

Lecture 10: Image Sensor Basics

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CSC 292/572, Fall 2022
Mobile Visual Computing

Logistics

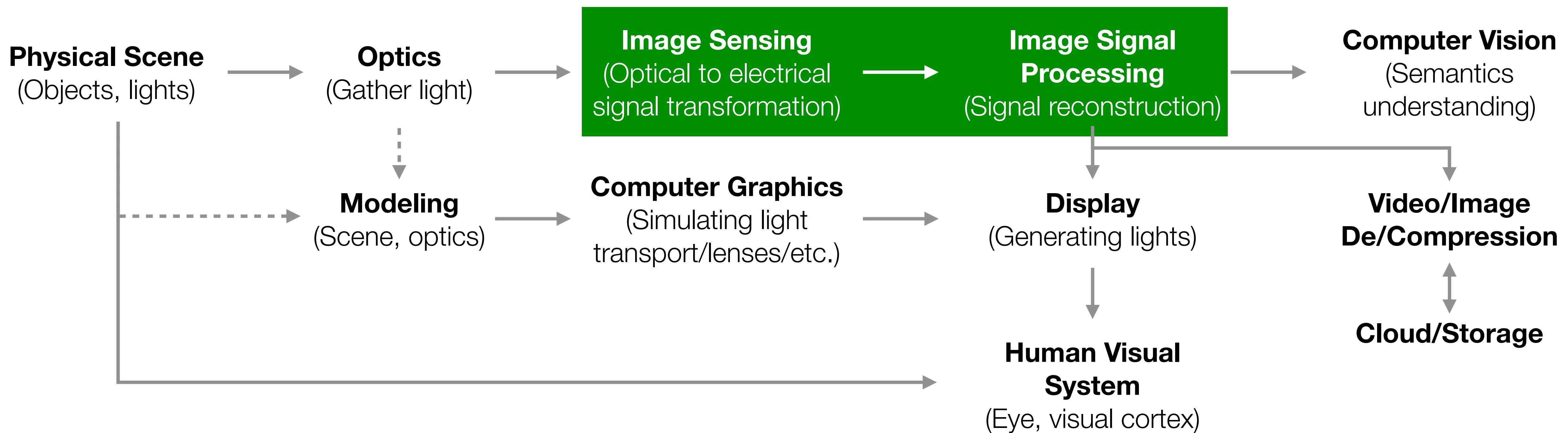
WA1 grades posted.

Project idea document is posted. Feel free to work on your own idea too.

- The link is on the assignment page
- Can work in groups of 2
- Submit a one-page proposal describing what you want to work on by Oct. 26, 11:30 AM.

Where Are We

For now, we will mostly focus on imaging with the goal of generating visually pleasing images for human, as opposed to for computer vision tasks.



The Roadmap

Theoretical Preliminaries

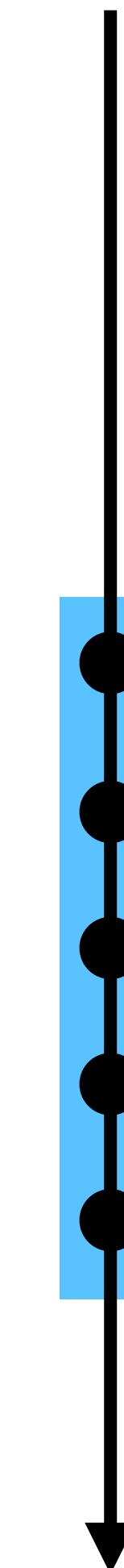
Human Visual Systems

Color in Nature, Arts, Tech
(a.k.a., the birth, life, and death of light)

Digital Camera Imaging

Modeling and Rendering

Applications



Optics in Camera

Image Sensor

Image Signal Processing

Image/Video Compression

Immersive Content

Digital Cameras

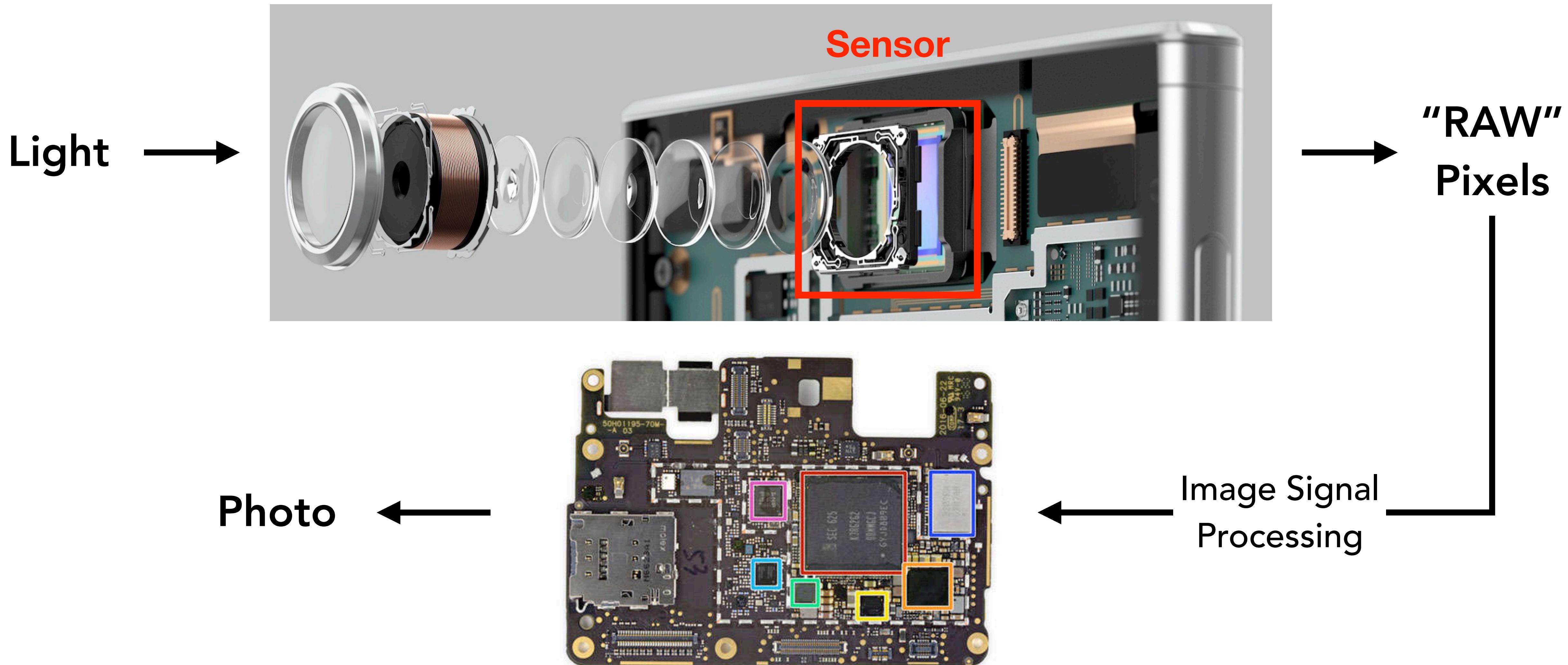
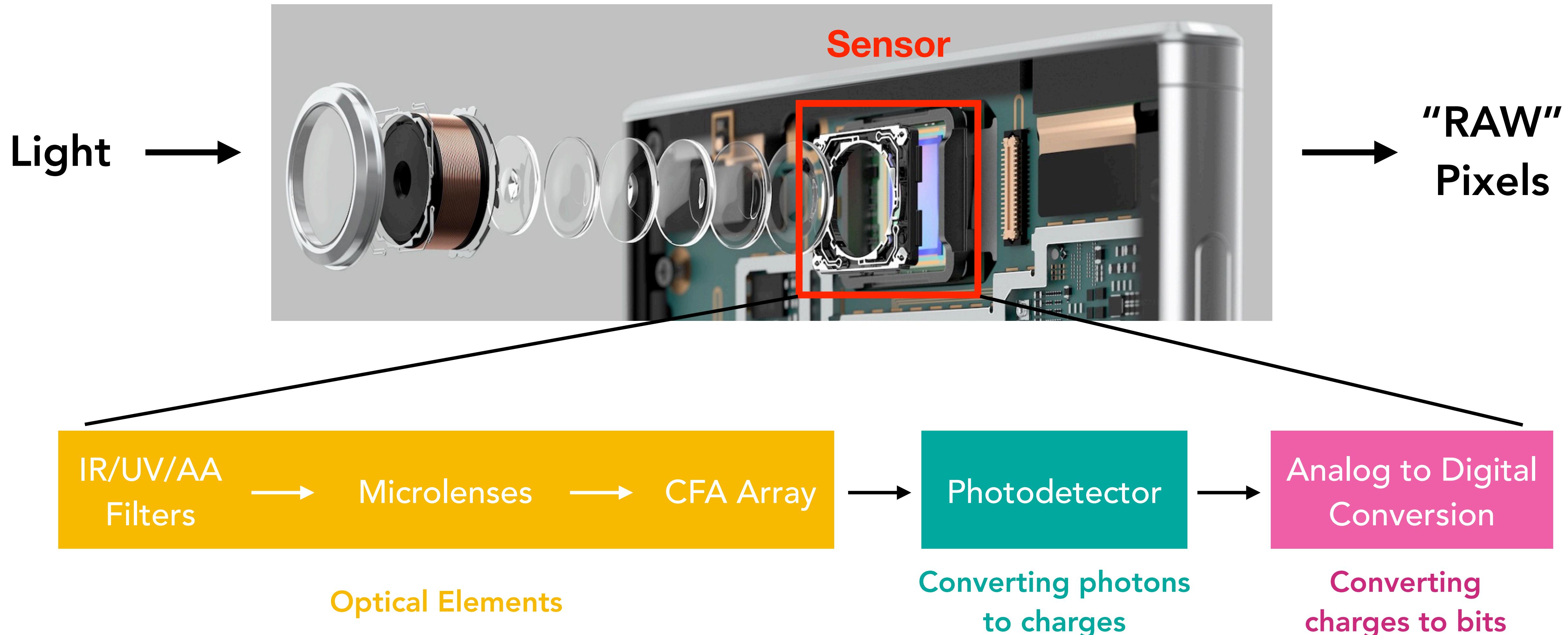
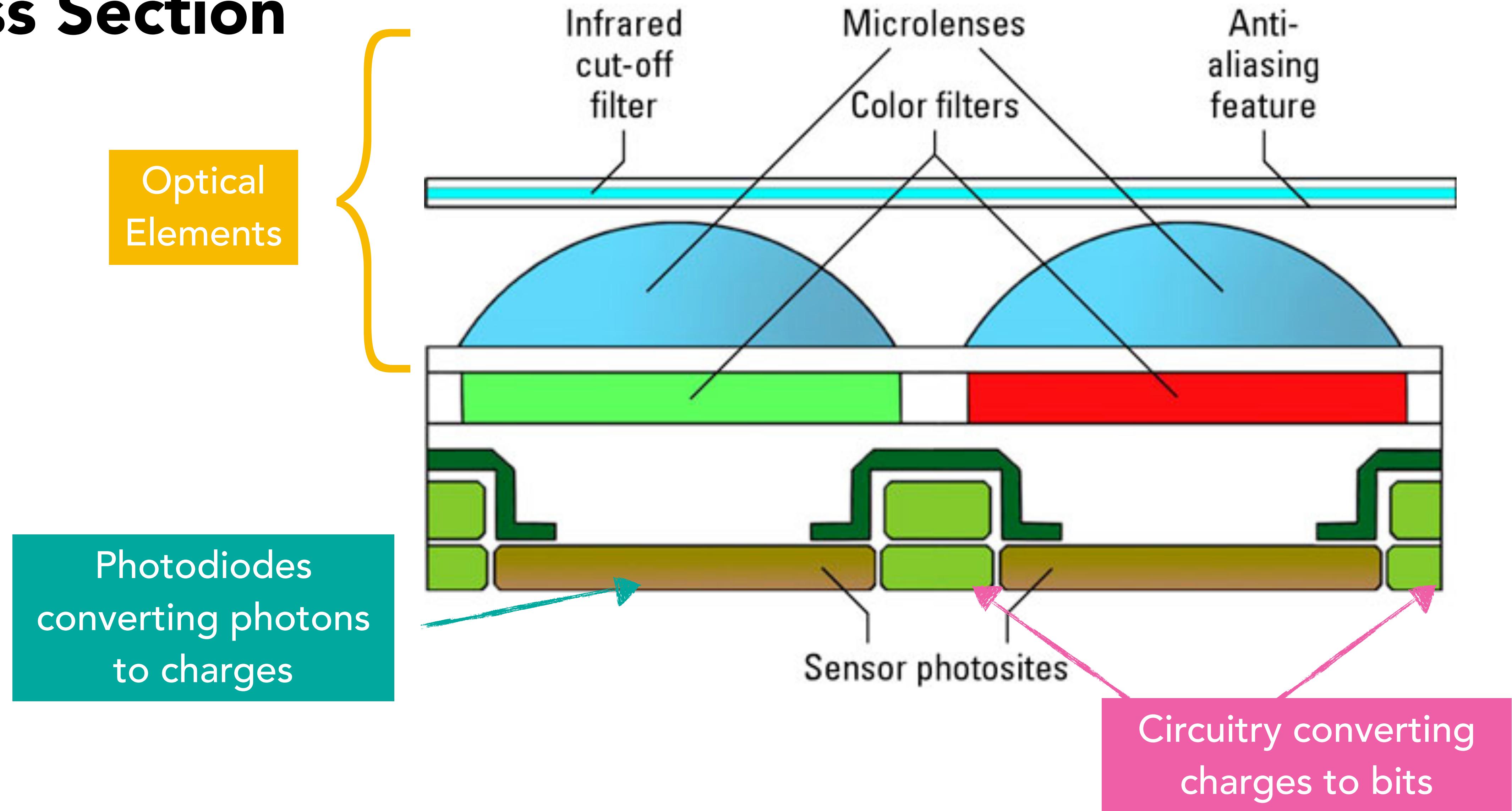


