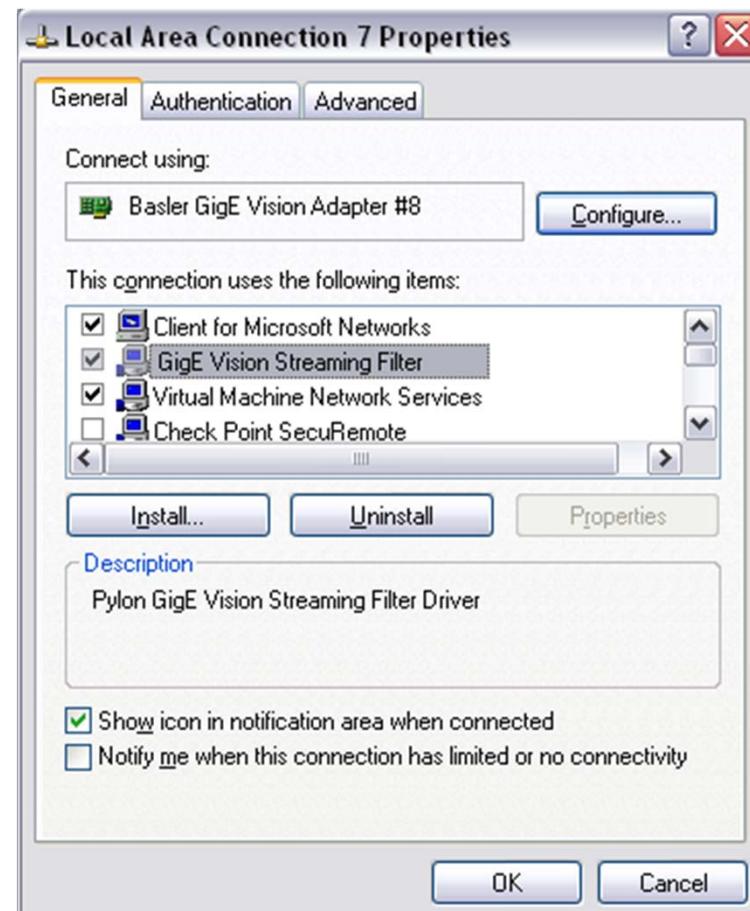
- Network cards can handle 4 cameras
- Multiple connections are possible
- No bus sharing like IEEE1394
- Ideal setup to replace analog cameras



# GigE Vision

## Filter Drivers

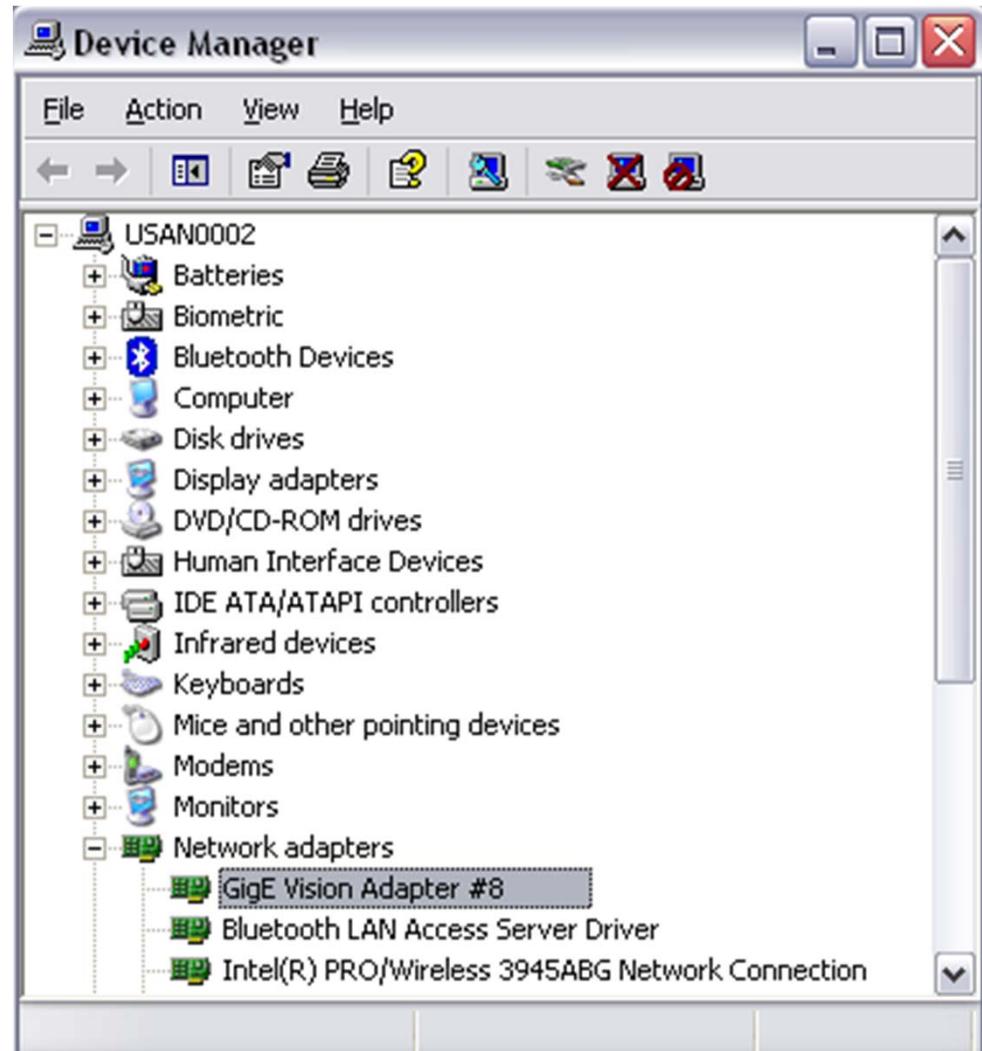
- A Filter Driver located above the NIC driver, but below the Windows IP Stack. It shows up as a network service.
- It detects any incoming GVSP (GigE Vision Streaming Protocol) packet and passes them directly to the GigE Vision library in the User Mode, thus *reducing the CPU load significantly*.
- GVCP take the normal way across the IP stack and the WinSock socket library.



# GigE Vision

## Performance Drivers

- A Performance Driver is a hardware driver for the NIC (*Intel chipset only*). It is basically the filter driver run on hardware.
- The main advantage of the performance driver is that it significantly lowers the CPU load needed to service the network traffic between the PC and the cameras.
- Compared to a Filter Driver, it also has a more robust packet resend mechanism.



# GigE Vision

## Network Interface Cards (NIC)

- 1, 2 and 4 port NIC's are available
- Multiple separate connections possible
- Cards are available for PCI/PCIe
- Starting at \$24.95 online
- Frame grabber companies may offer machine vision specific cards
- Prices for cards will continue to go down due to growing markets
- Most new PC's ship with on-board GigE now



# Ethernet Cable Categories



(Gigabit-) Ethernet uses CAT5, CAT6 and CAT7 cables. Most of these cables are well known from consumer electronics and PC networking.

## Cat5e

- Cat5e is a more detailed version of CAT5 (nearly all new installations now Cat5e)
- Developed for longer cable lengths with 100 Base-T

## Cat 6/7

- Developed for high speed multimedia, data and voice networks
- Special design for Gigabit Ethernet

## Note on Shielding...

- U/UTP (Unscreened Unshielded Twisted Pair) - No shielding
- S/UTP (Screened Unshielded Twisted Pair) – Medium shielding
- S/STP (Screened Shielded Twisted Pair) – Best shielding



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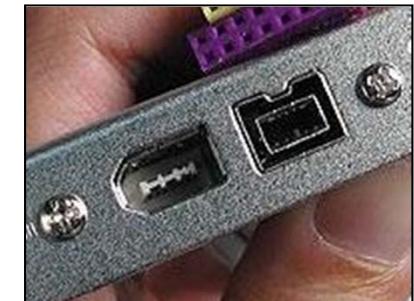


# DCAM (IEEE 1394 - FireWire)

- Invented by Apple (and TI) in the late 1980s
  - Apple's original name : "FireWire®"
- Standardized by IEEE in 1995:
  - Standard name "IEEE 1394"
- FireWire® is a trademark of Apple:
  - Basler and many others call it "1394"
  - Sony calls it "i.Link®"



→ BUT it's all the same! – So don't get confused ☺



*Note: 1394 has two flavors, 1394a and 1394b. The only differences are:*

- *Bandwidth: 1394b has double the bandwidth of 1394a.*
- *Cabling: 1394b has a different connector.*



# DCAM (IEEE 1394 - FireWire)

## *IIDC 1394-based Digital Camera Specification* “DCAM”

- Industry standard for 1394a/b digital cameras created in 1996
- Specifies video formats, registers, features
- User can choose many combinations of camera and software vendors
- Most industrial 1394 camera makers are DCAM compliant
- Older interface, gradually dying out in the consumer market



# DCAM (IEEE 1394 - FireWire)

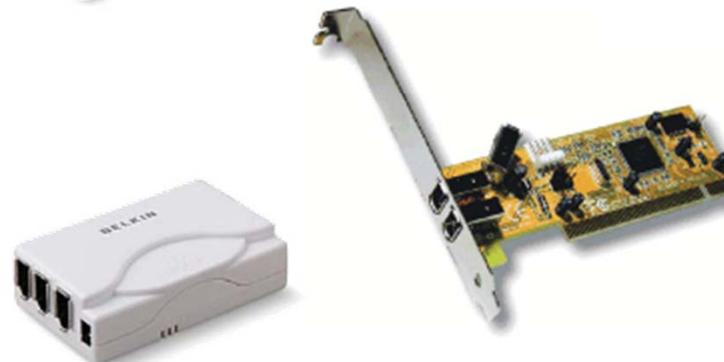
## Laptop:

- PCMCIA Card
- AC Power Adapter



## Desktop:

- PCI or PCIe card
- Power is from PC



## Accessories:

- Hubs
- Repeaters
- *Analog Frame Grabber ~ \$500*
- *IEEE 1394 Adapter Card ~ \$40*



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# Camera Link

**Camera Link** was launched in 1999 by *key players in vision* and formally adopted in 2000 by the AIA. Camera Link establishes a point-to-point dedicated link between camera and frame grabber for high speed and easy cable concept.



## Considerations:

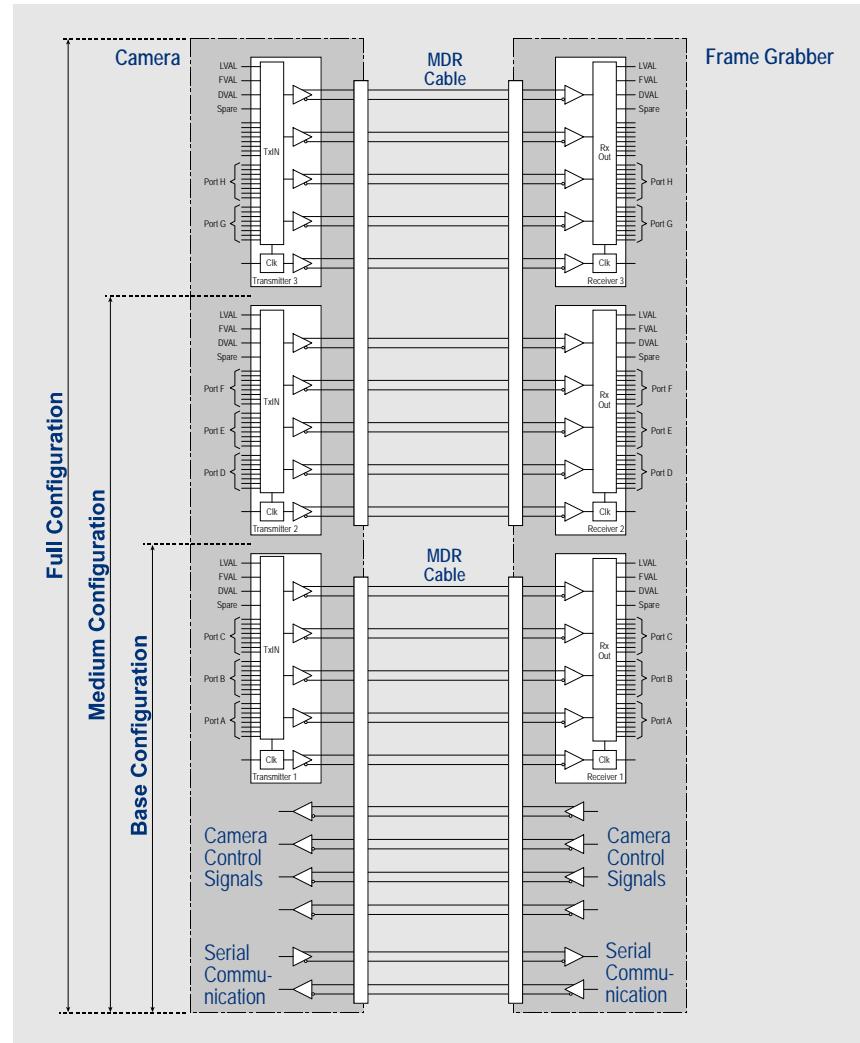
- Ground-up designed for connection of cameras + frame grabbers
- High speed modified parallel LVDS interface.
- Standardized for 8 / 10 / 12 bit, single, multi-tap, RGB.
- Includes provisions for PoCL single cable solution with power over the interface cable.
- ~10m copper cable length with repeaters, active extenders, and fiber optic solutions available.



# Camera Link

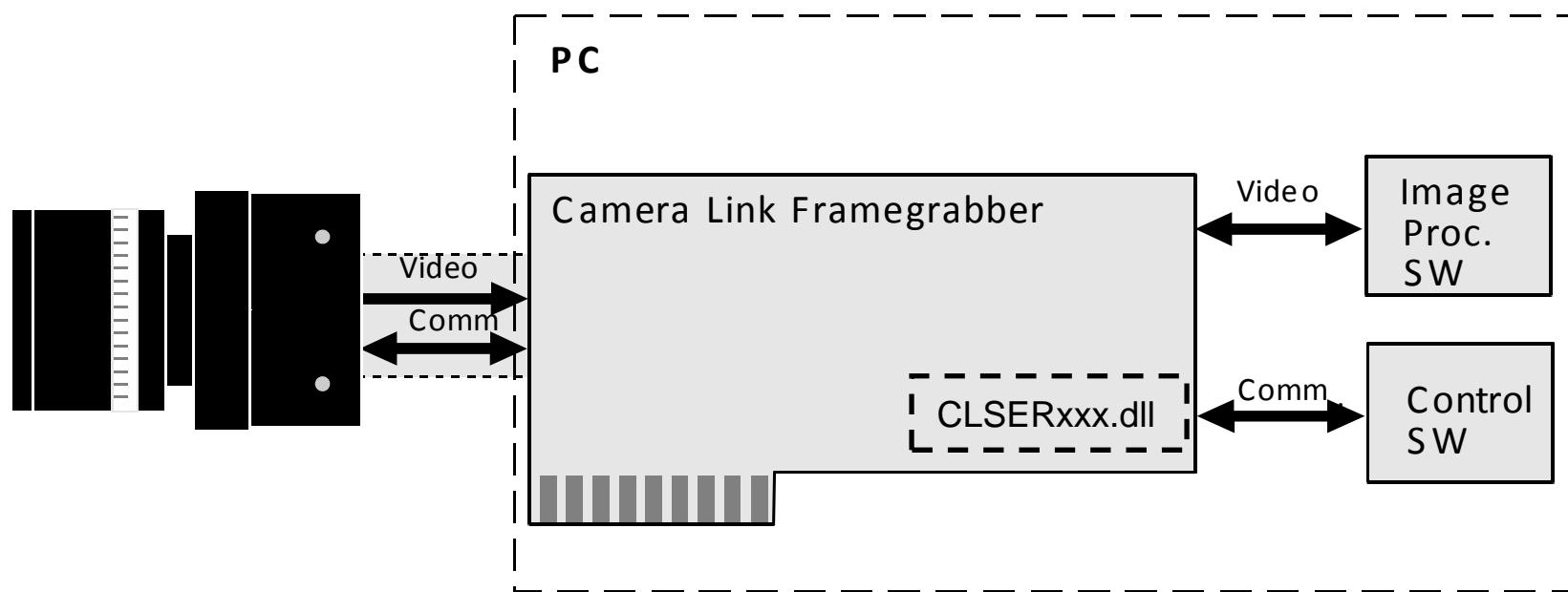
## 3 Levels of Camera Link:

- **Base Configuration:**  
**2.0 Gbit / sec**  
**One cable needed**
  
- **Medium Configuration:**  
**4.1 Gbit / sec**  
**Two cables needed**
  
- **Full Configuration:**  
**6.8 Gbit / sec**  
**Two cables needed**



# Camera Link

- The serial communication is routed through a separate channel than image capture.
- The frame grabber provides a special DLL file for software to access through.



# Camera Link

## Frame Grabbers:

- Usually supplied with processing software
- Can be PCI, PCIe, PCIx
- Some have additional IO
- Require a “Camera File” which tells the grabber what camera is attached and how to handle it



# Camera Link

**Cables are very robust and designed for industry**

- Can be found in various lengths up to 10m
- Right angle and high flex available
- MiniCL reduces connector size
- PoCL Power over Camera Link offers one cable solution



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# Camera Link HS

Camera Link HS (CLHS) is a good choice for:  
Demanding machine vision applications...  
with high bandwidth, (16.8Gbits/s)  
real-time demands,  
and error free data transmission needs.



# Camera Link HS Design Goals

- Successor of Camera Link
- CLHS keeps Camera Link advantages:
  - High speed
  - Reliability
  - Real-time guarantee
  - Both Copper and Fiber options defined
- CLHS is far superior by:
  - Increased bandwidth
  - Much longer cables (10K meters)
  - Plug & Play capability



# Camera Link HS Reliability

- High degree of transfer reliability
- Headers and real time signals ensured by 2 of 3 voting
- CRC-32 check and resend for video and communications
- Fiber optic offers immunity to electric and magnetic fields



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# CoaXPress - A Brief History

## Pan-European R&D Project:

2007 - Adimec and EqcoLogic research high speed interface options  
2008 - Technology demonstrator at Vision 2008, Stuttgart, Germany

## CoaXPress Consortium formed early 2009:

Adimec (NL) .....	Cameras
Active Silicon (UK) .....	Frame Grabbers
EqcoLogic (BE) .....	Transceivers
Components Express (USA) .....	Cable Solutions
AVAL DATA (JP) .....	Frame Grabbers
NED (JP) .....	Line-scan Cameras

2010 – Version 1.0 released

2014 – Planned updates



# CoaXPress Protocol Highlights

Essentials:	Like most modern interface standards, CoaXPress is a packet based protocol using 8B/10B coding
Bitrate:	1.25, 2.5, 3.125, 5.0, or 6.25 Gbps Through link aggregation: N x 6.25 Gbps (i.e CXP4)
Image formats:	Arbitrary image size & speed Multiple data streams in parallel
Data integrity:	Redundant coding CRC32 Link BER test
Control data:	Uplink: Maximum 20.8 Mbps (shared with trigger)
Trigger:	Uplink: Fixed latency of 3.4µs, +/- 4 ns accuracy
Plug & Play:	GenICam including GenTL is mandatory. Also auto bitrate, link setup, device detection, data packing format, bit depth, etc.



# CoaXPress Benefits

- Long cable length (130 ft./40m to over 330 ft./100m).
- High speed (6.25 Gbps per link).
- Good choice for data rates over 5 Gbps, and for 1 Gbps or greater when long cables are needed.
- Plug and Play (GenICam, GenTL).
- Digital video, control, GPIO, triggering and power over **one** cable.
- Coax ease of use, flexibility and reliability.
- Support of legacy coax cables (upgrade analog systems).
- Near real-time trigger accuracy.



# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- Concept of the Digital Camera
- **Camera Interface Standards (Interface)**
  - GigE Vision (Gigabit Ethernet - GigE)
  - DCAM (FireWire - IEEE 1394)
  - Camera Link (Framegrabber)
  - Camera Link HS (Framegrabber)
  - CoaXPress (Framegrabber)
  - **USB3 Vision (USB 3.0 – SuperSpeed USB)**
  - GenICam (Software common to many standards)
  - Interface Comparison
- Camera Types and When to Use



# USB 3.0 Fact Sheet

## Specs

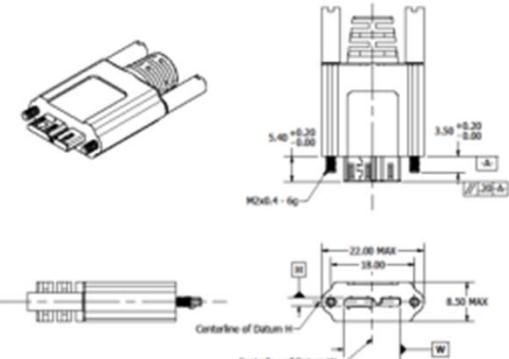
- Up to 400MB/sec bandwidth
- 5/14/50m cables passive/active/optical
- 5V / 4.5W power to device
- Intel/AMD chipset support
- Win8 native support, Win7 SP expected



Type A (Host) connector



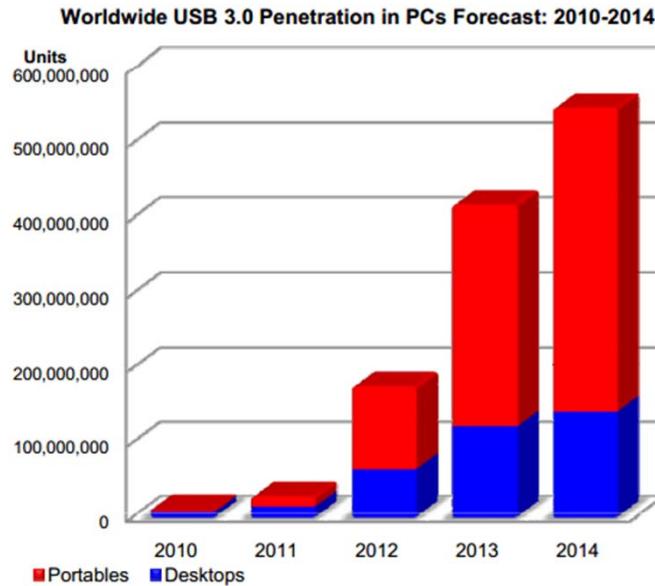
Type Micro B (Device) connector



Screw-lock connectors defined



# USB 3.0 Adoption



Source: [2011 USB DevCon Keynote](#)

- “USB is the most successful interface in the history of the PC”
  - 3+ billion units/year
  - Near 100% adoption
- Likely 100+ million USB 3.0 controllers shipped to date
- Native USB 3.0 support integrated in latest Intel & AMD chipsets
- Windows 8 has out-of-the-box support



# USB3 Vision Standard Details

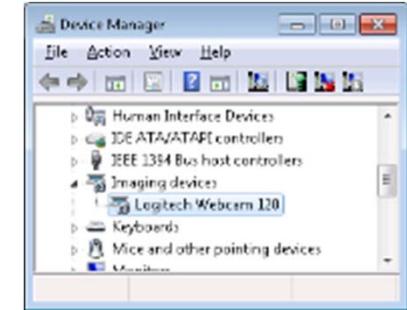
- Hosted by AIA and has been deemed an international standard by the “G3” (EMVA, AIA, and JIIA)
- Based off existing, well-defined USB mechanisms for device discovery, control, and image streaming
- Builds off of experience with GigE Vision and other standards
- Uses GenICam to allow access to common and vendor-specific features
- Machine vision specific features:
  - Variable-sized image/data frames
  - Zero-copy transfers
  - Reliable recovery of error conditions
  - Standardizing a screw-lock USB 3 connector



# What it Means

## Plug & Play

- It just works, no configuration or multiple vendor software needed
- Windows P&P manager binds camera automatically

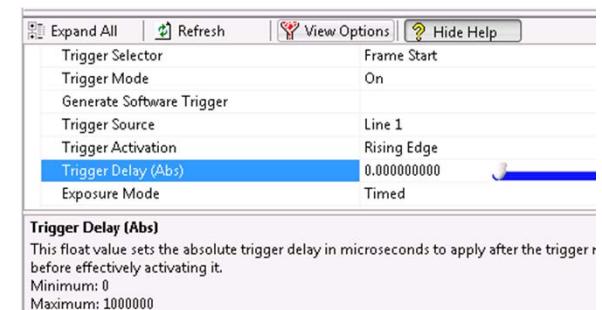


## GenICam

- Standard and vendor-specific camera features automatically available

## Zero-copy Image transfers

- Video data is copied to RAM by bus master DMA.
- The PC's CPU is not involved. Typical CPU load < 1%



## Low Latency and Jitter

- Uses bulk access with 5 GBit/s transfer speed
- Typical latency: Write =  $45 \pm 5 \mu\text{s}$ , Read =  $140 \pm 5 \mu\text{s}$

## Variable Image Size

- The camera can decide on-the-fly to send a smaller frame without the host knowing this in advance
- Applications
  - Line scan, e.g.; log inspection in a sawmill
  - Pick & Place
  - Live & Trigger



# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
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- **Camera Interface Standards (Interface)**
  - GigE Vision (Gigabit Ethernet - GigE)
  - DCAM (FireWire - IEEE 1394)
  - Camera Link (Framegrabber)
  - Camera Link HS (Framegrabber)
  - CoaXPress (Framegrabber)
  - USB3 Vision (USB 3.0 – SuperSpeed USB)
  - **GenICam (Software common to many standards)**
  - Interface Comparison
- Camera Types and When to Use



# GenICam Standard

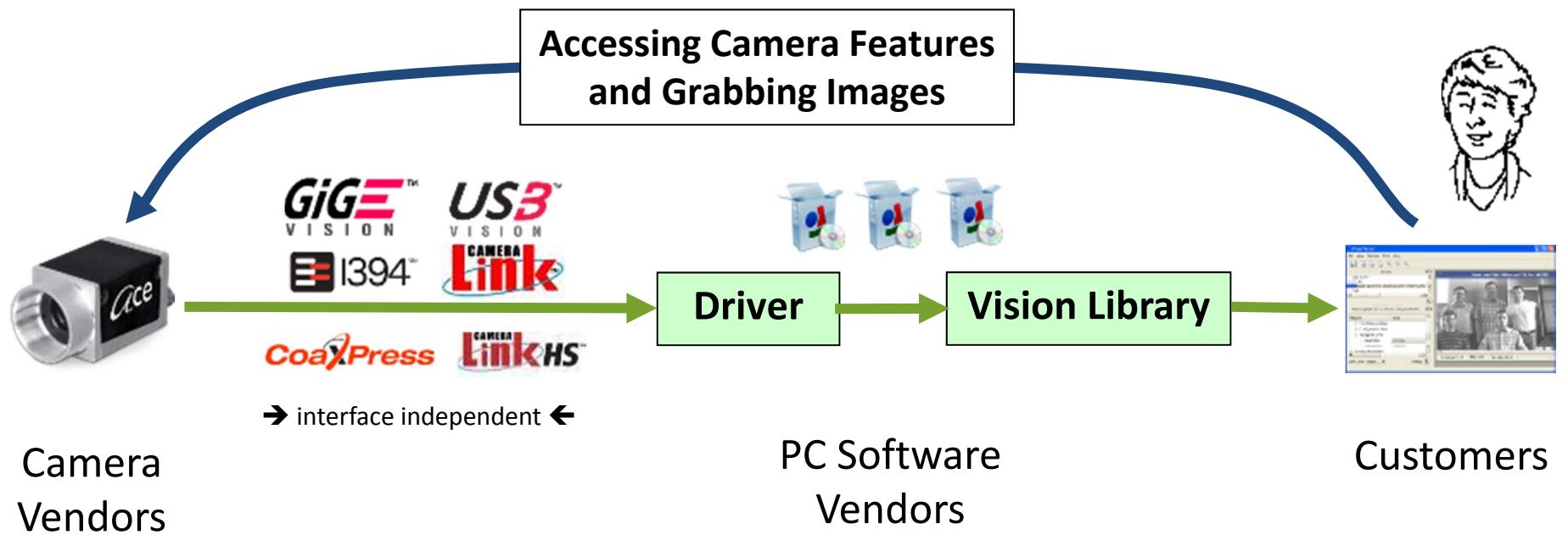
- The Goal of GenICam is to unite the various machine vision interfaces
- Cooperatively developed by industry-leading vendors
- Hosted by European Machine Vision Association (EMVA)
  - [www.genicam.org](http://www.genicam.org)
- Unified API to seamlessly control many interfaces with one program