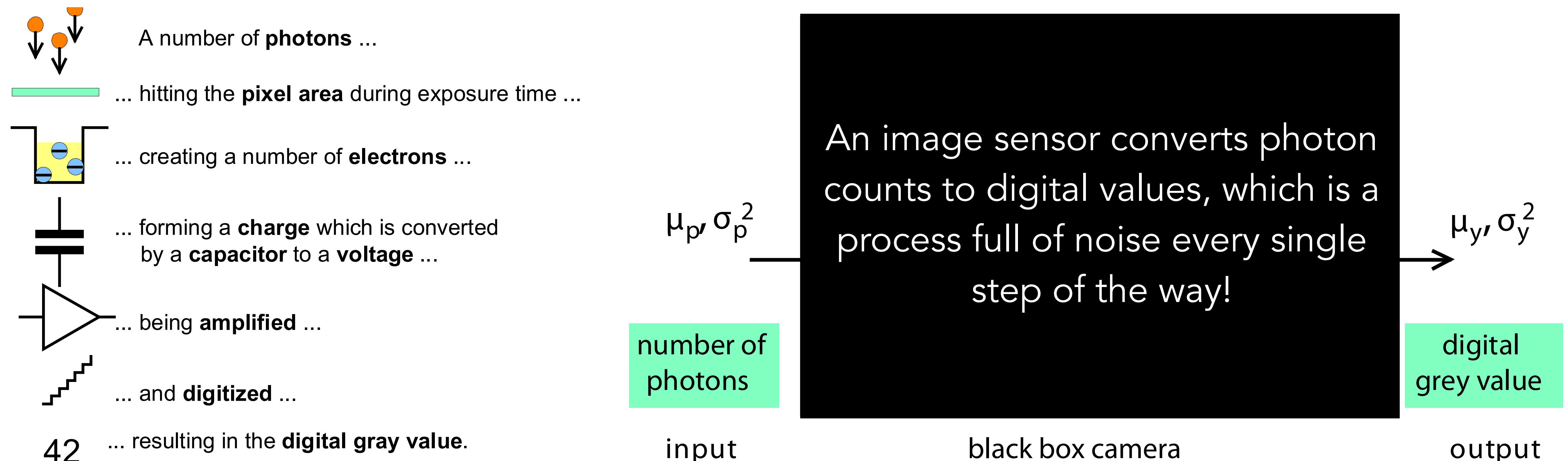
Image Sensor in Digital Cameras



Cross Section



The Big Picture

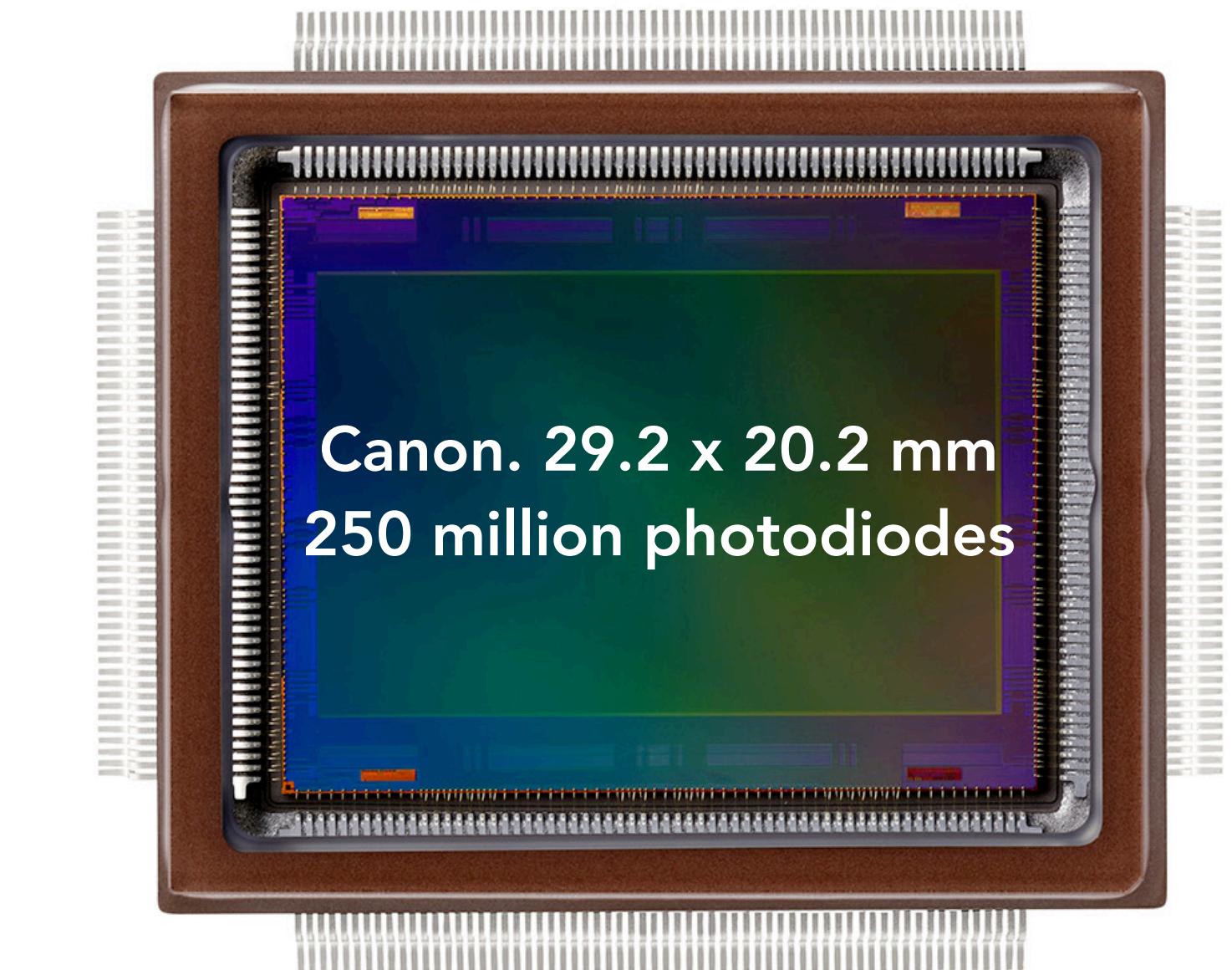
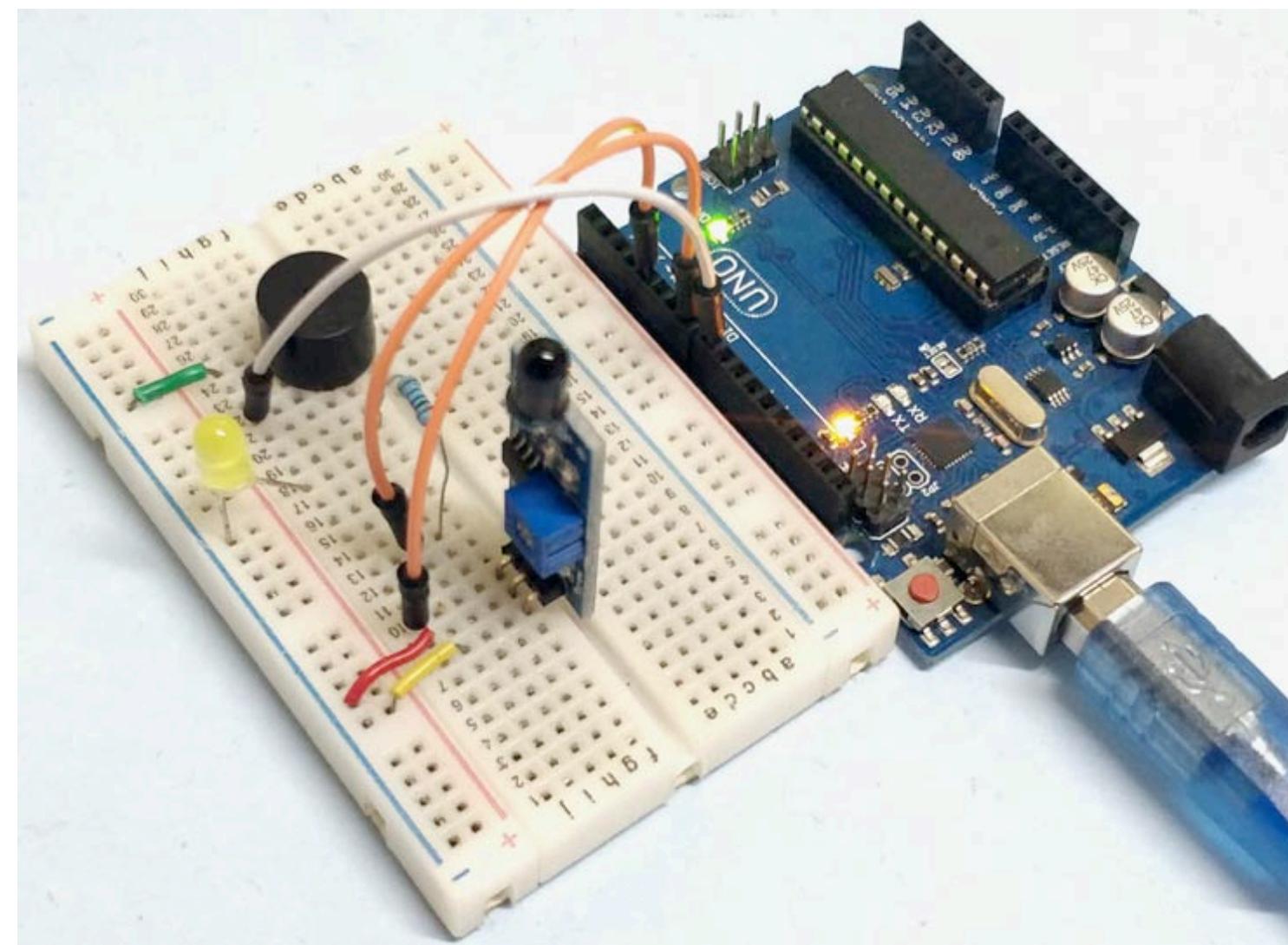
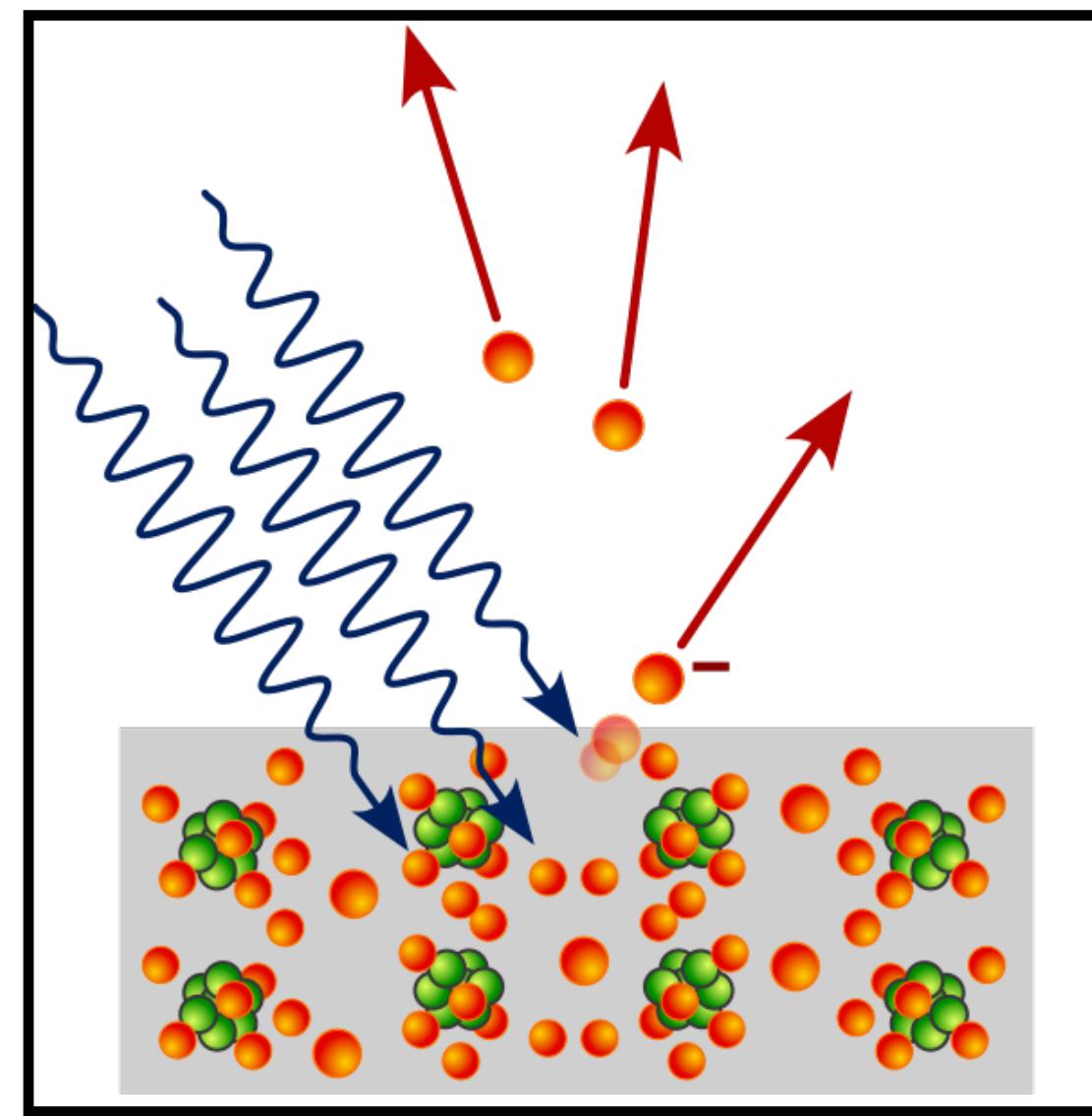


Pixel: From Photons to Charges

Photoelectric Effect

When a photon strikes material, an electron may be emitted.

- Cameras use silicon
- Quantum nature of light matter interaction.



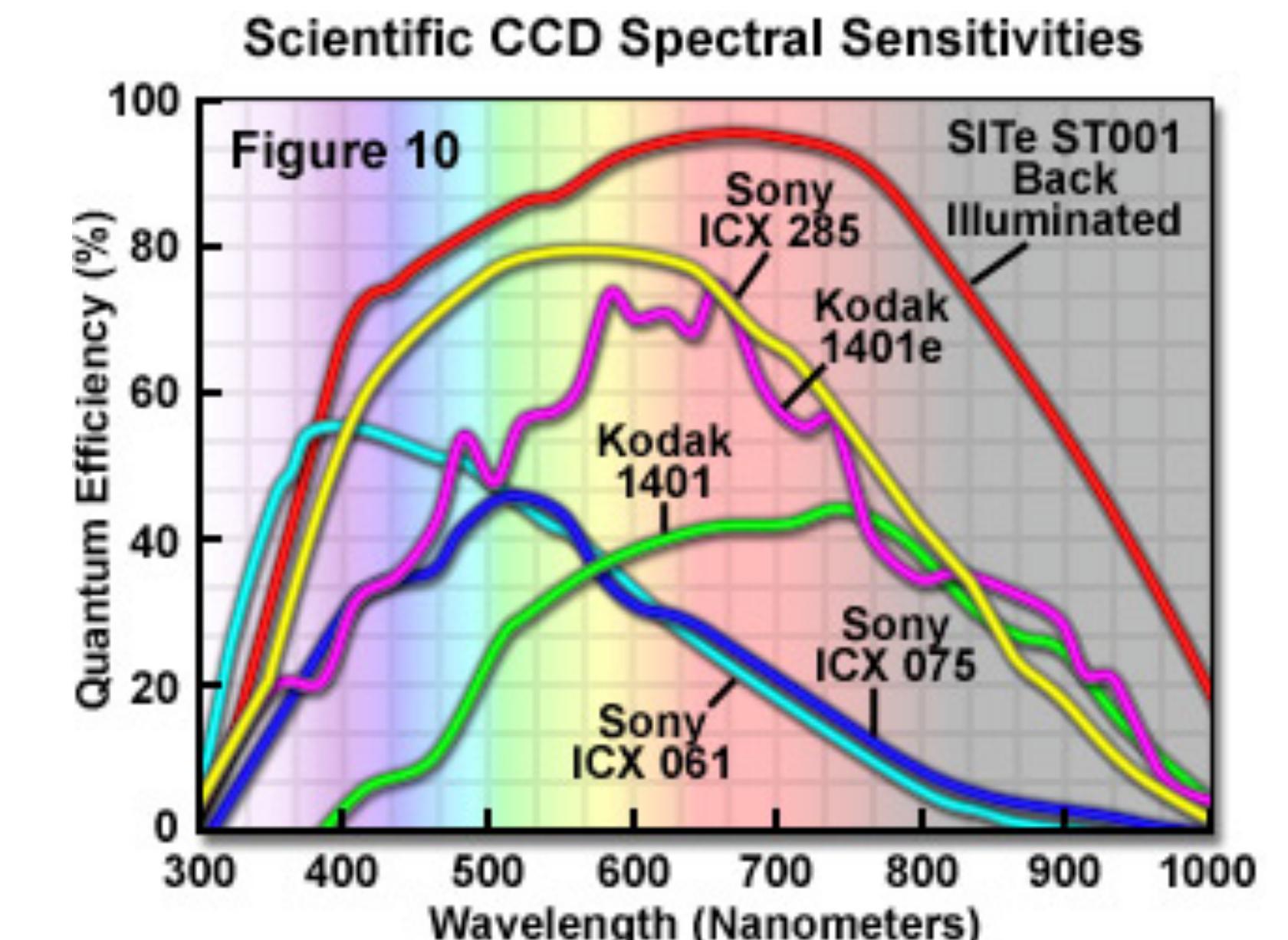
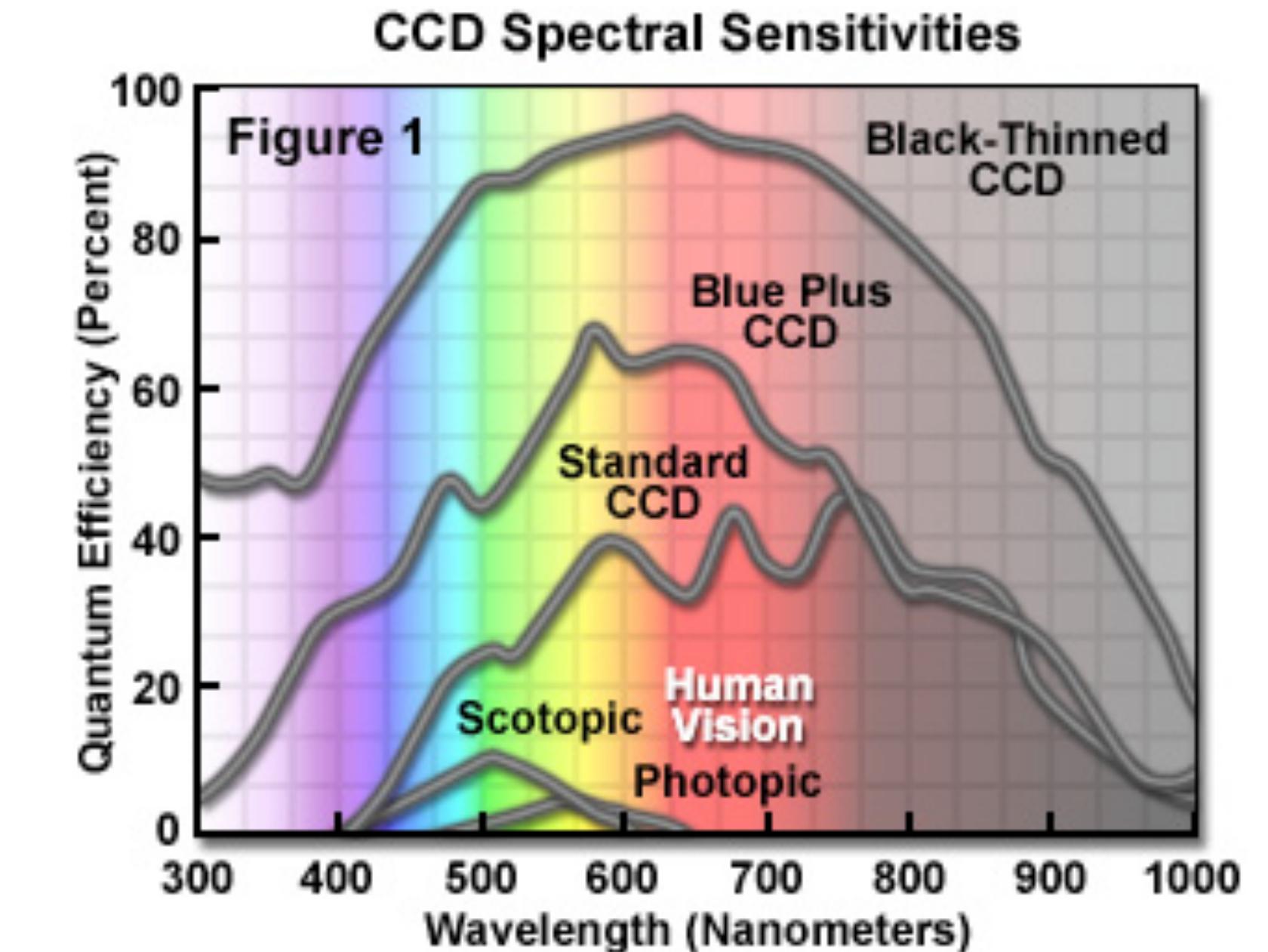
Quantum Efficiency

Electron emission from photon is probabilistic, which depends on the **quantum efficiency** (QE) of the material. QE is wavelength-dependent (just like about everything in optics).

Human QE vs. Camera QE

- Human QE is much lower than camera sensor QE.
- Human eyes are not sensitive to IR and UV light, but camera sensors are.