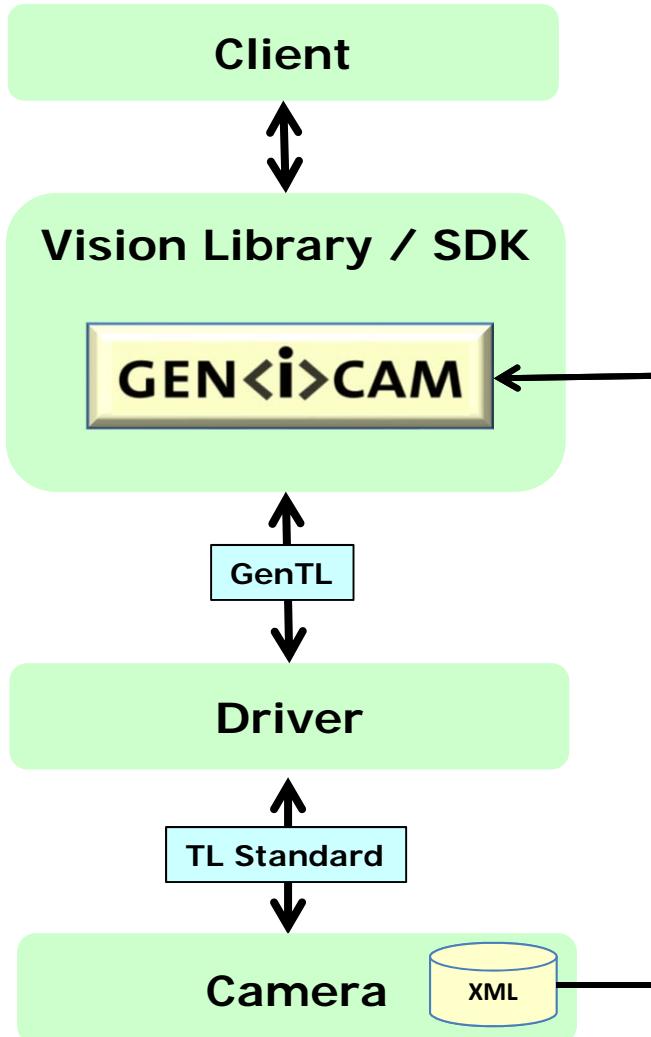
# GenICam in a Nutshell

# GEN*< i >*CAM

provides **plug&play** to machine vision cameras



# GenICam Modules



**SFNC** – camera features

**GenICam reference implementation**  
– interpret XML file content

**CLProtocol** – Camera Link support

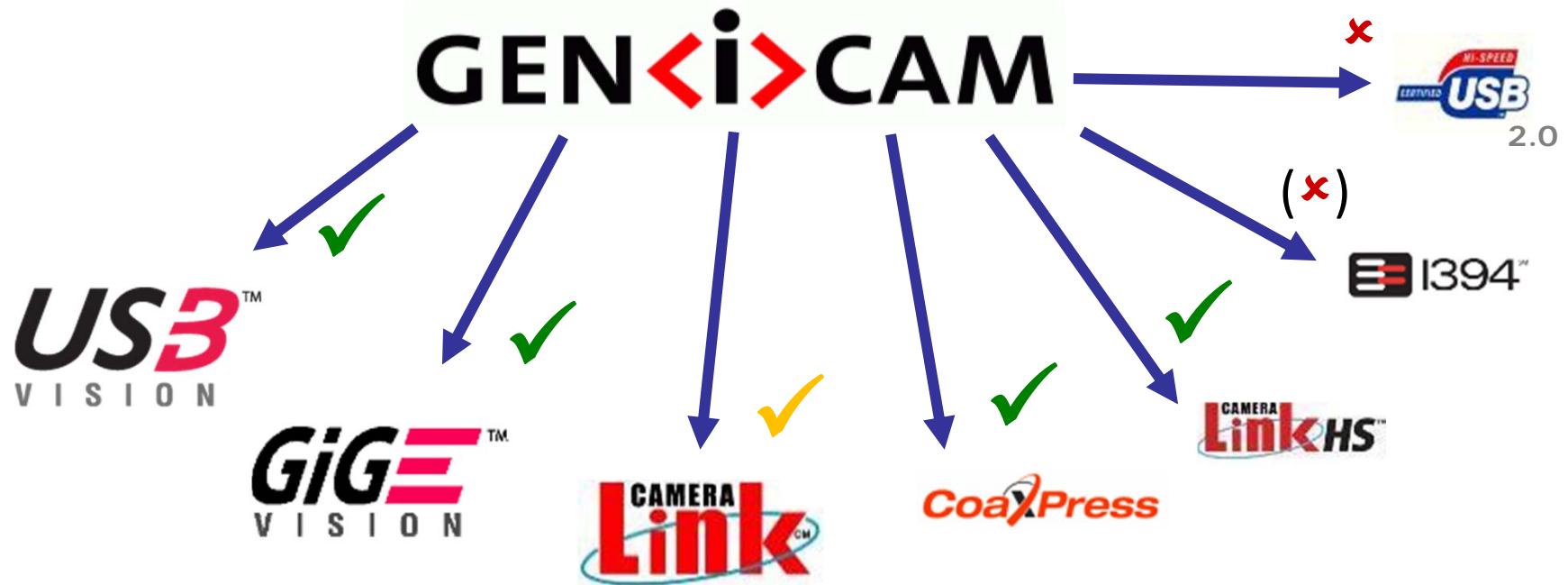
**GenTL** – transport layer API

**GenCP** – packet layout

**GenApi** – XML file format



# GenICam is a core element of all modern interfaces



Latest newcomer: **USB3 Vision**

- Pure transport layer standard
- Fully relies on GenICam as mandatory front end
- Cameras are SFNC compliant

✓ *Mandatory*

✓ *Optional*



# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
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  - Camera Link (Framegrabber)
  - Camera Link HS (Framegrabber)
  - CoaXPress (Framegrabber)
  - USB3 Vision (USB 3.0 – SuperSpeed USB)
  - GenICam (Software common to many standards)
  - **Interface Comparison**
- Camera Types and When to Use



# Interface Comparison

## Camera Interface Bandwidth

- IEEE1394a 400 Mbits/s
- USB 2 480 Mbits/s
- IEEE1394b 800 Mbits/s
- GigE Vision 1.0 Gbits/s
- USB3 Vision 3.5 Gbits/s
- CoaXPress 6.25 Gbits/s
- Camera Link 6.8 Gbits/s
- 10 GigE Vision 10 Gbits/s
- Camera Link HS 16.8 Gbits/s

## PC Bus Bandwidth

- PCI Bus 120 MBytes/s (~1Gbits/sec)
- PCIe Bus 1200 MBytes/s (~10 Gbits/sec)



# Interface Comparison

## Cable Length

- USB3 Vision      3-5m, greater with active cables
- IEEE1394b      10m
- IEEE1394a      10m
- Camera Link      10m
- GigE Vision      100m
- CoaXPress      100m
- Camera Link HS 10,000m



# Summary / Tips

- There is no “perfect” interface. Always prioritize application requirements and compare.
- Key Parameters For Vision Standard Selection:
  - Cost
  - Bandwidth requirements
  - Current infrastructure
  - Cable lengths required
  - Triggering requirements



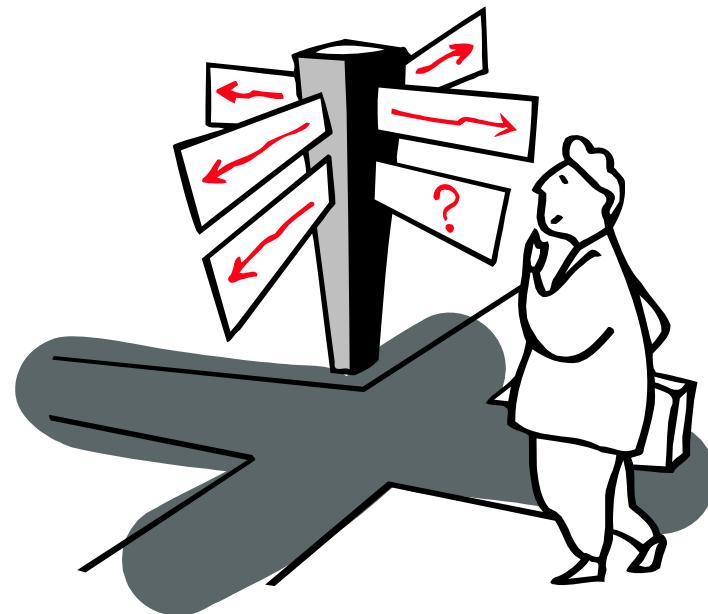
# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- Concept of the Digital Camera
- Camera Interface Standards
- **Camera Types and When to Use**
  - Area scan
  - Line scan



# Area Scan

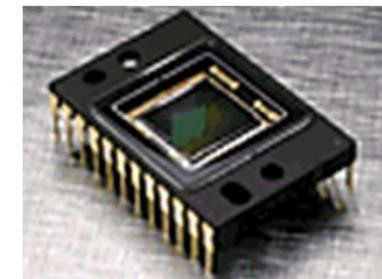
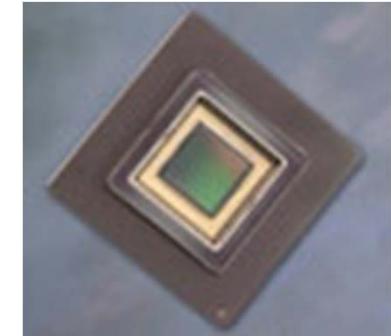
- Main aspects
- Architecture
- AOI
- Binning
- Color



# Area Scan

## Main Aspects

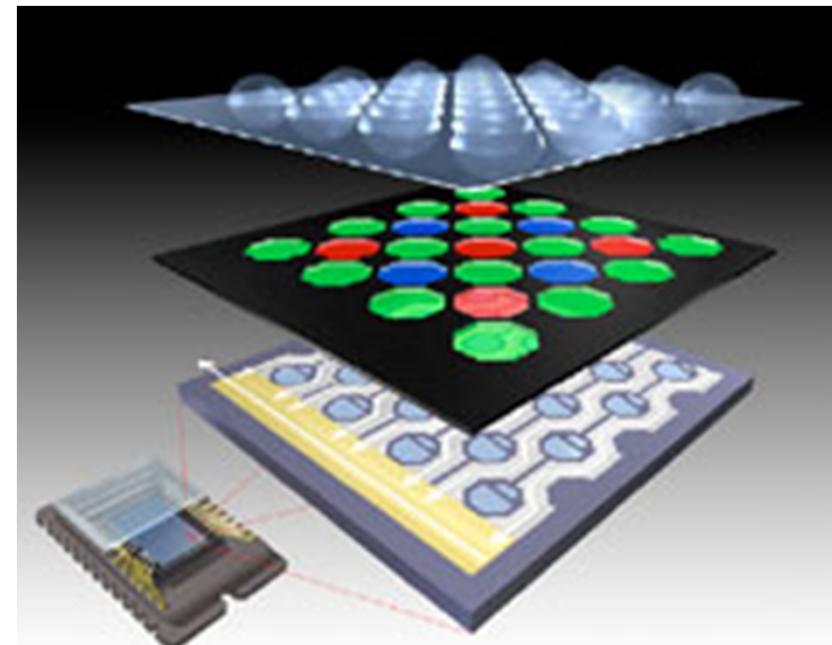
- Like a Photo camera
- Fixed aspect ratio (4:3, 16:9)
- Easy design in
- Easy image processing
- Longer integration time possible



# Area Scan

## Architecture

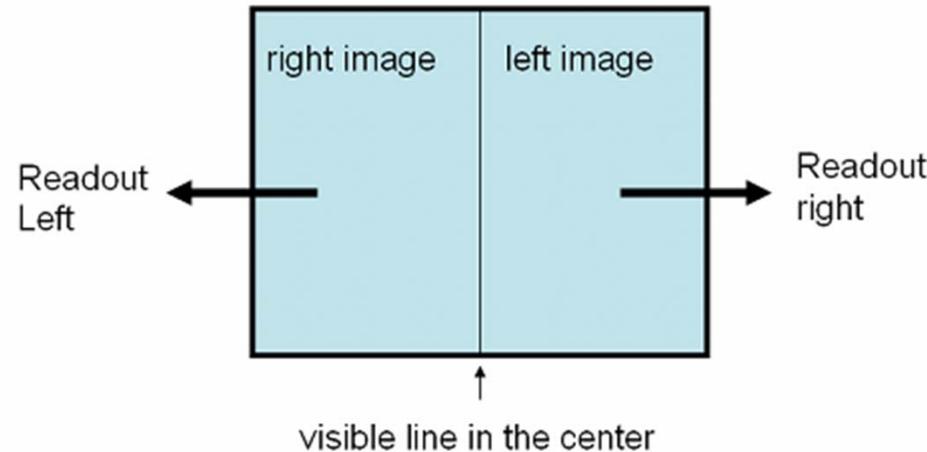
- Micro lenses
- Color filters (opt.)
- Silicon



# Area Scan

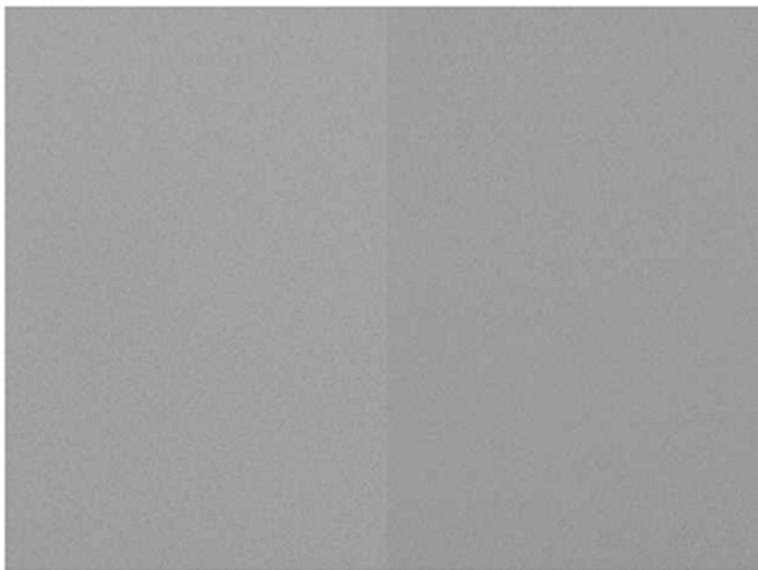
- **Architecture Special Trend: Multi-Tap Sensors**
  - Kodak manufactures high speed CCD's with 2 or 4 output channels ("Taps").