$$QE = \frac{\text{\# of electrons}}{\text{\# of photons}}$$



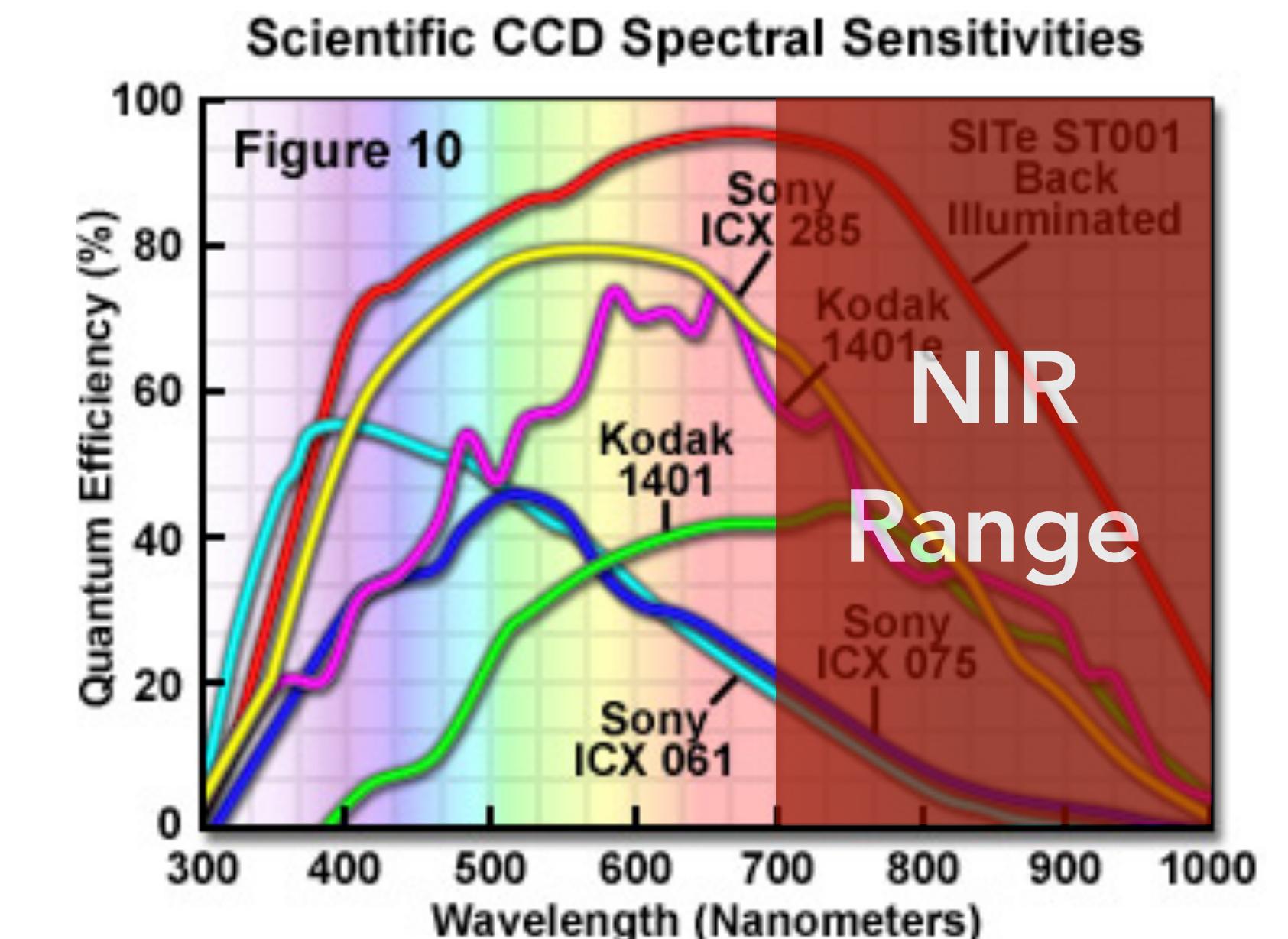
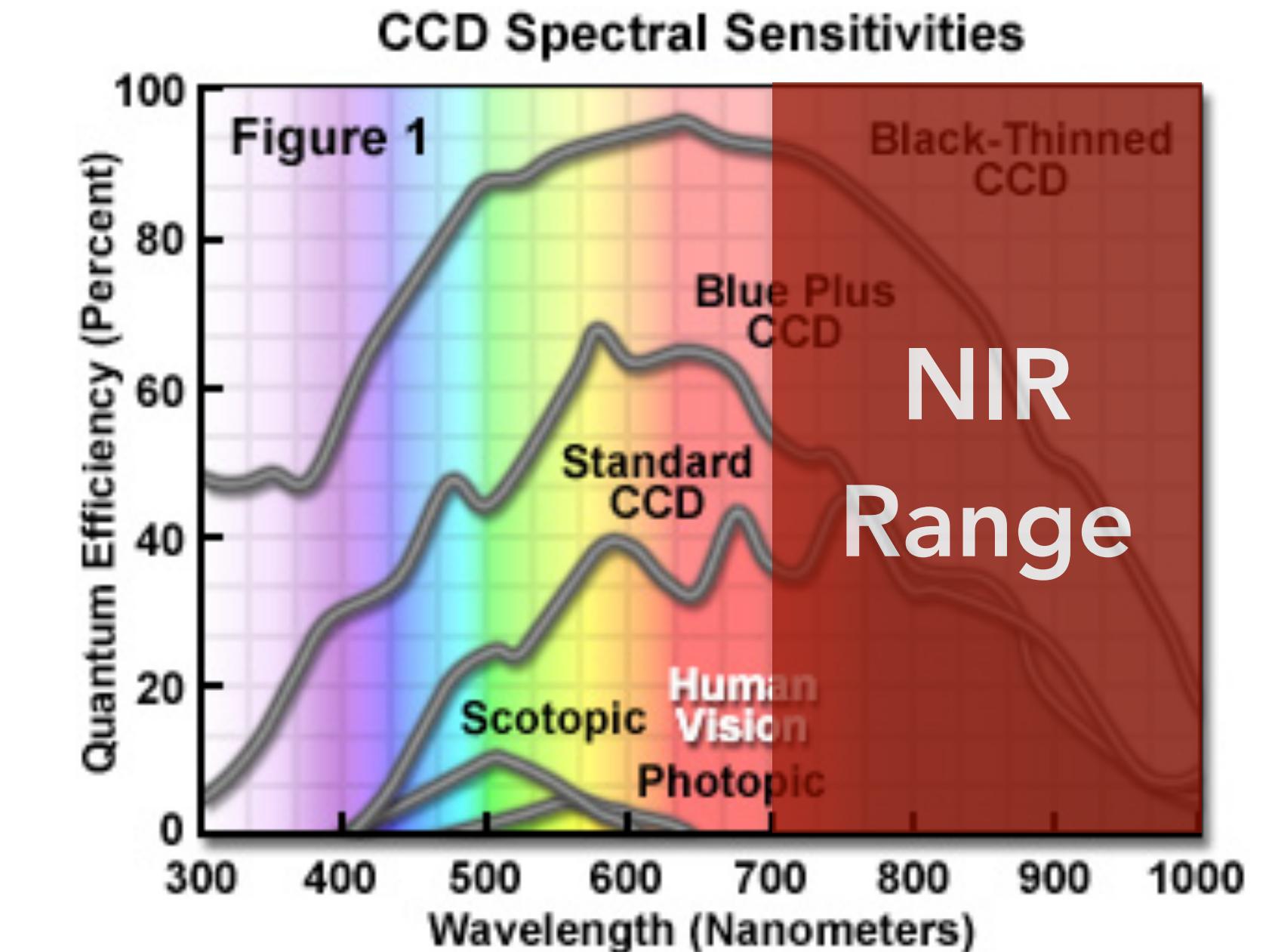
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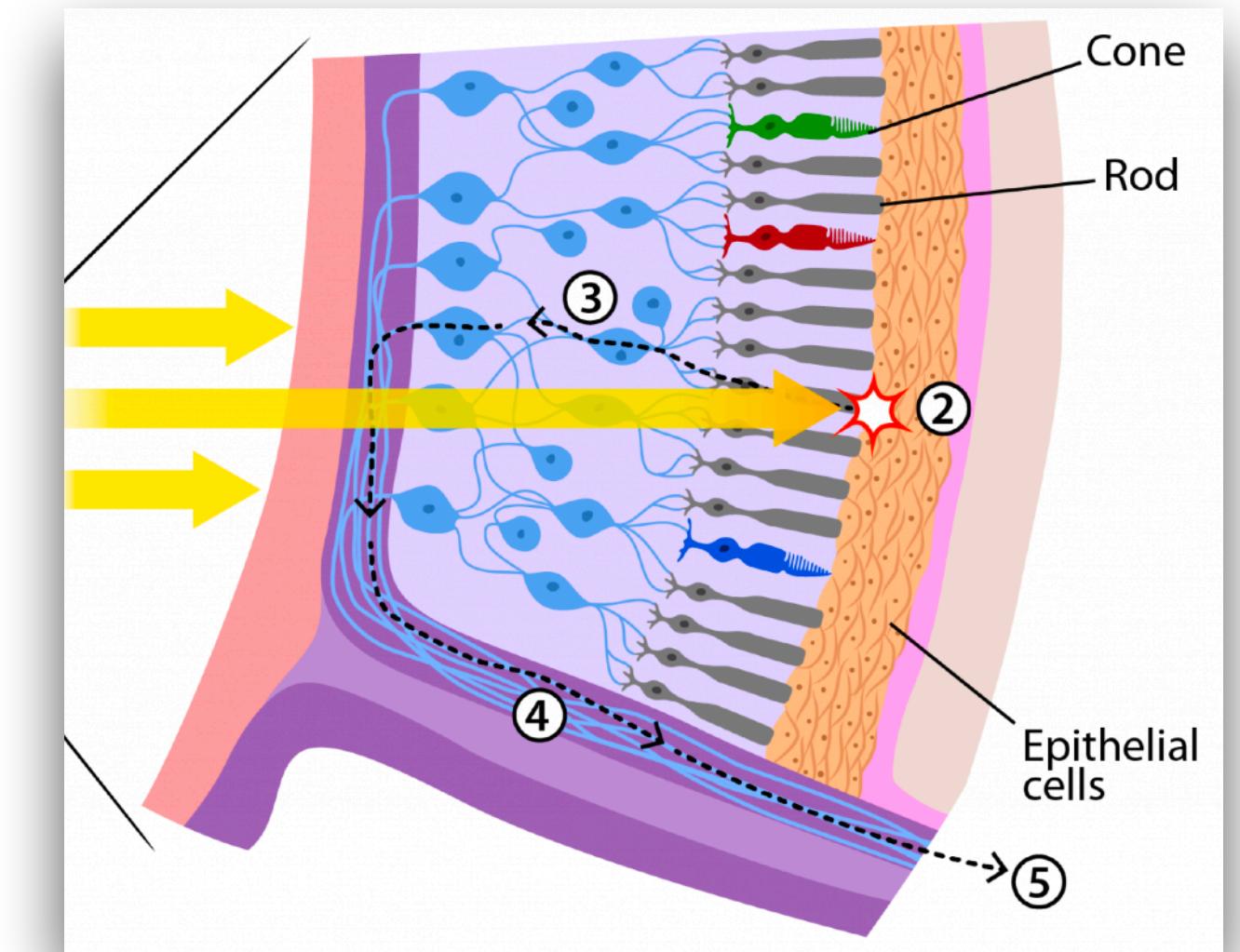
Other Uses/Forms of Light-Matter Interactions



Solar panels



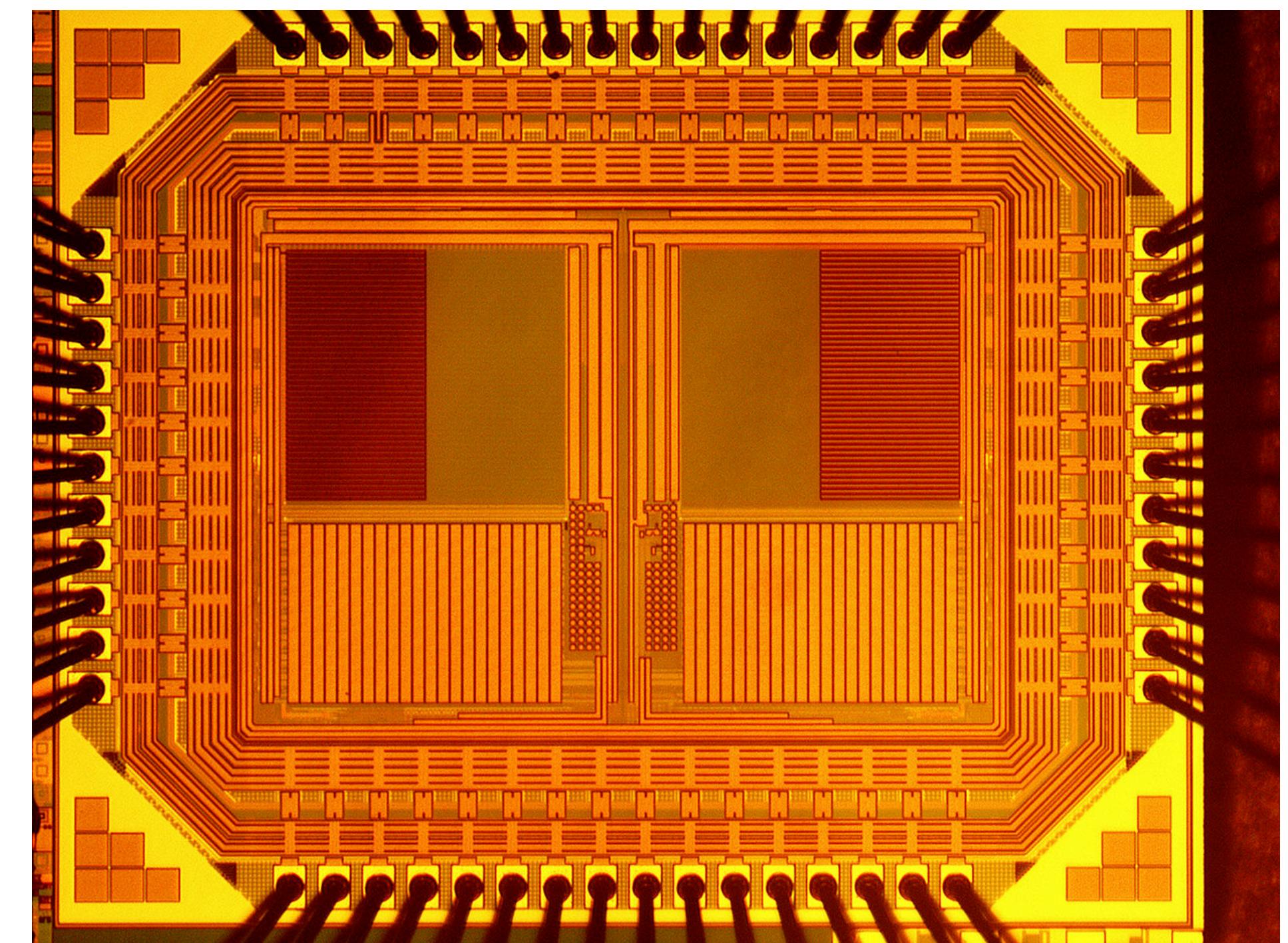
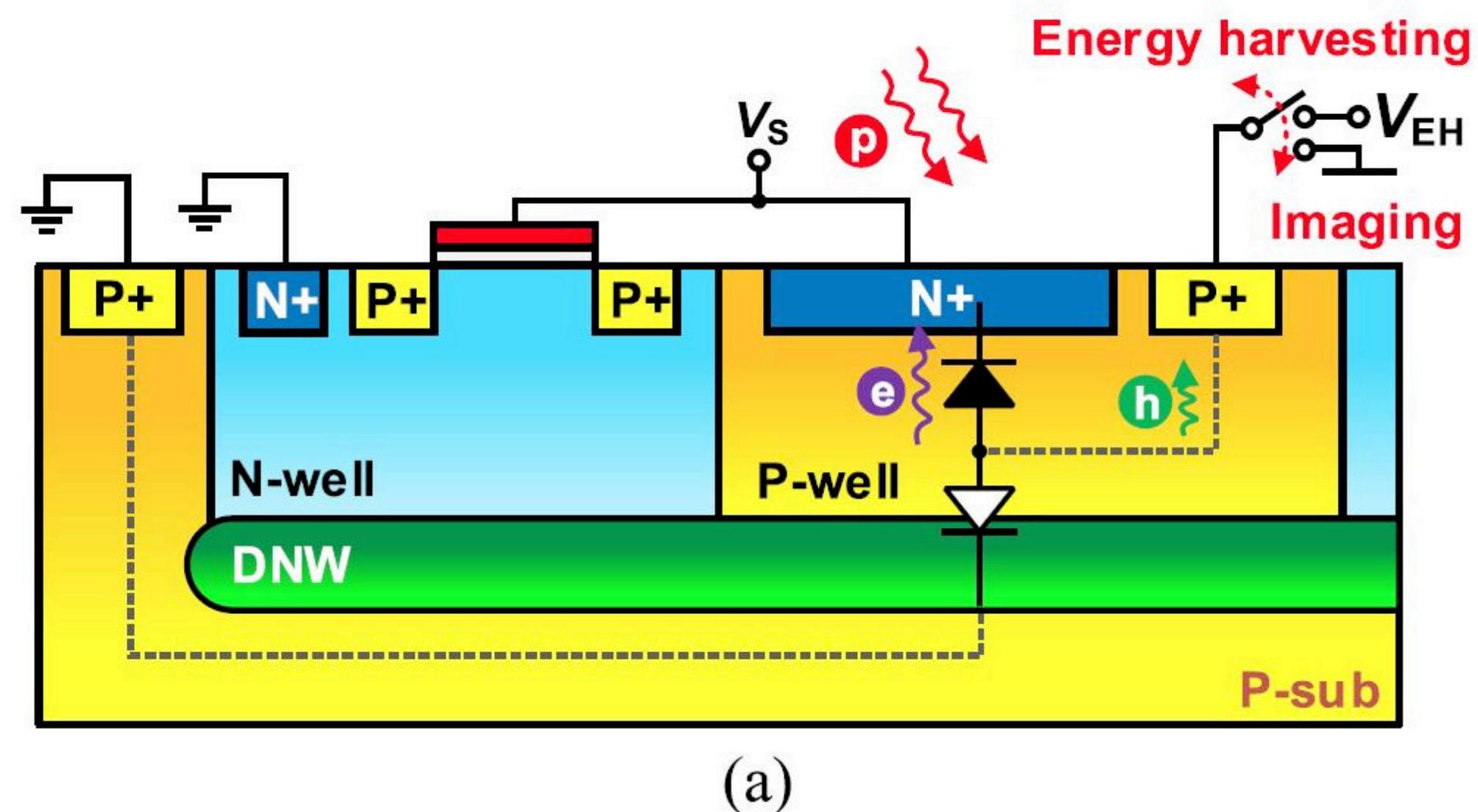
Photosynthesis



Photoreceptor cells

Energy-Harvesting Cameras

Switch between “solar panel mode” and “image sensing mode”.