These sensors have great image quality, but must be handled very carefully in the camera.

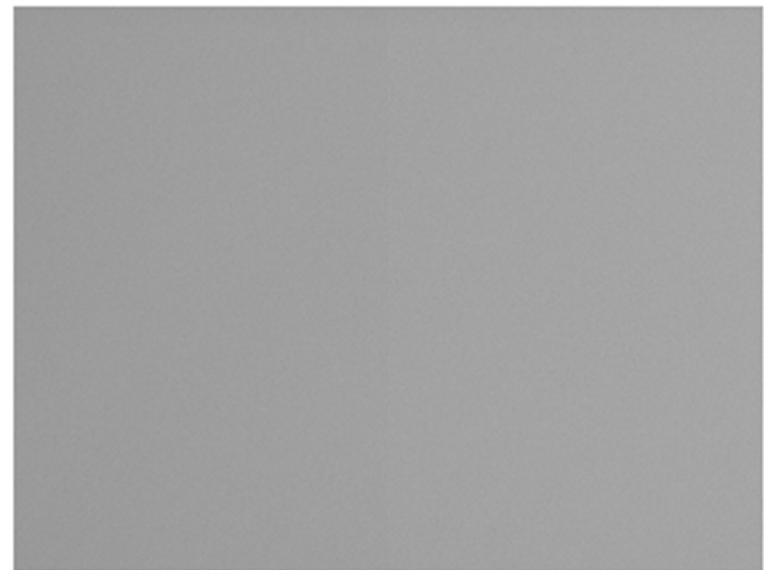


# Area Scan

- If the taps are not “balanced” properly, the user will see a line in their image.



Tap imbalance problem

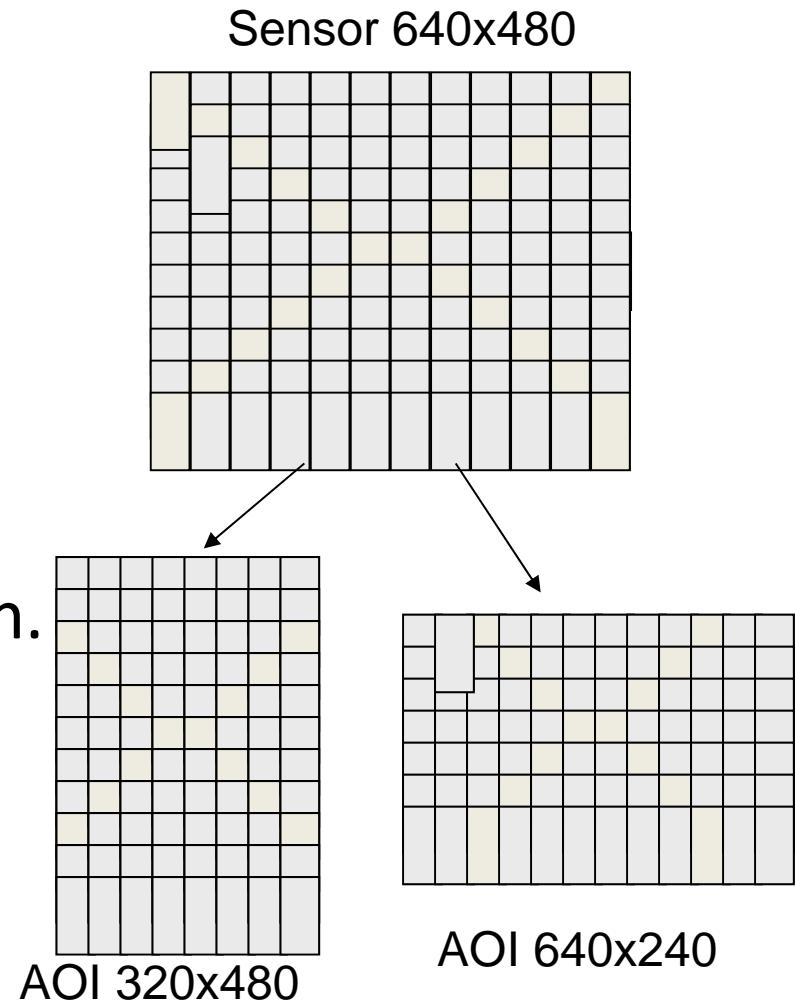


Properly balanced Taps



# Area Scan

- **Area Of Interest (AOI / ROI)**
- Sensor can be cropped at the hardware level.
- By only reading out selected pixels, we can increase the frame rate.
- We also save some bandwidth.



# Area Scan

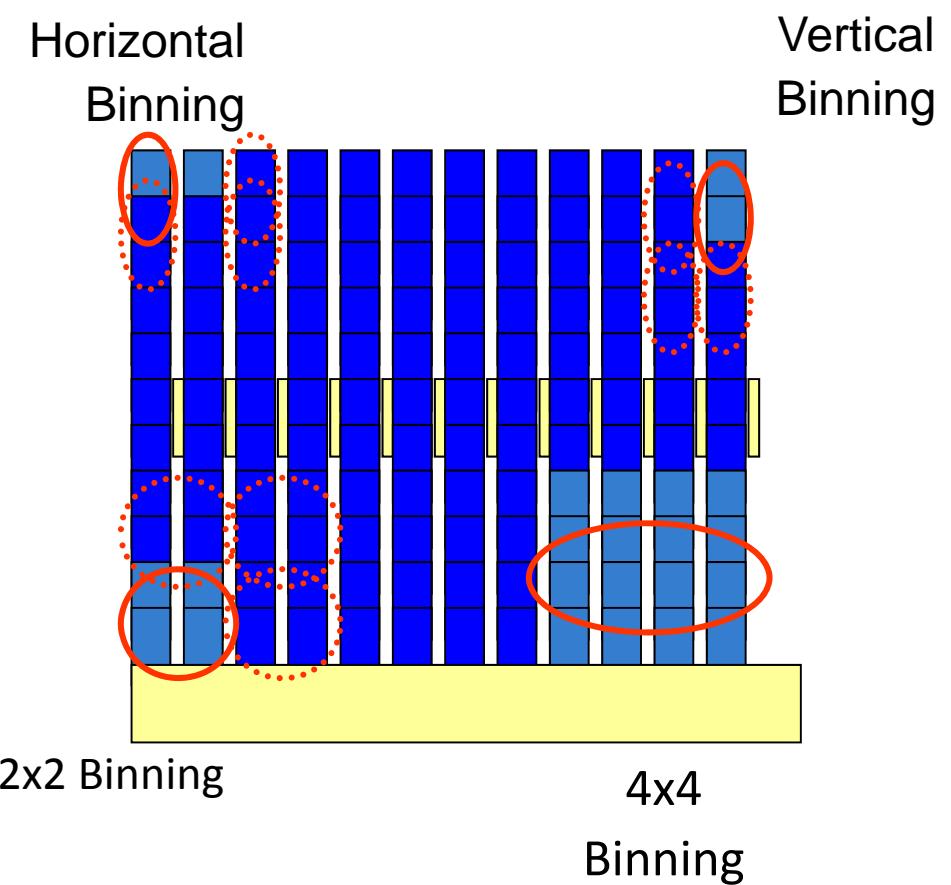
**Binning:** The physical combining of charges between pixels during readout

## Advantages:

Brighter image, bandwidth saved due to smaller image size.

## Disadvantages:

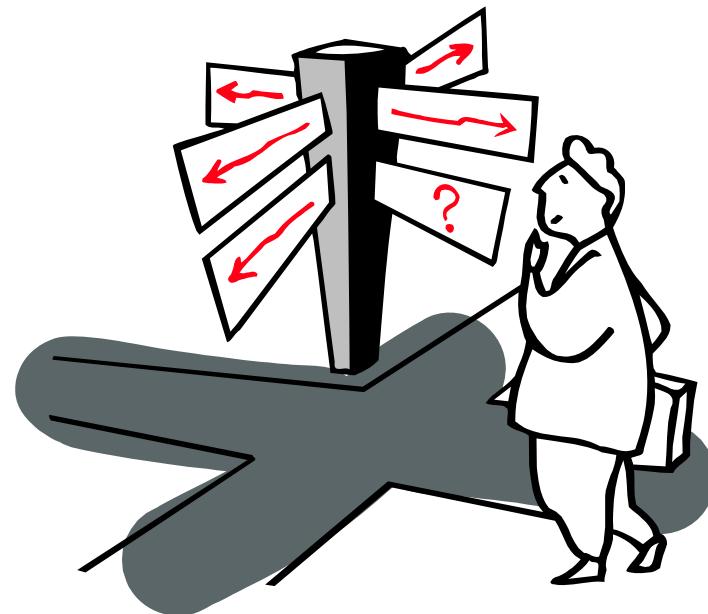
Reduces resolution, can change aspect ratio



# Area Scan

## COLOR

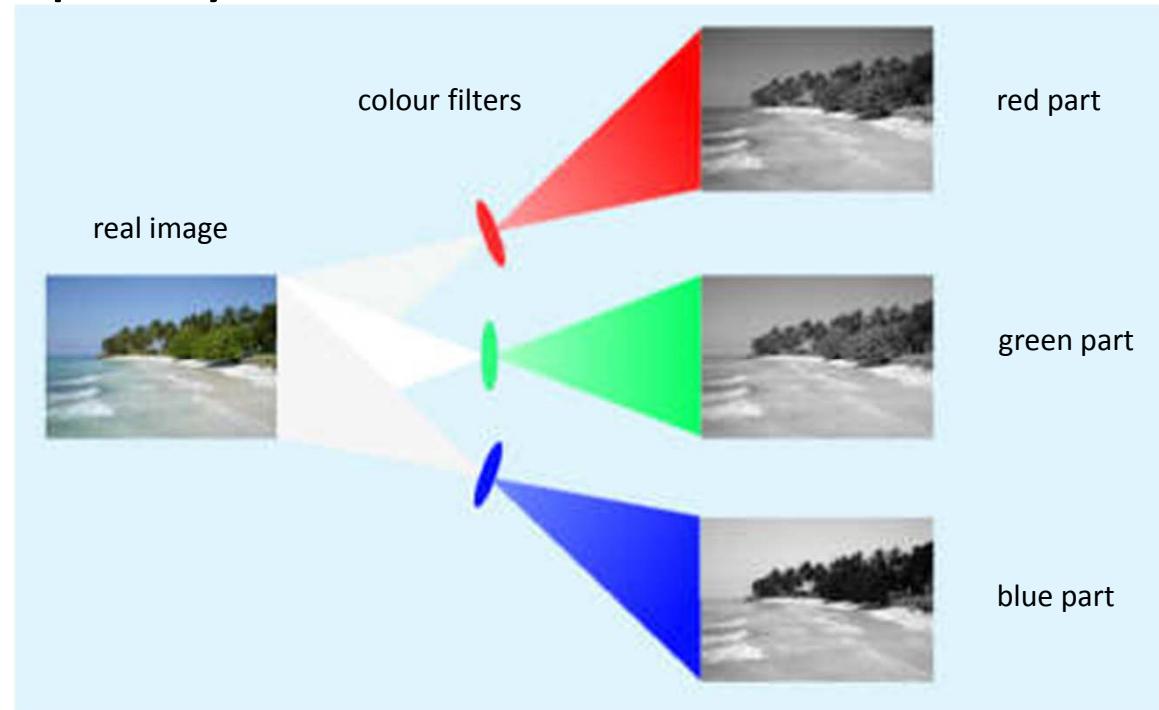
- 3- CCD
- 1- CCD (Bayer)



# Area Scan

## 3CCD Color

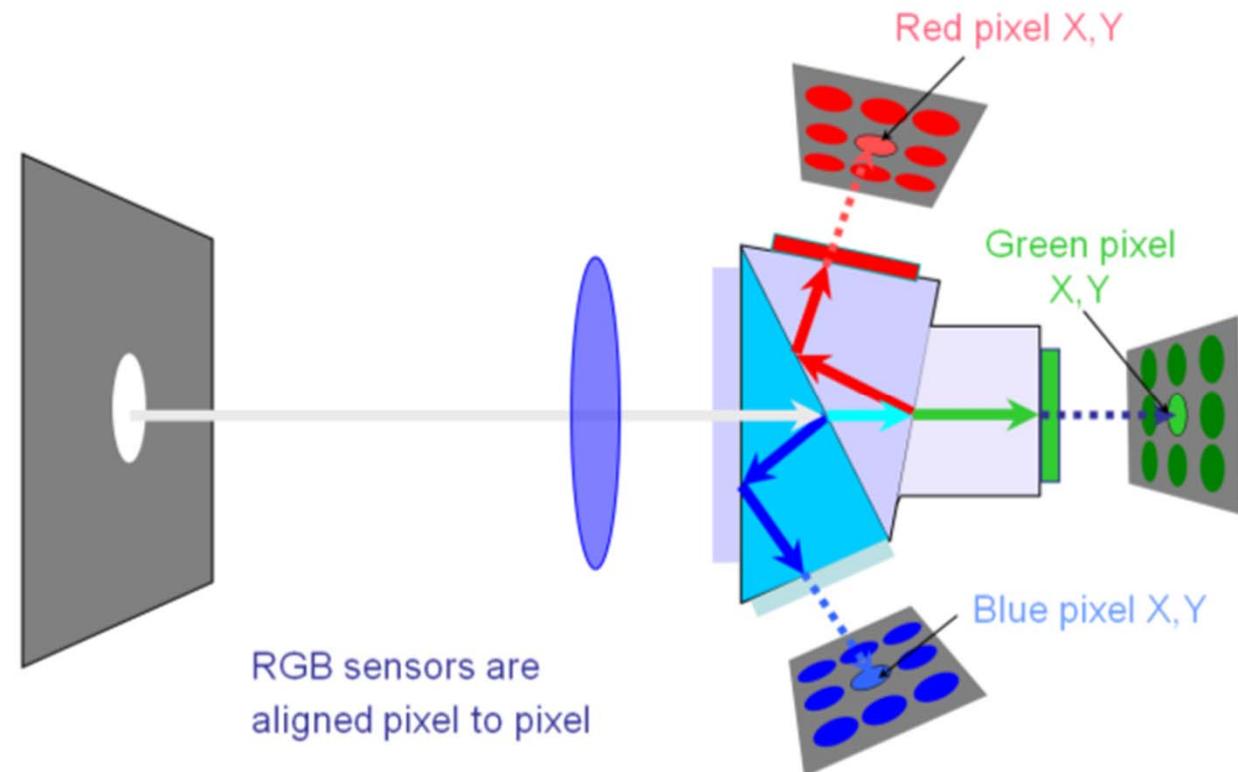
- **3-CCD Color: Uses a separate CCD for each color**
- Very good image quality
- More expensive



# Area Scan

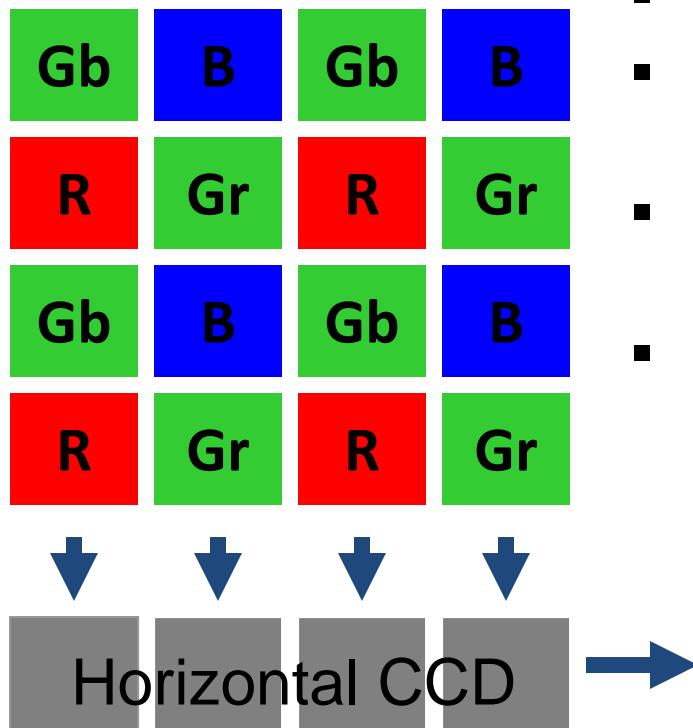
## 3CCD Color

- No color interpolation (pixel to pixel)
- Controllable filter specifications
- Co-site sampling



# Area Scan

## Single imager Color – Bayer Pattern

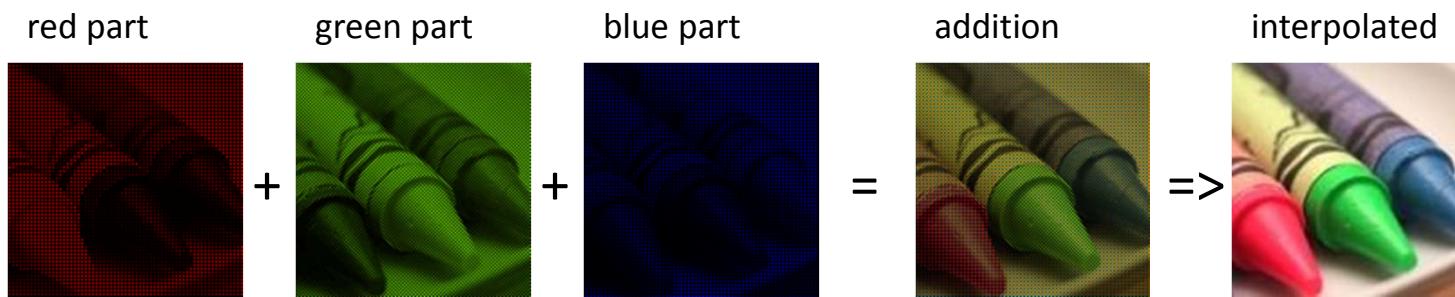
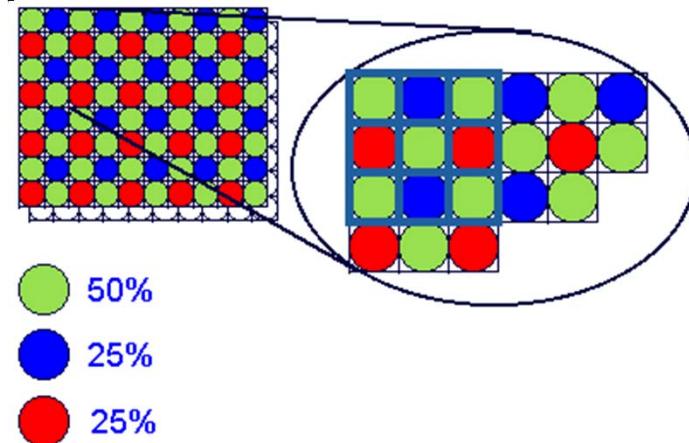


- The camera outputs a monochrome signal
- Color interpolation has to be done for every second pixel
- Color rendition is often done in the host - Bayer to RGB conversion
- The BAYER filter cannot be changed or modified



# Area Scan

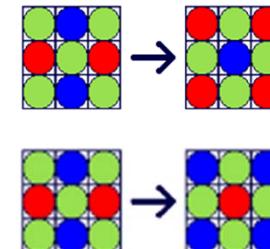
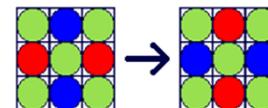
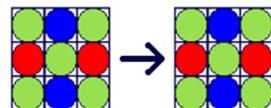
- 1-CCD Color: Bayer Pattern
- Lower Color spatial resolution
- Lower manufacturing cost



# Area Scan

## Bayer Pattern Considerations

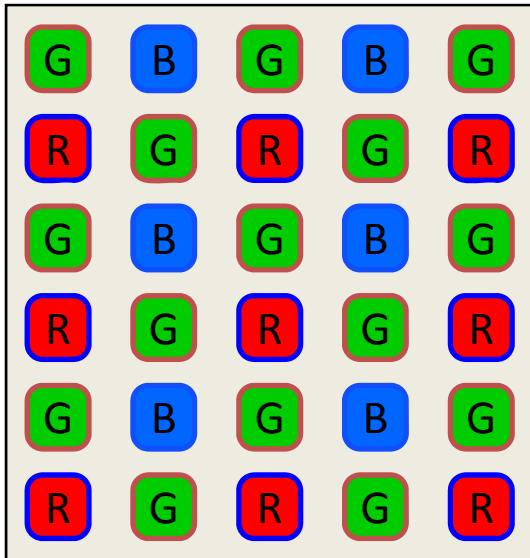
- The frame grabber or software must know the orientation of the pattern on the sensor.



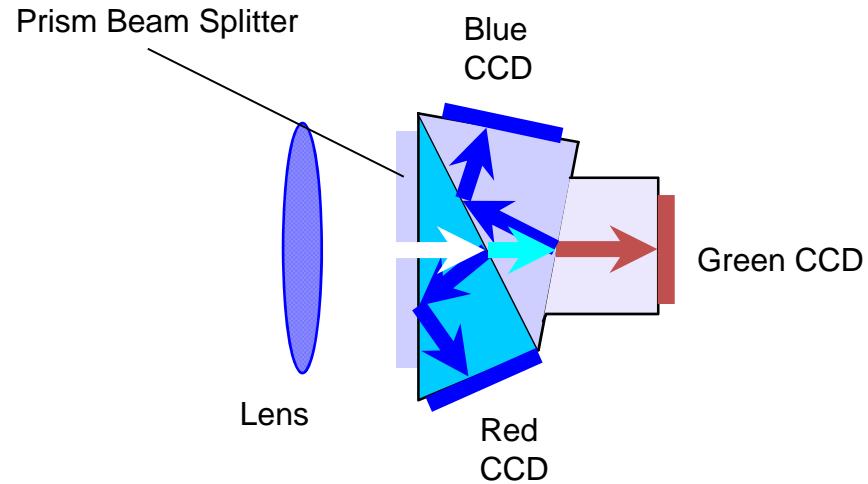
# Area Scan

## Single Chip vs. 3-CCD Color

Single CCD Color Camera



3CCD Color Camera



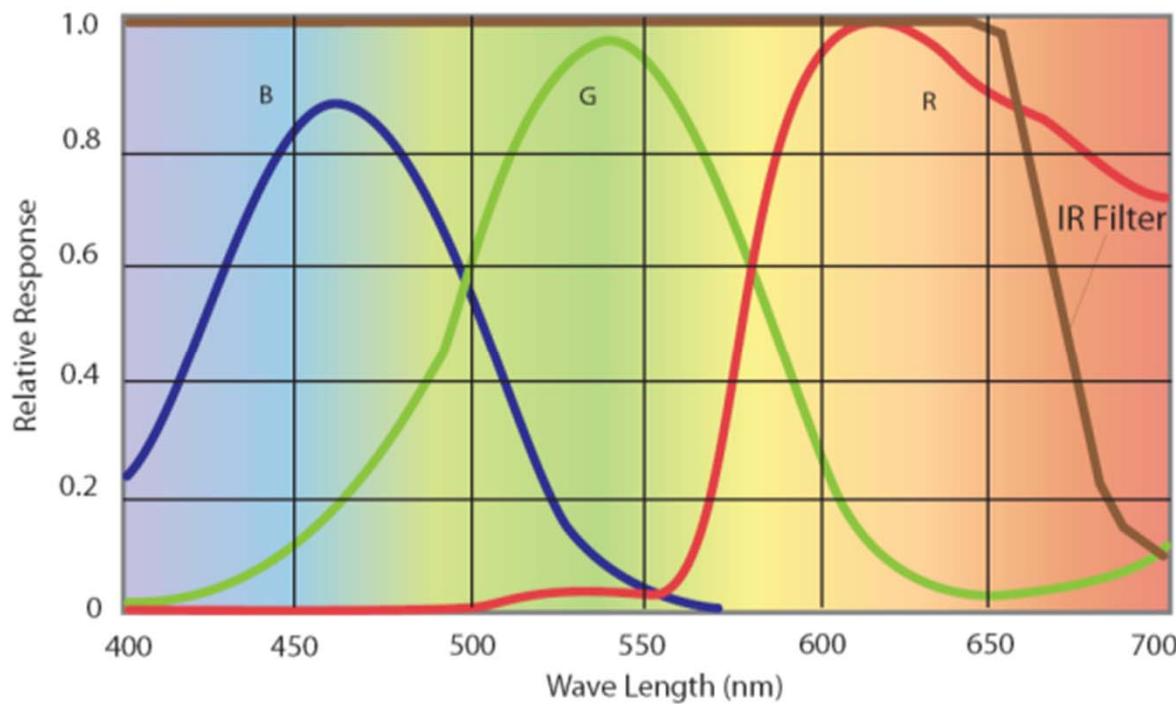
- Each pixel has just one color filter
- Color interpolation is needed
- Not true color
- Spectral response depends on the design of the color filter

- RGB each independent CCD
- Each pixel has full RGB data
- Spectral response can be flexible by the design of optical block