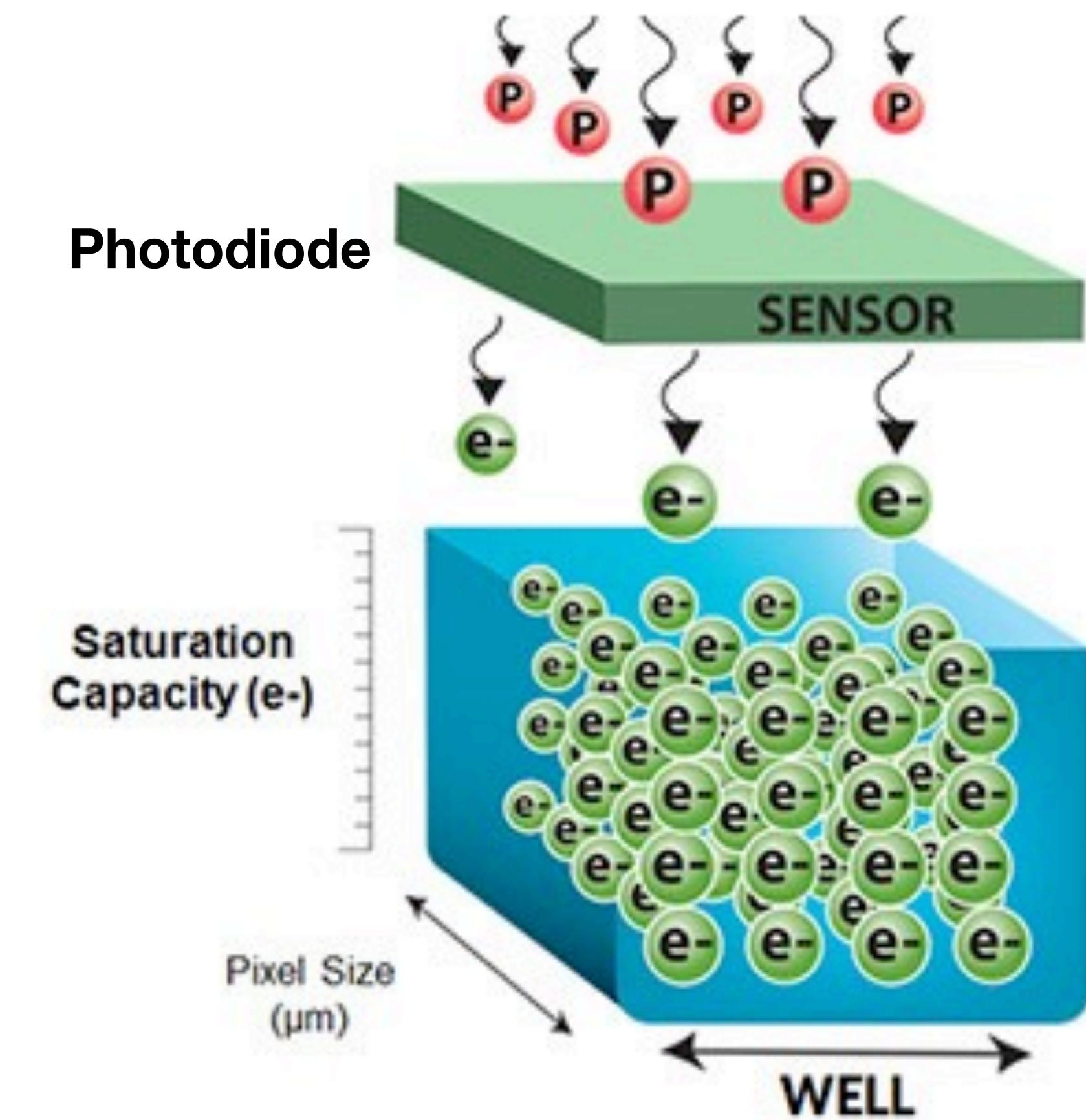


Pixel Well

Think of a pixel in a sensor as a well that holds the emitted electrons.

What determines the number of electrons going into the well:

- light power (dictates the number of photons per unit time) and
- exposure time (integration time).



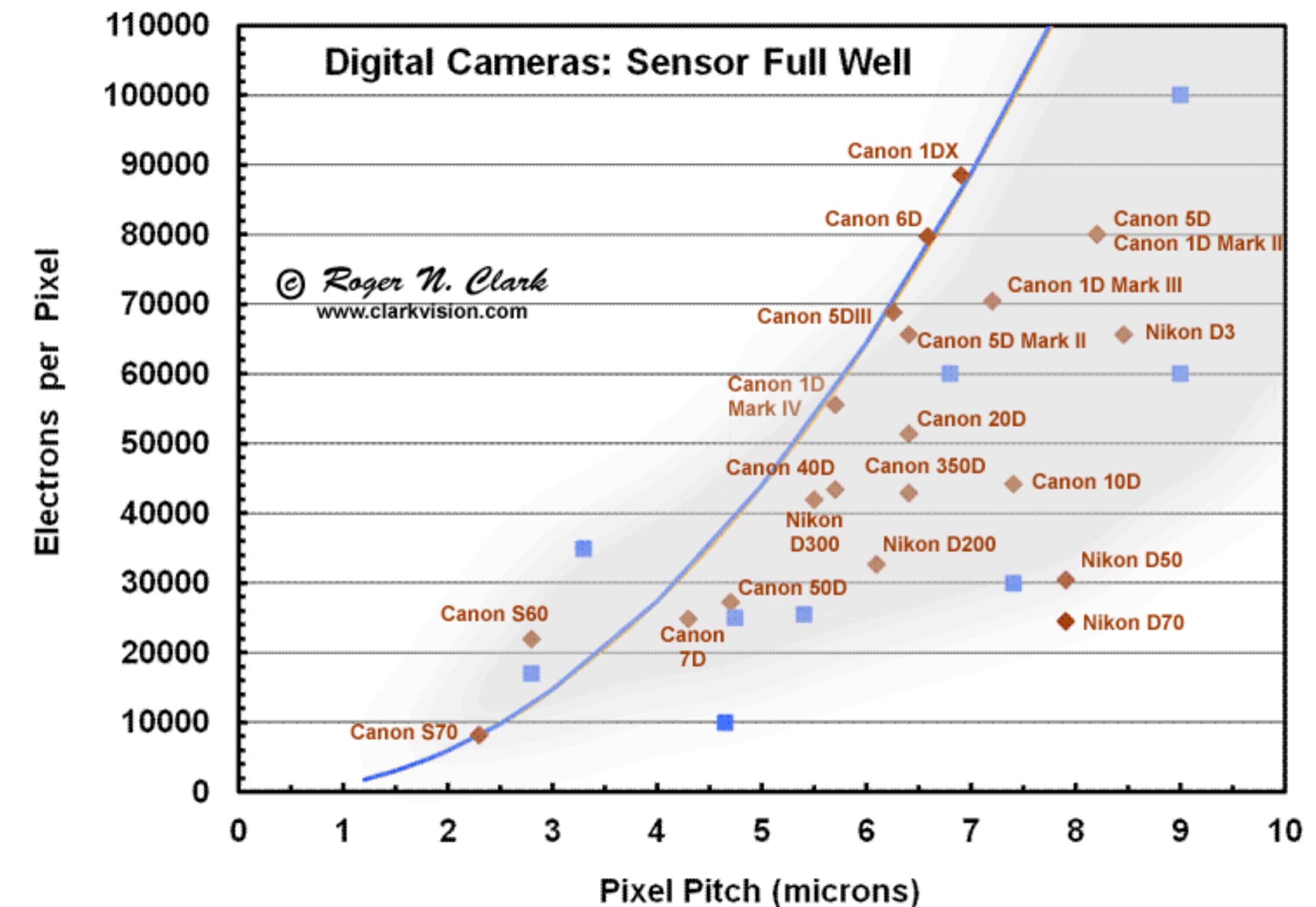
Full Well Capacity

The **full-well capacity**, the max amount of electrons that can be held, depends on pixel size.

More electrons than the capacity **saturates** the well.

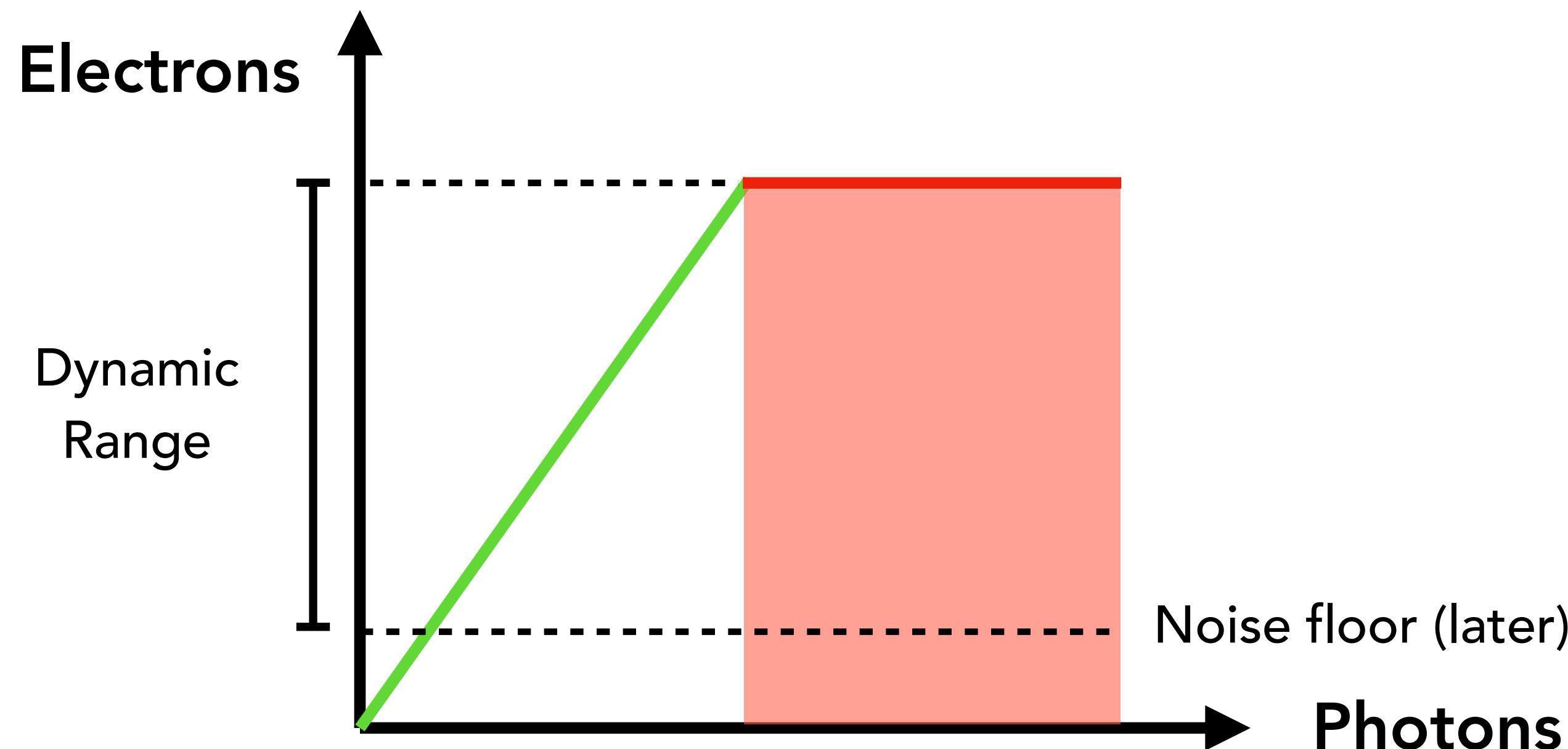
A saturated well doesn't store more electrons.

Quadratic. Why?