# Area Scan

## Additional Color Considerations – Filter Response

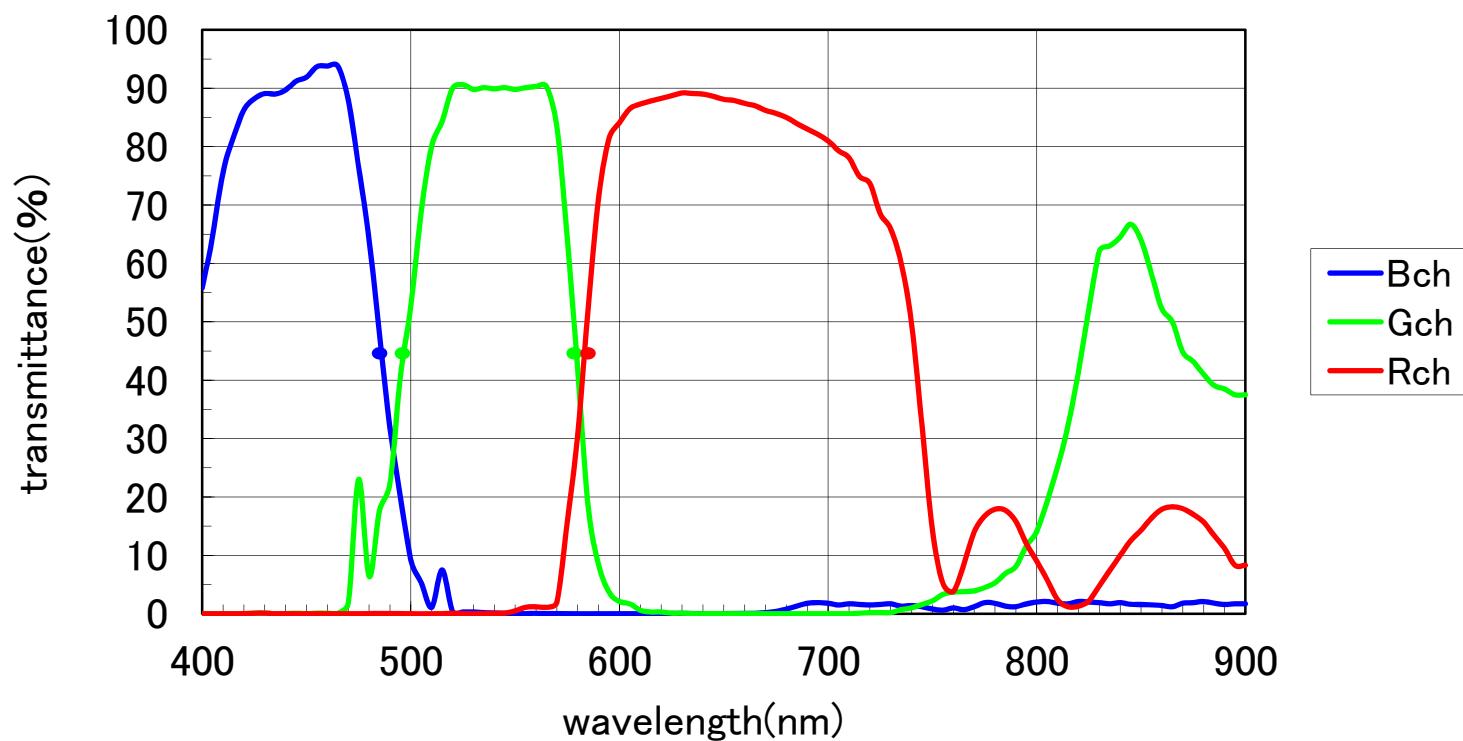


Typical Bayer CFA Response



# Area Scan

## Additional Color Considerations – Filter Response



3-CCD prism block transmittance

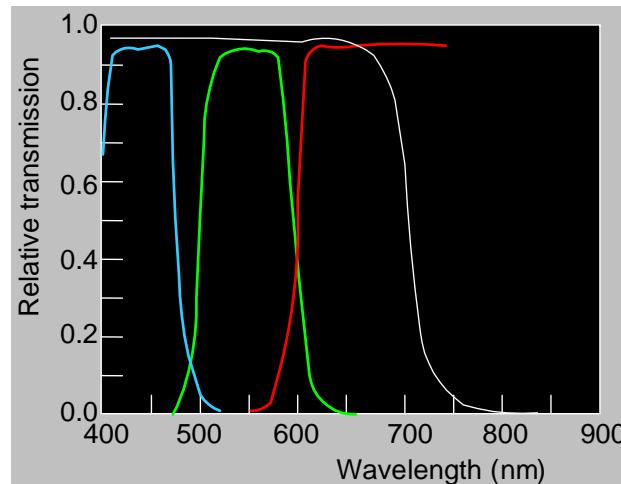
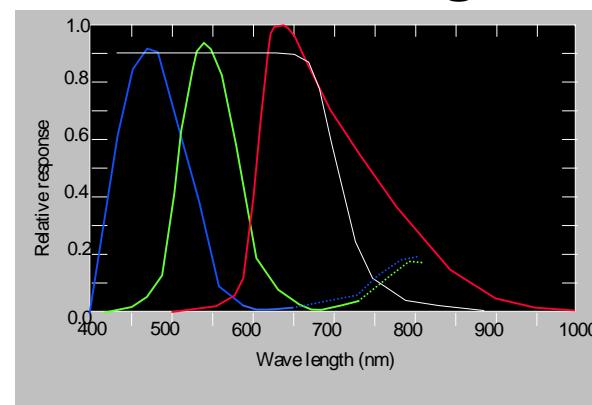


# Area Scan

## Advantages of dichroic coatings

### Filter coatings

- Soft polymer dye
  - Large overlap between colors
  - Batch-to-batch variation
  - Limited long term stability
  
- Hard dichroic coating
  - Steep edges, very little overlap between colors
  - Controllable specification, low variation
  - Very good long term stability
  - Used in 3CCD cameras



# Digital Cameras: Basic Course

- Light and CCD/CMOS Sensor Fundamentals
- Concept of the Digital Camera
- Camera Interface Standards
- **Camera Types and When to Use**
  - Area scan
  - Line scan



# Line Scan

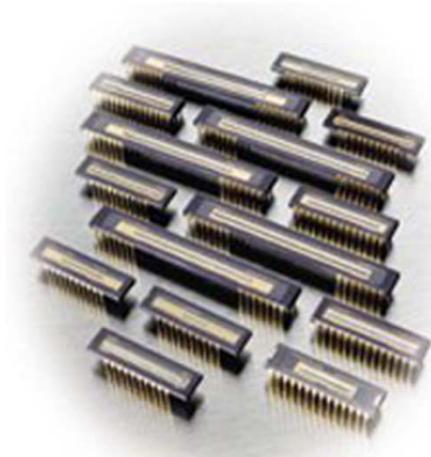
- Main aspects
- How does that work?
- Architecture
- Trigger
- Color



# Line Scan

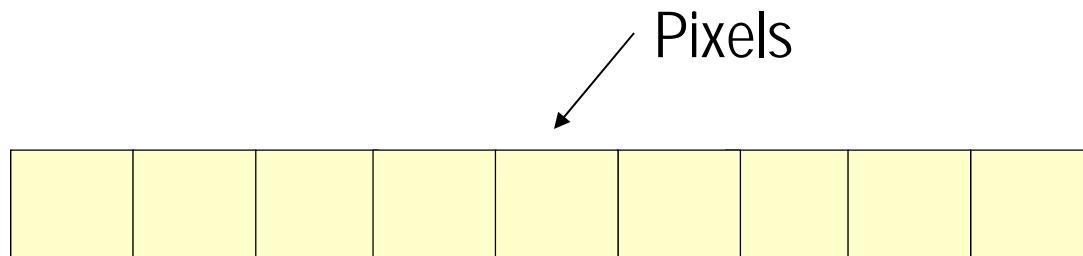
## Main Aspects

- Like a scanner or fax
- 2<sup>nd</sup> dimensions comes by movement
- Very good price / pixel performance
- High pixel fill-factor - typically 100%
  - Typically big pixels
- Smear-free images
- Very short integration times
- Illumination intensity generally needs to be high
- Difficult design in / image processing



# Line Scan

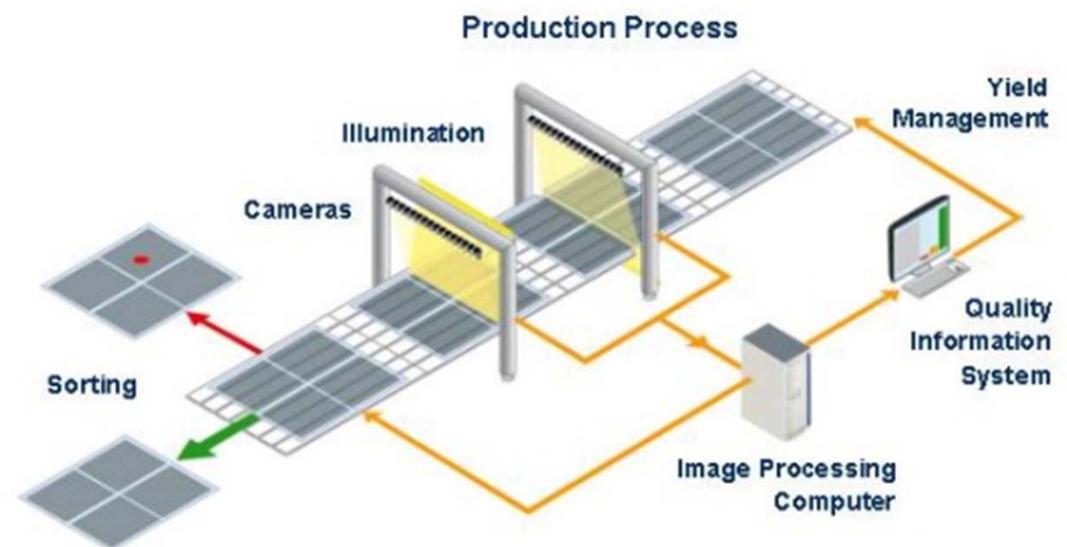
- 1d array of pixels (Line)
- Image produced line by line by scanning object
- **Main Advantage: Excellent for scanning / web applications**
- **Examples: food sorting, wafer inspection, medical slide scanning.**



# Line Scan

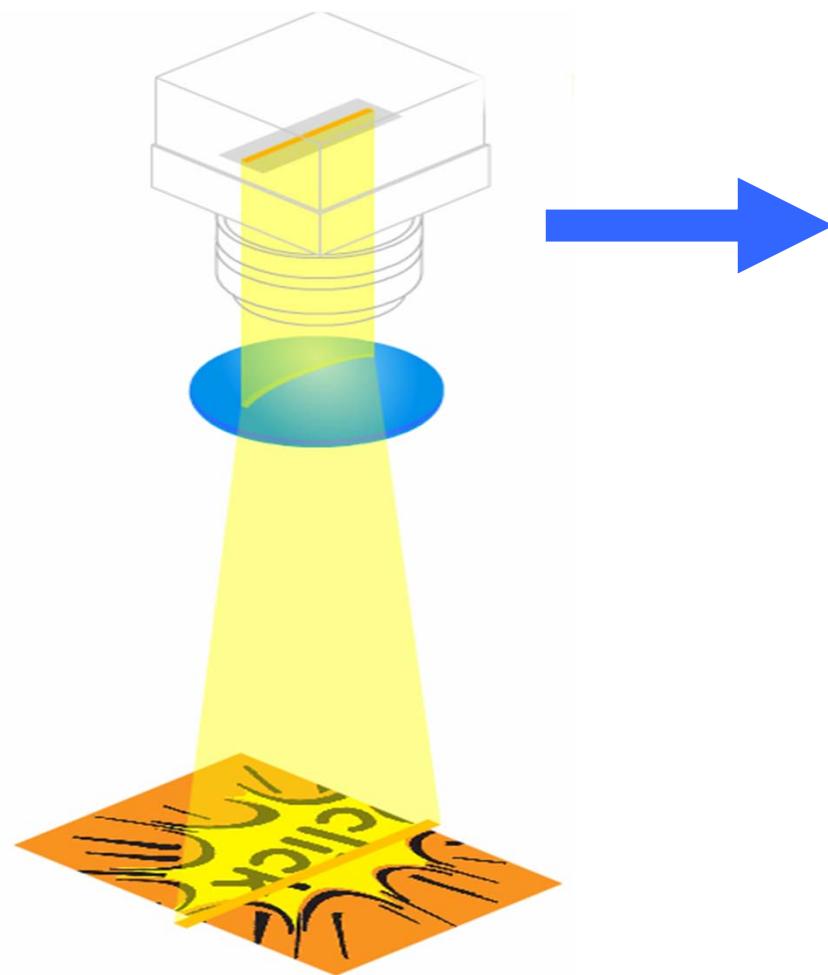
## How Does that Work?

- Line Scan fits anywhere where sensitivity and constant object motion are needed.
- Semiconductor wafer inspection
- Photovoltaic cells
- Food inspection/sorting
- Film scanning
- Postal applications
- Medical/microscopy



# Line Scan

How Does that Work?