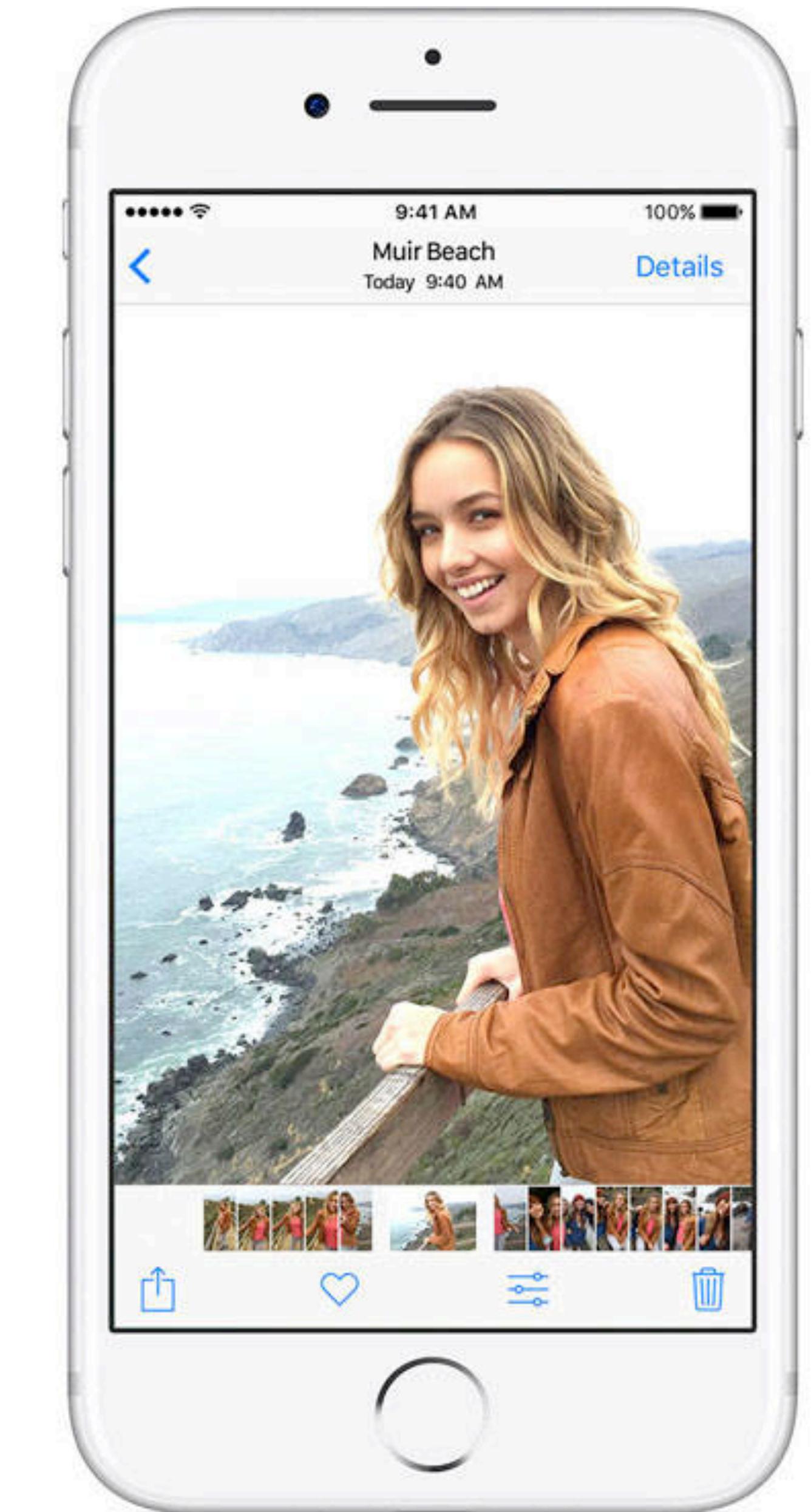
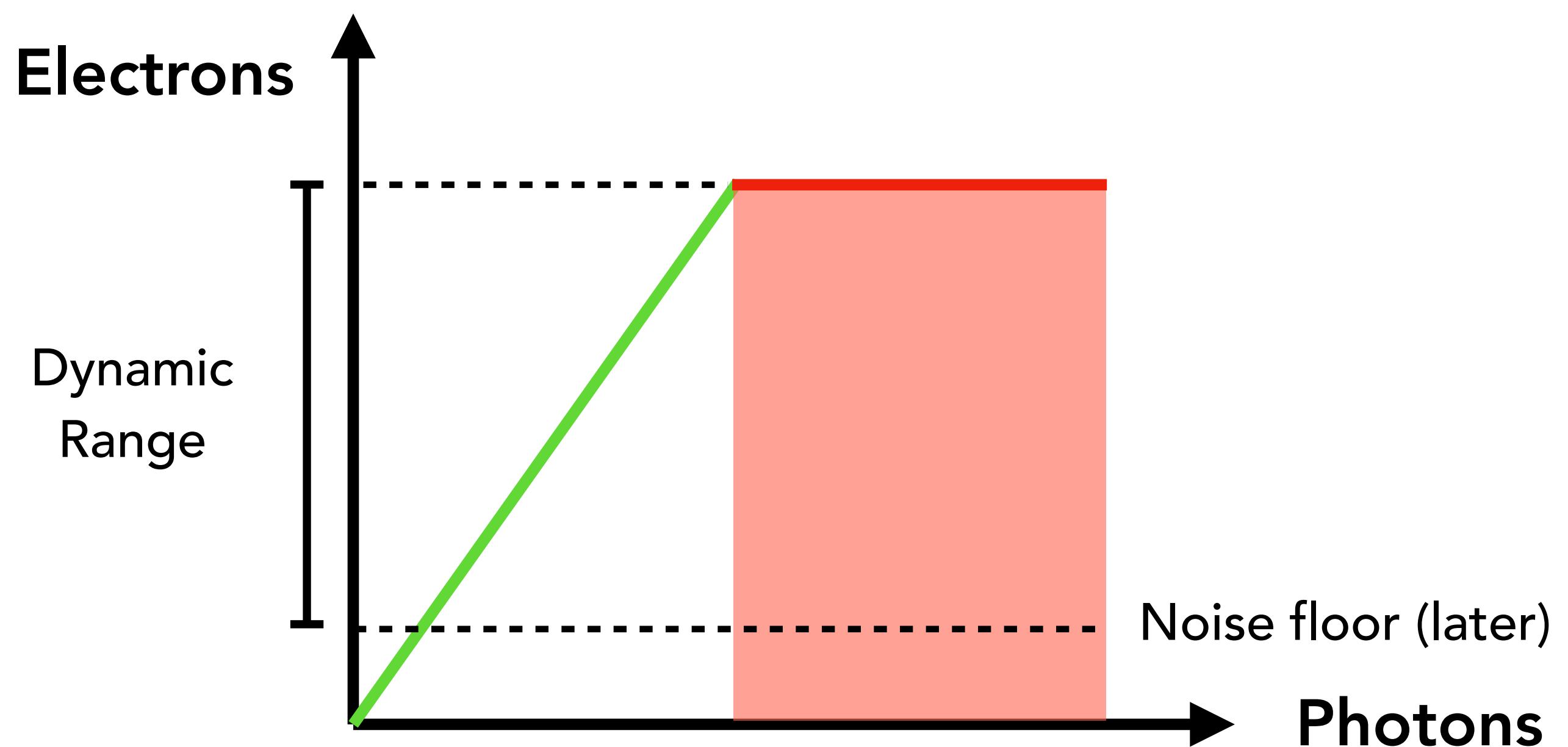
Dynamic Range (Informal Treatment)

A larger well capacity leads to a higher sensor dynamic range, which can capture/accommodate larger differences in scene luminance.