# Line Scan

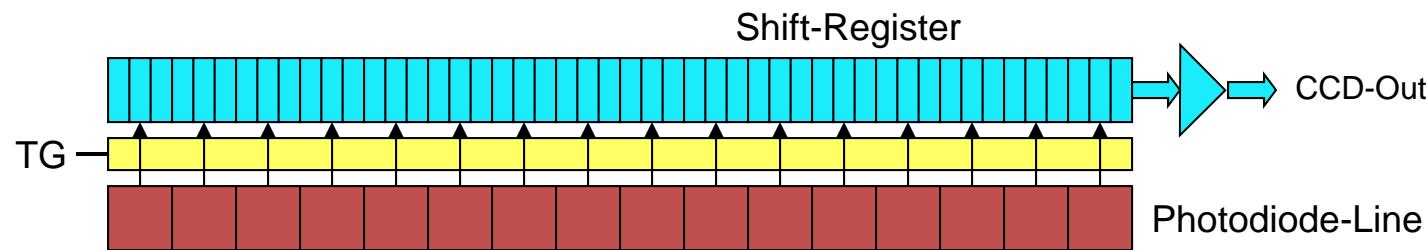
## Architecture

- Single Tap Sensors
- Dual Tap
- Quad Tap

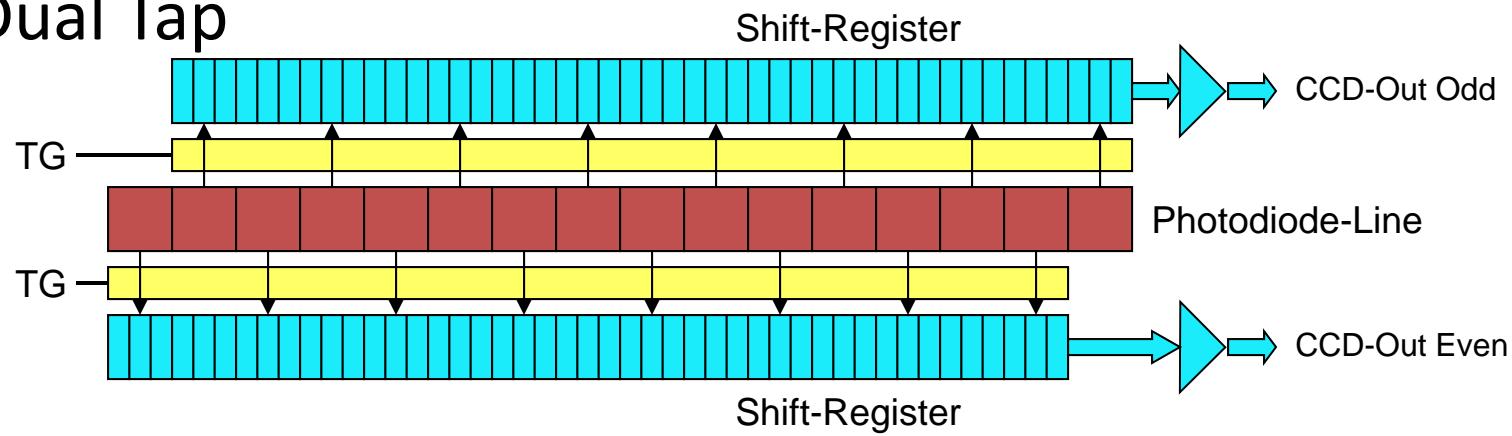


# Line Scan

- Single Tap

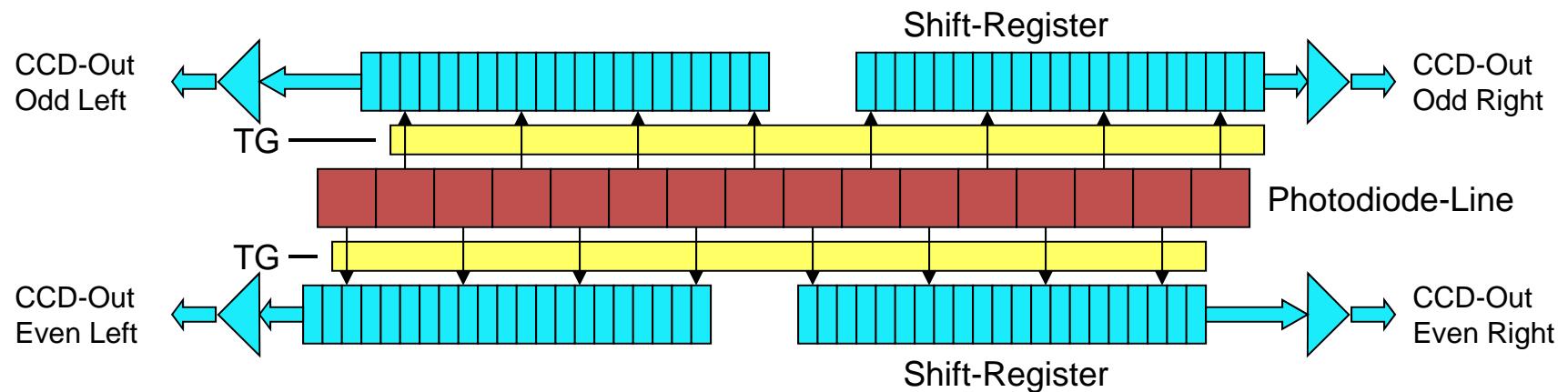


- Dual Tap



# Line Scan

- Quad Tap



# Line Scan

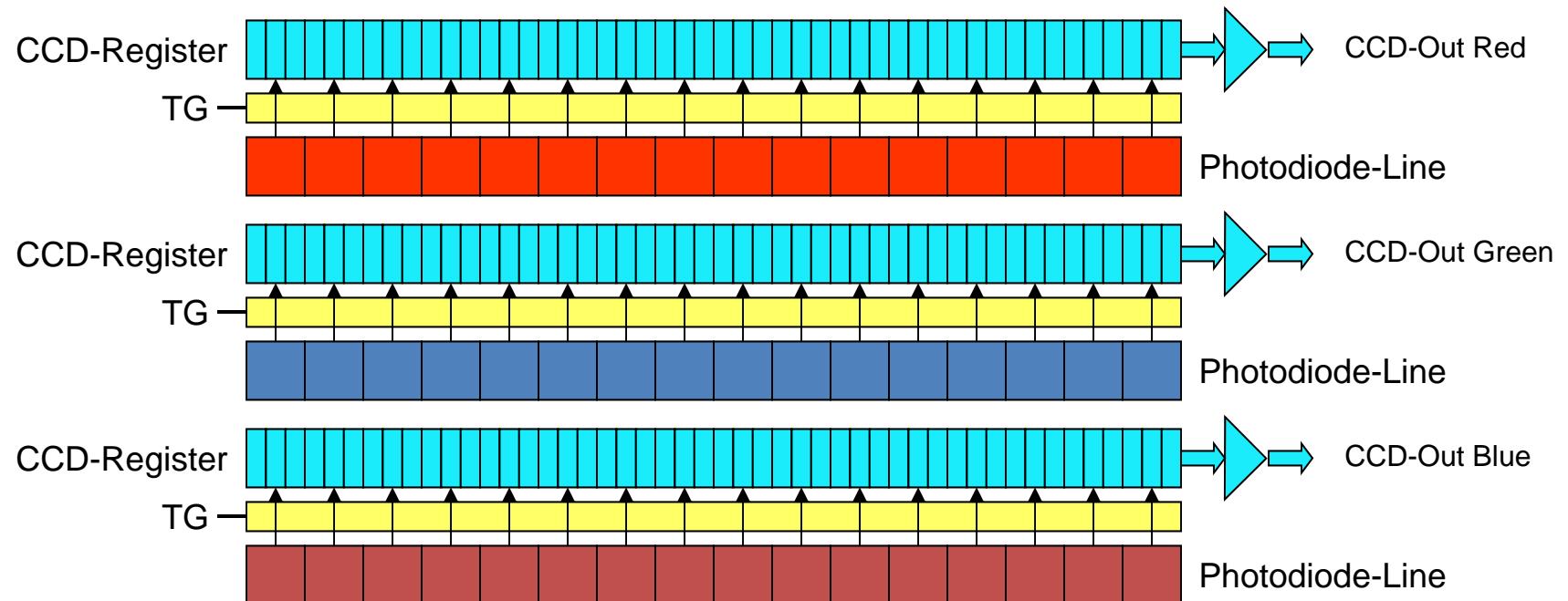
## Color

- Types of color Line Scan
- Tri-linear in more detail
- Summary



# Line Scan

## ■ Tri-Linear



# Line Scan

- A tri-linear line scan camera takes three different scans, but the red, green, and blue line do not look onto the same position of the object.
- Falling and rotating objects can only be inspected by the colors individually.
- Visualization is difficult, but machine vision is possible.



# Line Scan

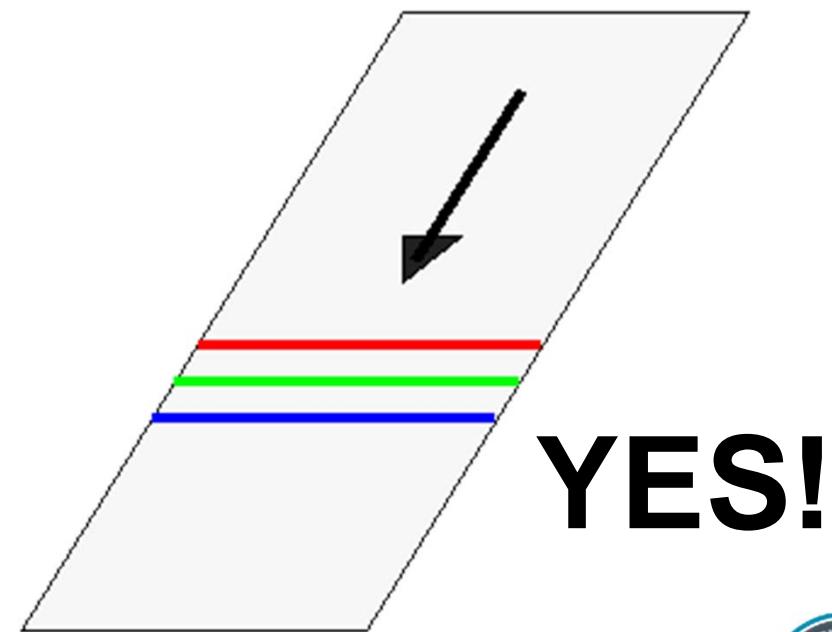
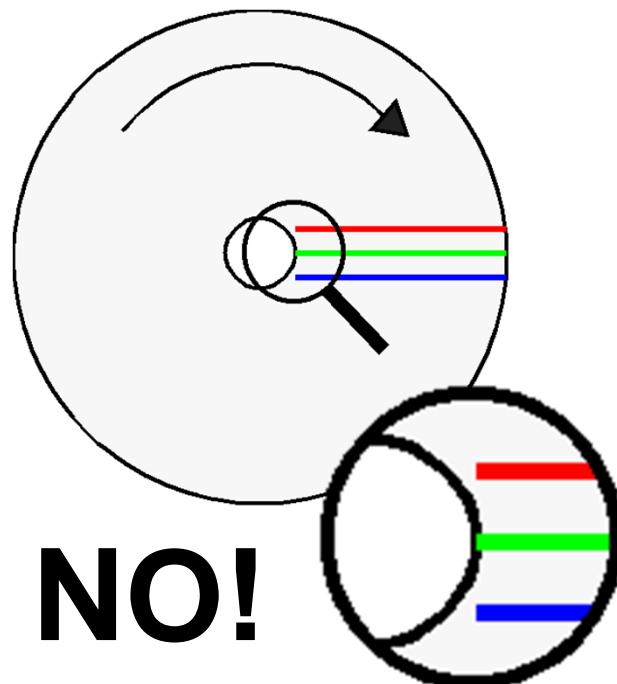
## Spatial Trigger Importance

- A trigger by time squeezes the object for different speeds (e.g., acceleration after a traffic light).
- Only a spatial trigger (Encoder) gives the right information.



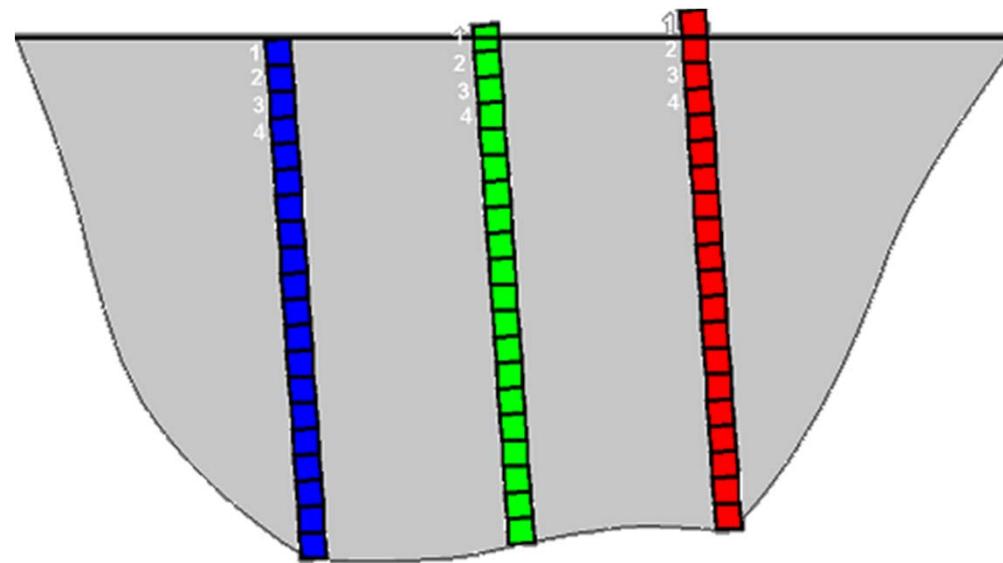
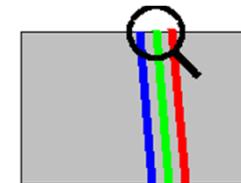
# Line Scan

- No rotation of the object for matching to a RGB trilinear image.
- The conveyer belt has to move straight.



# Line Scan

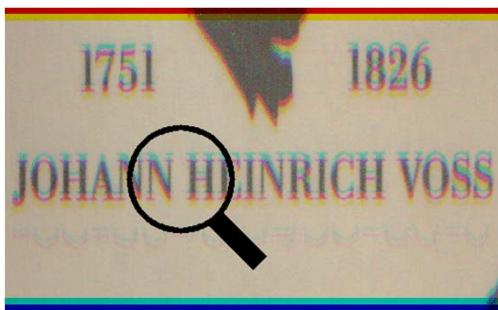
- The tri-linear camera must be aligned perpendicular to the conveyor



# Line Scan

**Spatial Correction's impact on Color with tri-linear**

Raw Image



Corrected Image

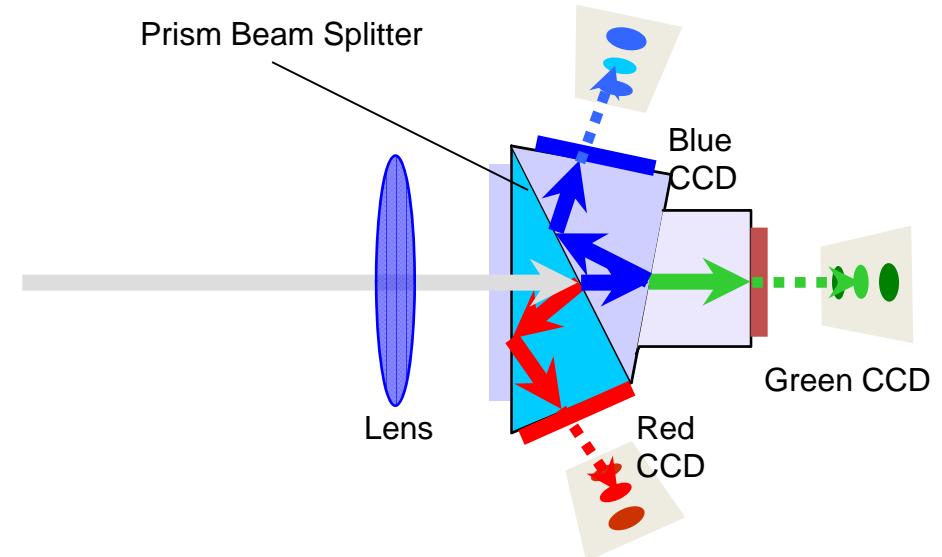
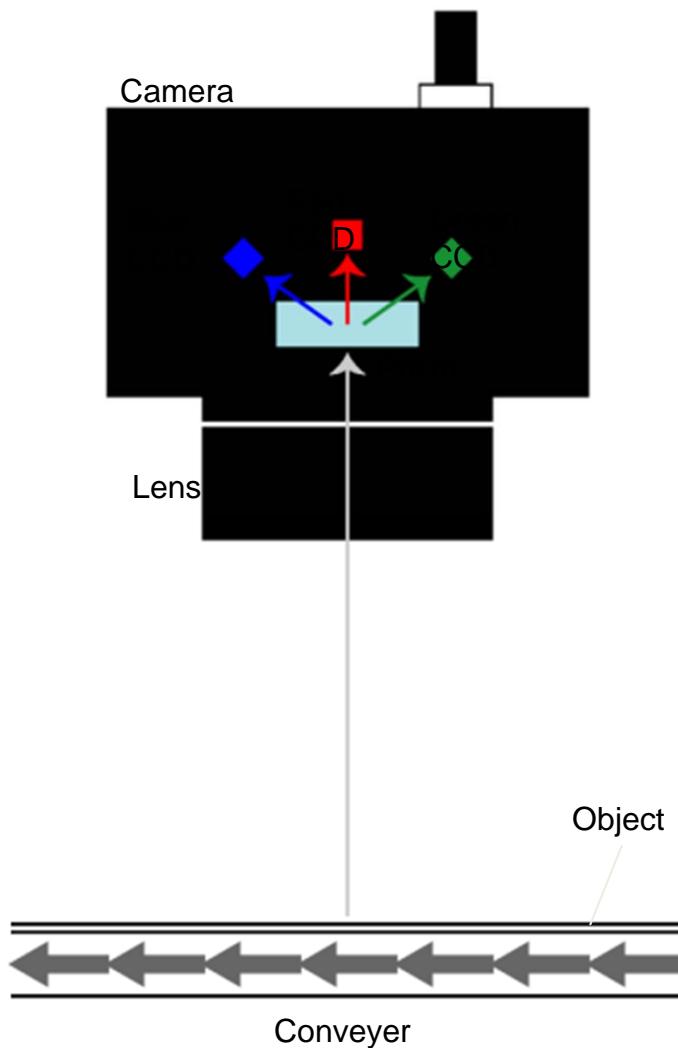


Raw

Corrected



# Prism-based Line Scan Camera Advantages



One focal point for all channels

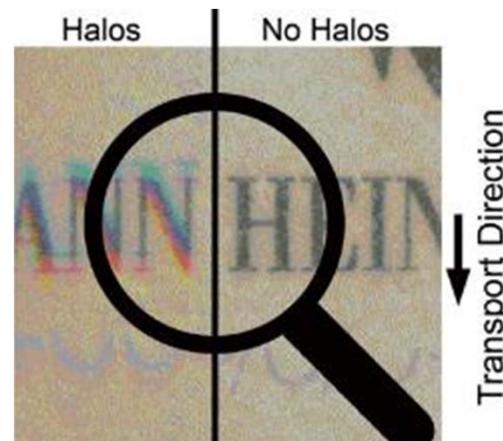
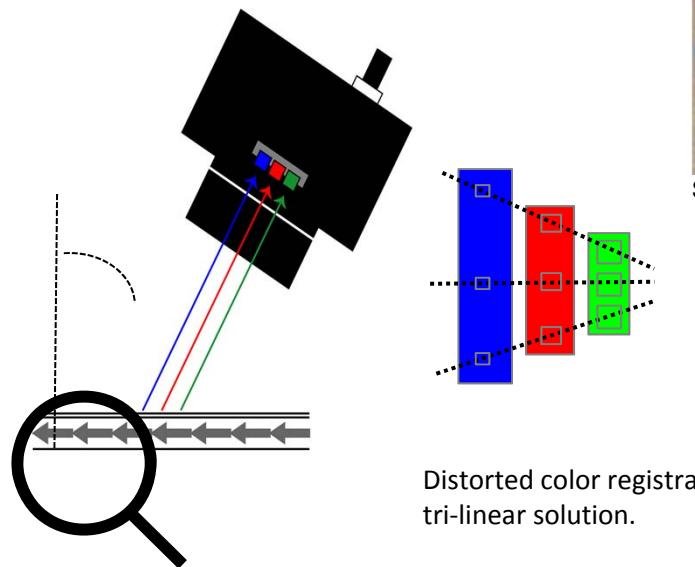
- Reflected light is separated by wavelength through the optical beam splitter and sent to independent RGB CCD sensors simultaneously.
- As a result, all CCDs capture the exact same point of the object at the same time.



# Prism-based vs Tri-linear Technology Off-axis Position

## Drawback of tri-linear technology

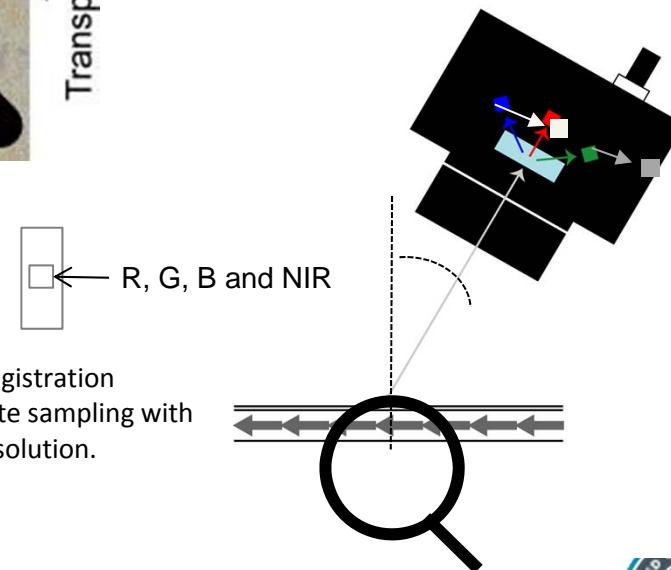
Camera positioned off-axis to the inspected object creates unwanted halo effects (distortion in color registration). Different magnification for all spectral bands



Source: Vision & Sensors, May 2010

## Advantages of prism technology

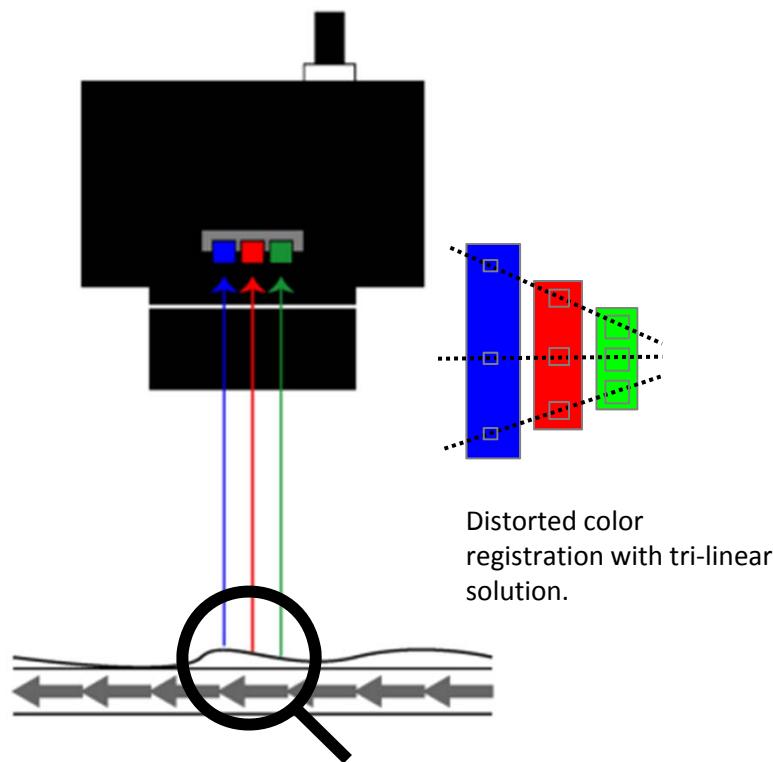
Camera positioned off-axis to the object. No problem with spatial alignment – no halo effects. All CCDs capture the exact same point of the object at the same time. Same magnification for all spectral bands.



# Prism-based vs Tri-linear Technology Undulating Objects

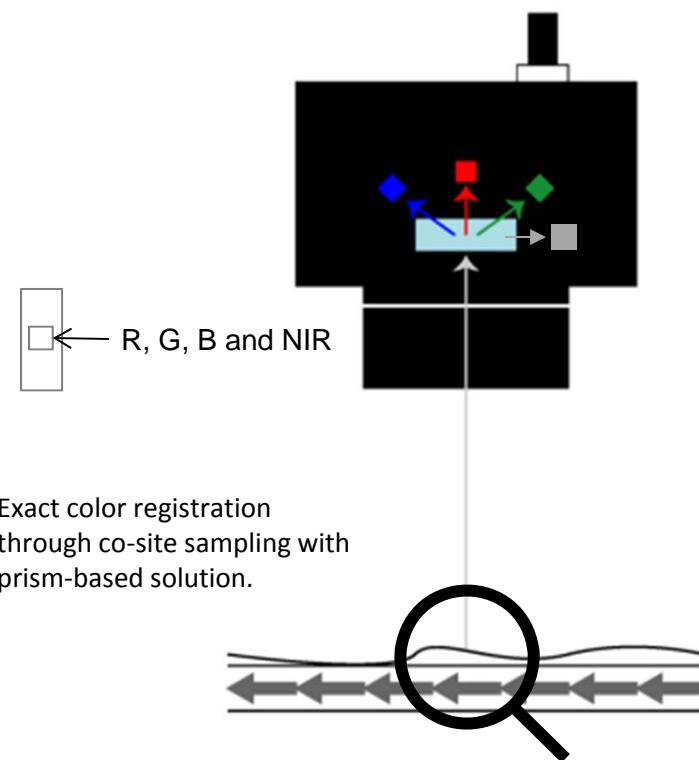
## Drawbacks of tri-linear technology

When inspecting undulating objects, the waviness causes constant timing and focus variations between the R,G and B lines.



## Advantages of prism-based technology

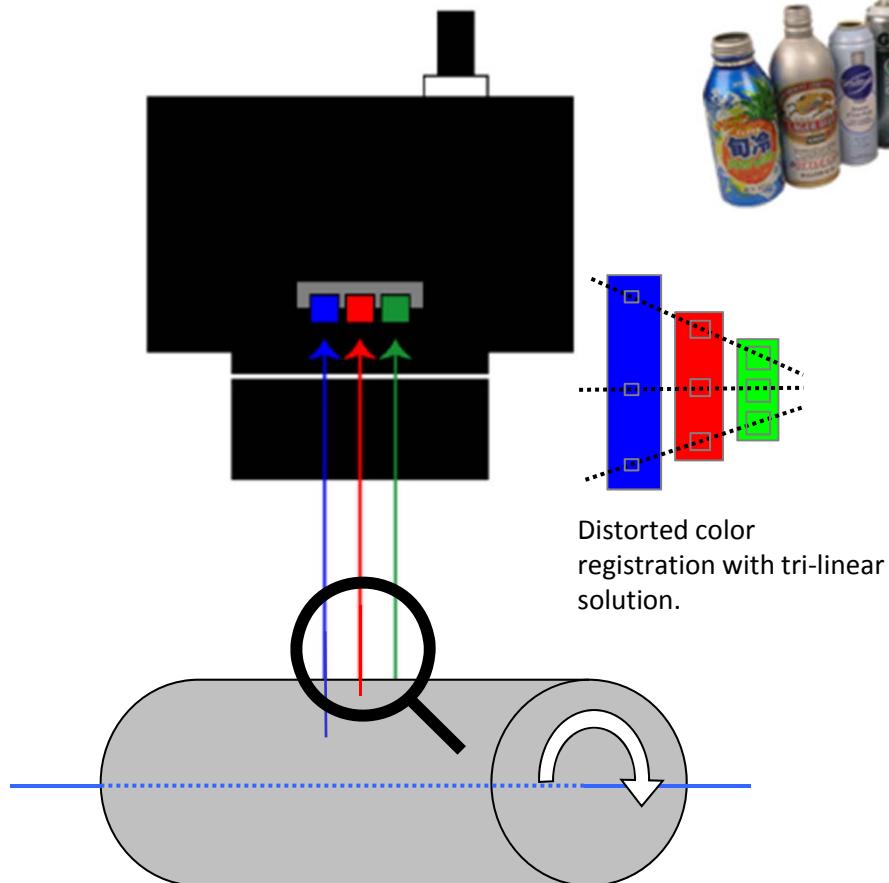
Always one optical axis with precise pixel-to-pixel alignment.



# Prism-based versus Tri-linear Technology Cylindrical Objects

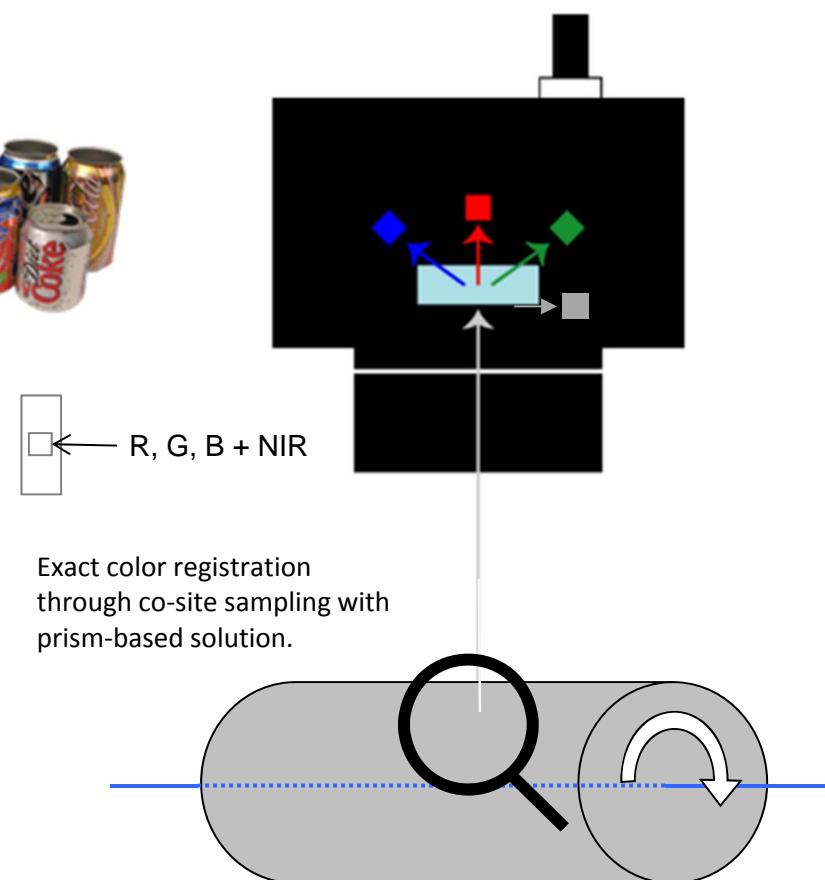
## Drawbacks of tri-linear technology

When inspecting cylindrical objects, the R,G and B lines of the CCD are imaged as separate lines of the object.



## Advantages of prism-based technology

Always one optical axis ensuring pixel to pixel accuracy and same magnification.



# Summary / Tips

- Area Scan cameras are fairly straight forward.
- Line Scan requires more attention to alignment and timing.
- Best color and spatial resolution come from 3-CCD cameras.
- Tip: 80% of Machine Vision applications are probably monochrome area scan.
- Area scan and Linescan applications rarely overlap.  
When in doubt, prototype with area scan.



# Basic Course Summary

- Frame rate and resolution are usually not enough to pick a camera.
- Use sensor performance, camera design, feature set, and cost-effectiveness to narrow selection.
- Camera design can make or break image quality.
- No “one size fits all” interface. Remember to look at cabling, peripheral cost, and scalability requirements.
- Area scan and Line scan should be viewed as two separate disciplines. Skill-set, efficiency and cost vary greatly between the two.



# Questions?



# Contact Information



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