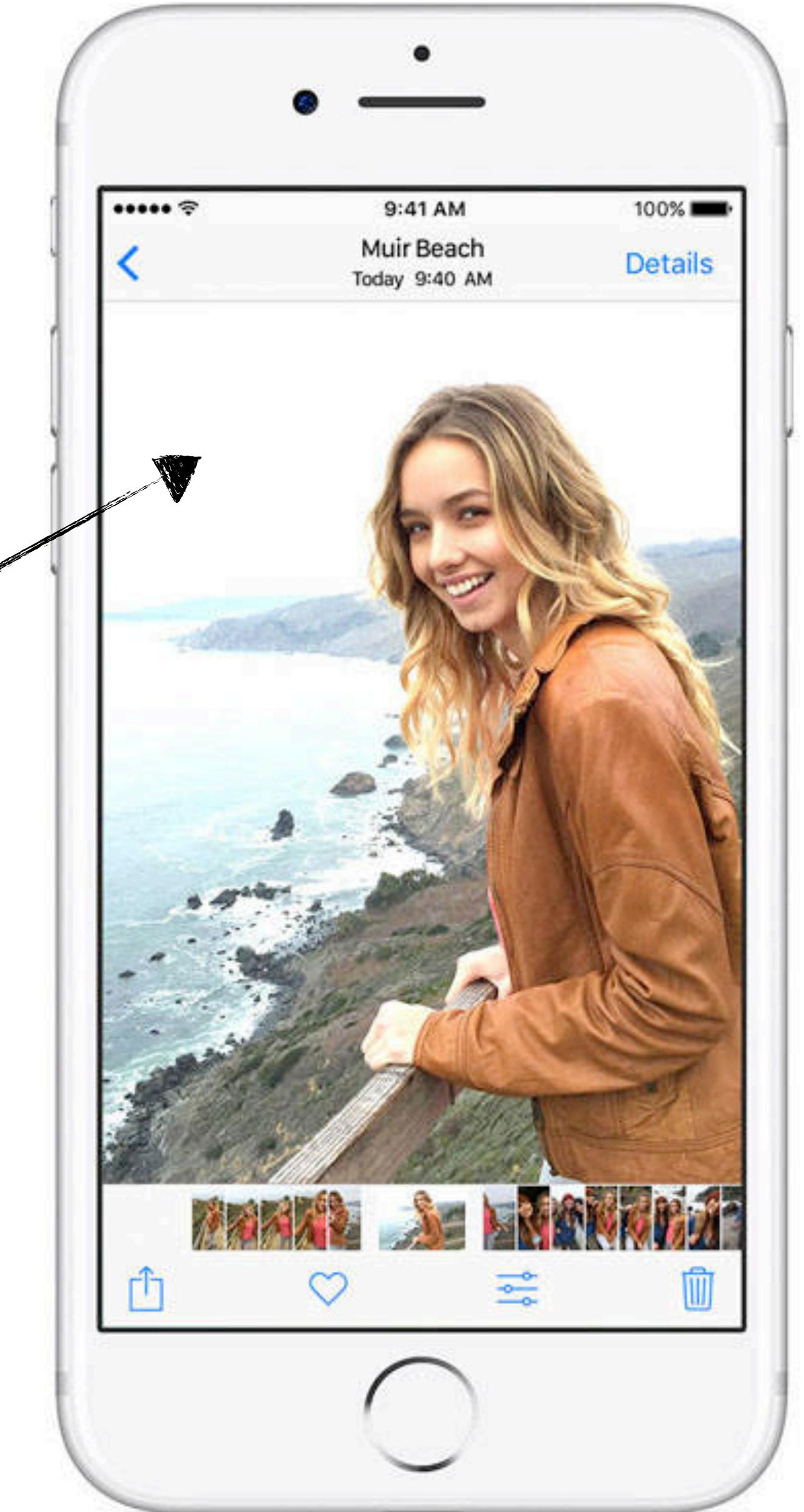
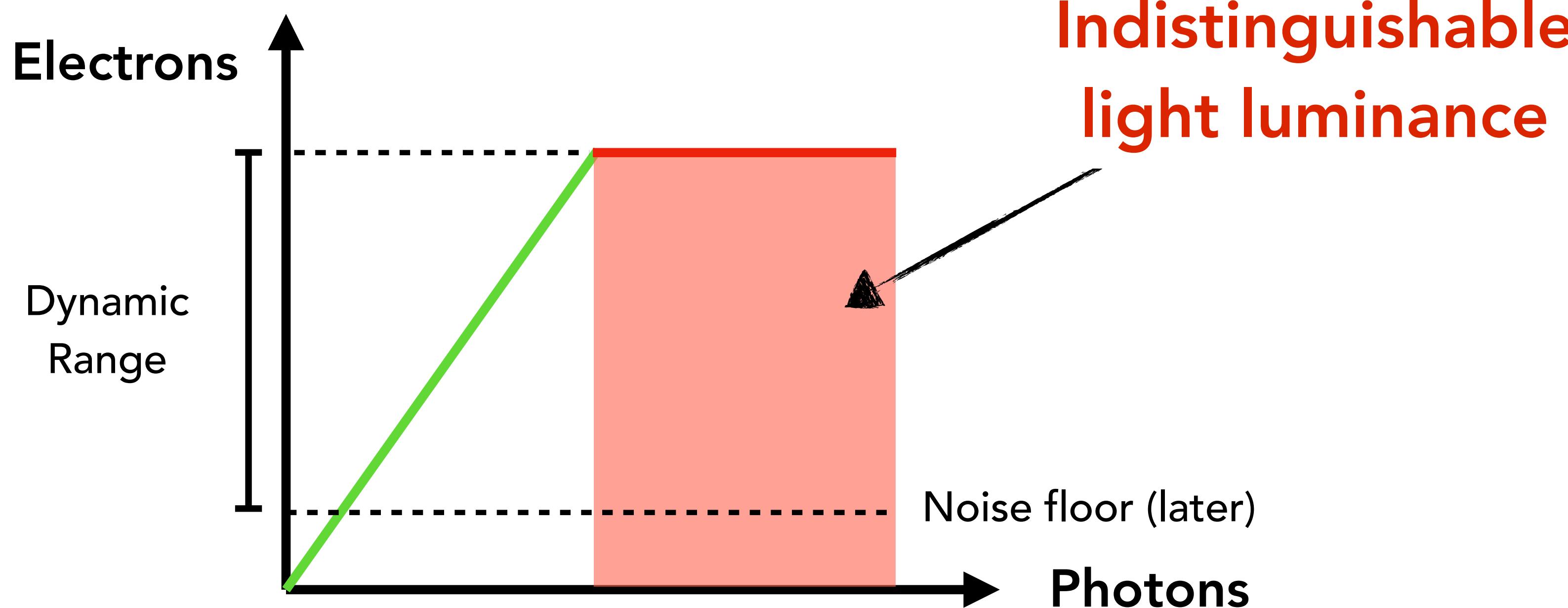
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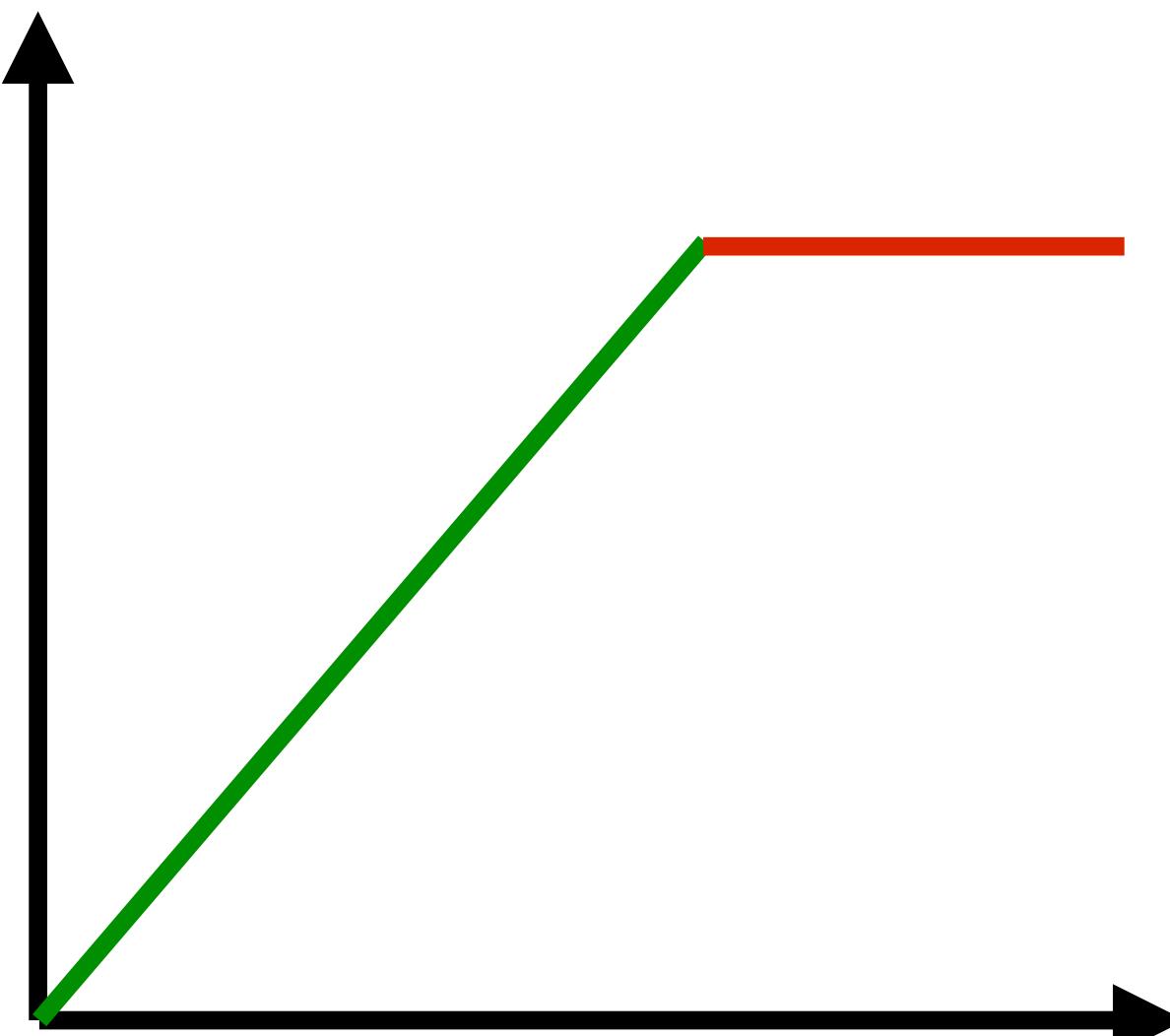
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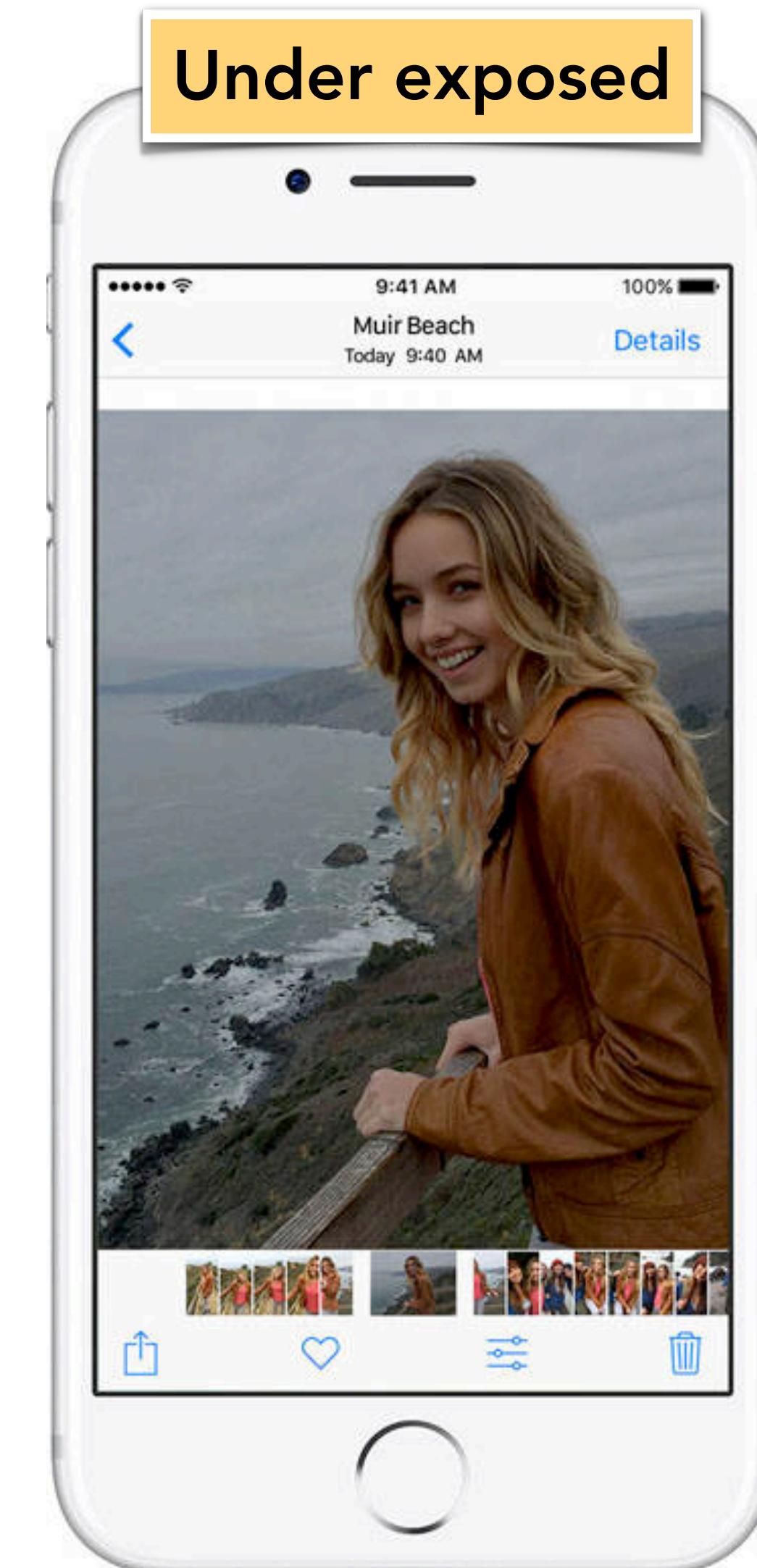


Dynamic Range (Informal Treatment)

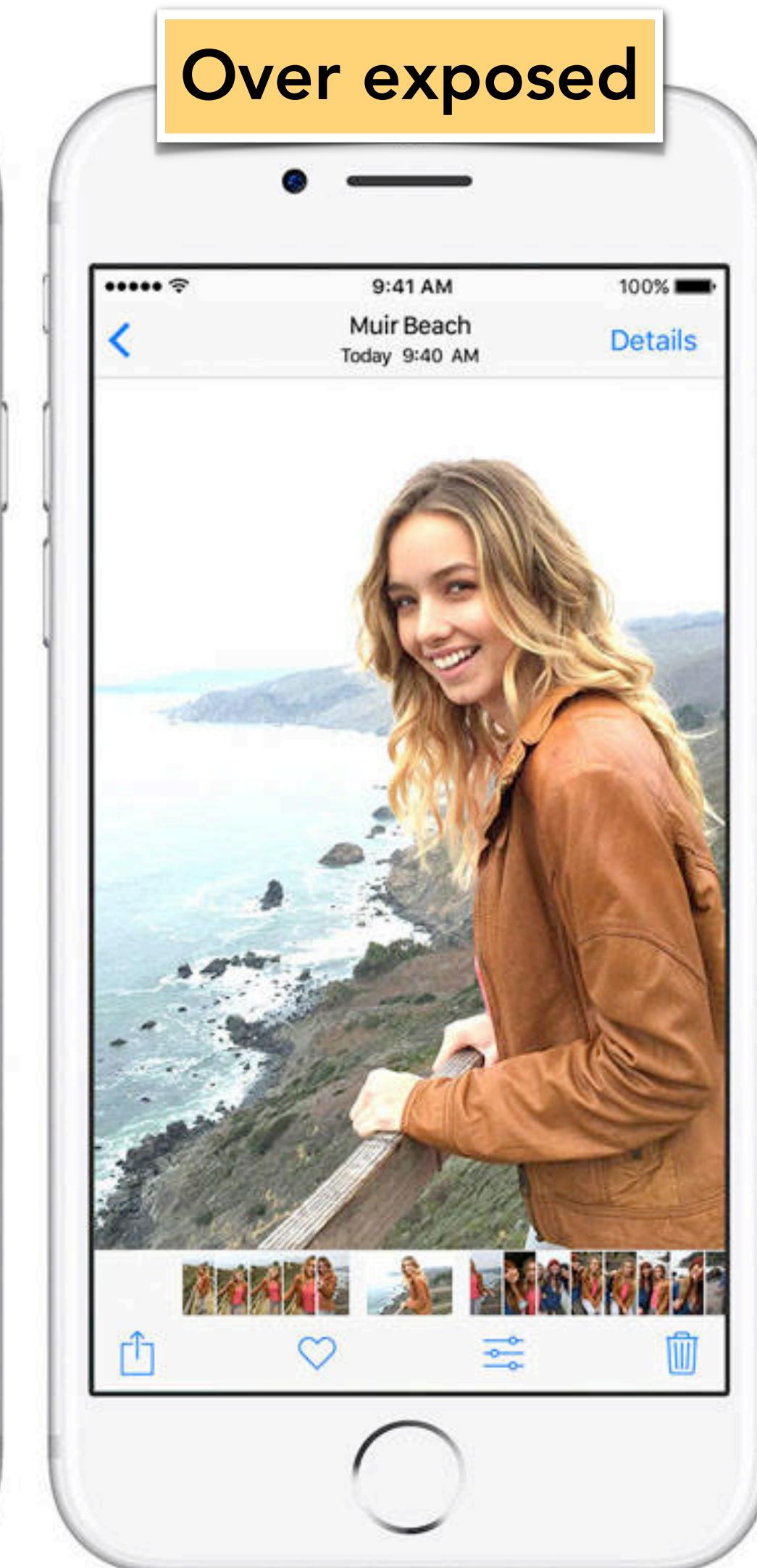
Electrons



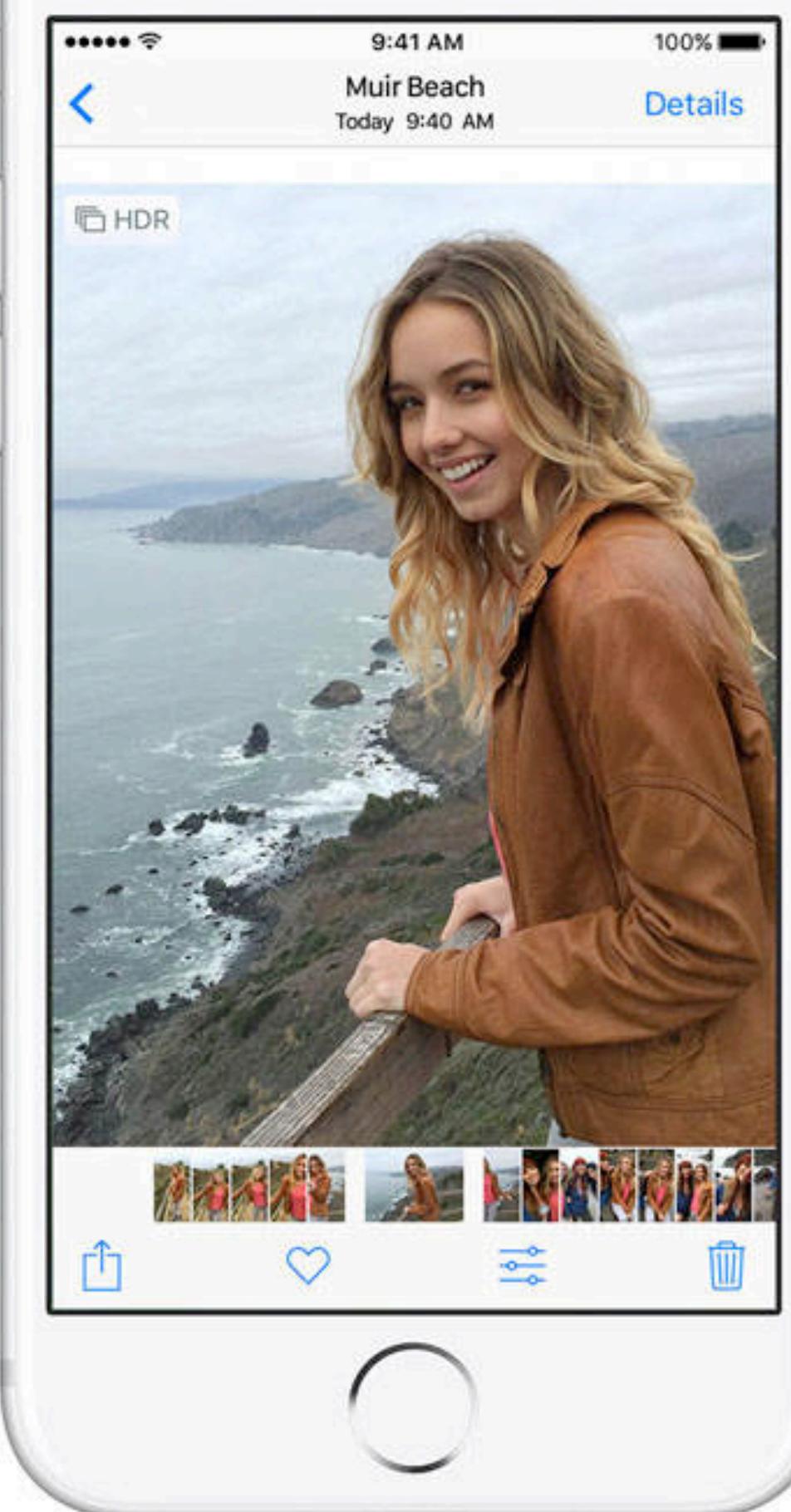
Under exposed



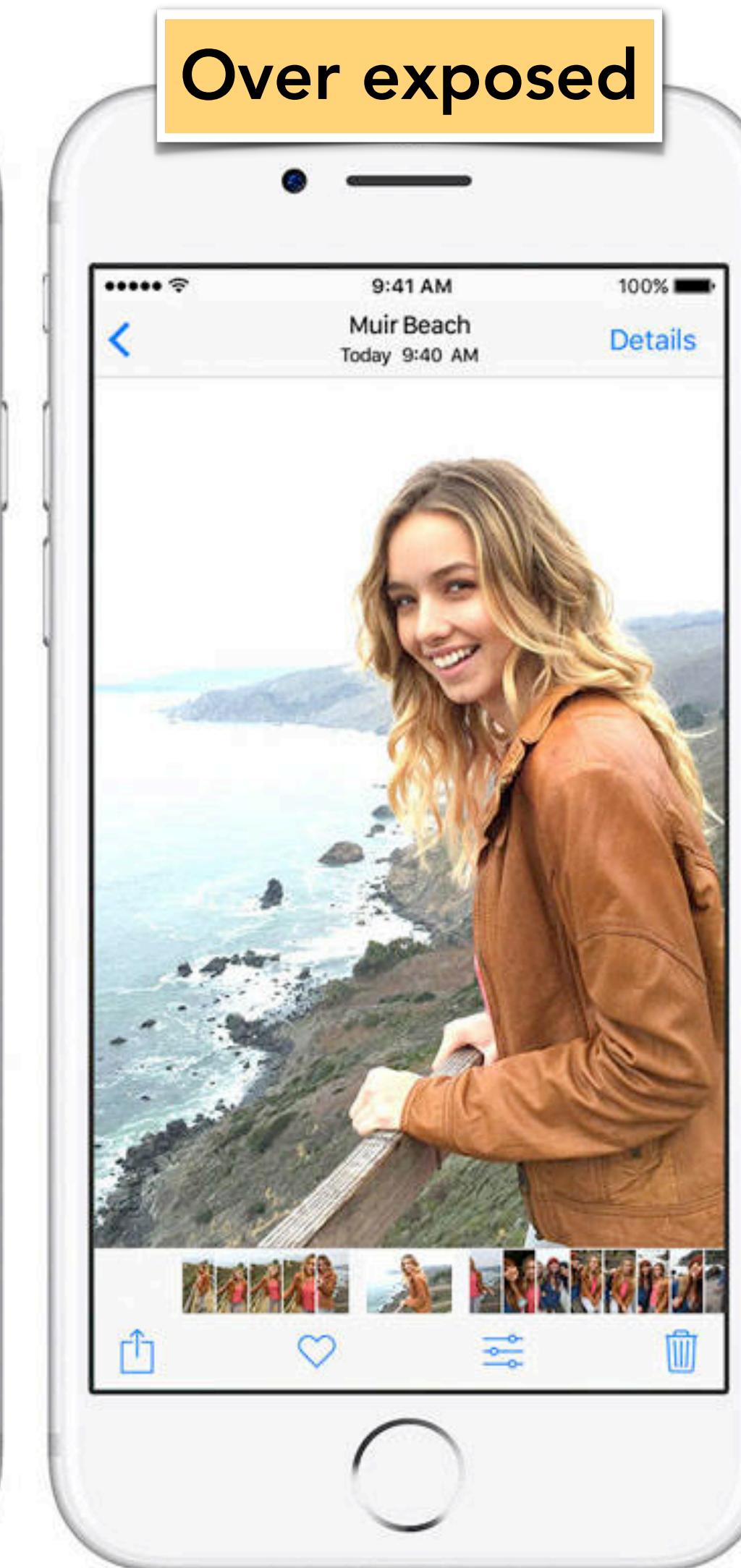
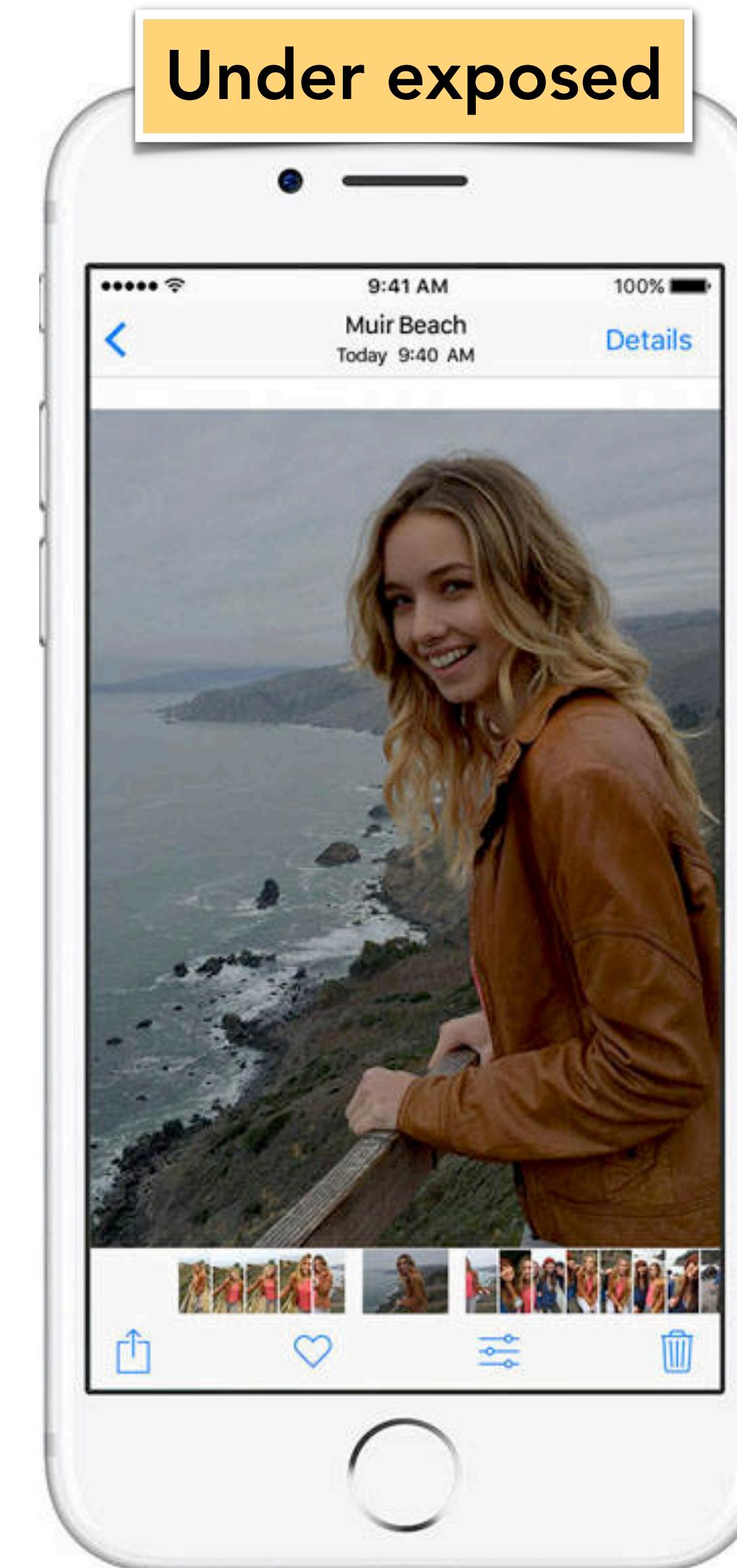
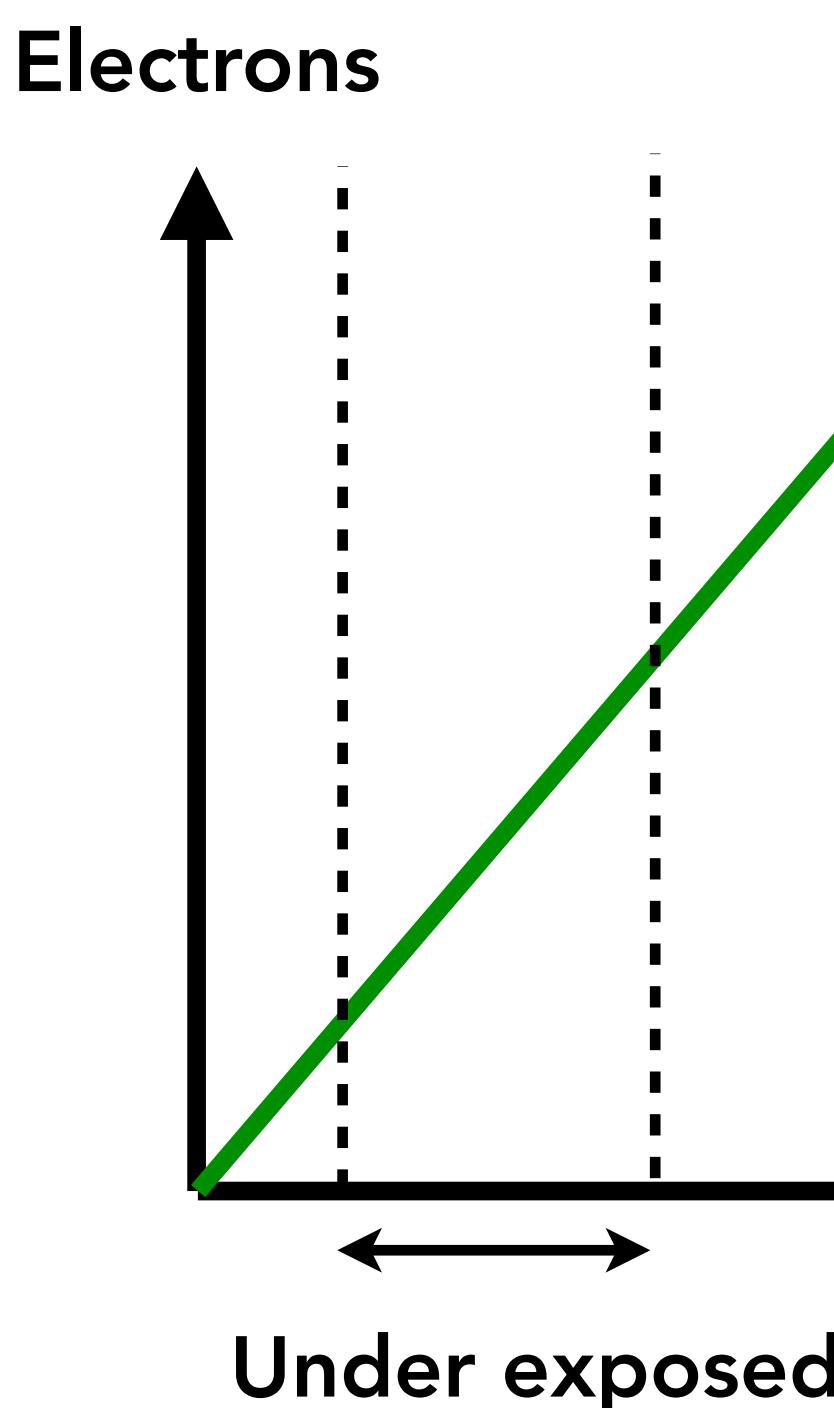
Over exposed



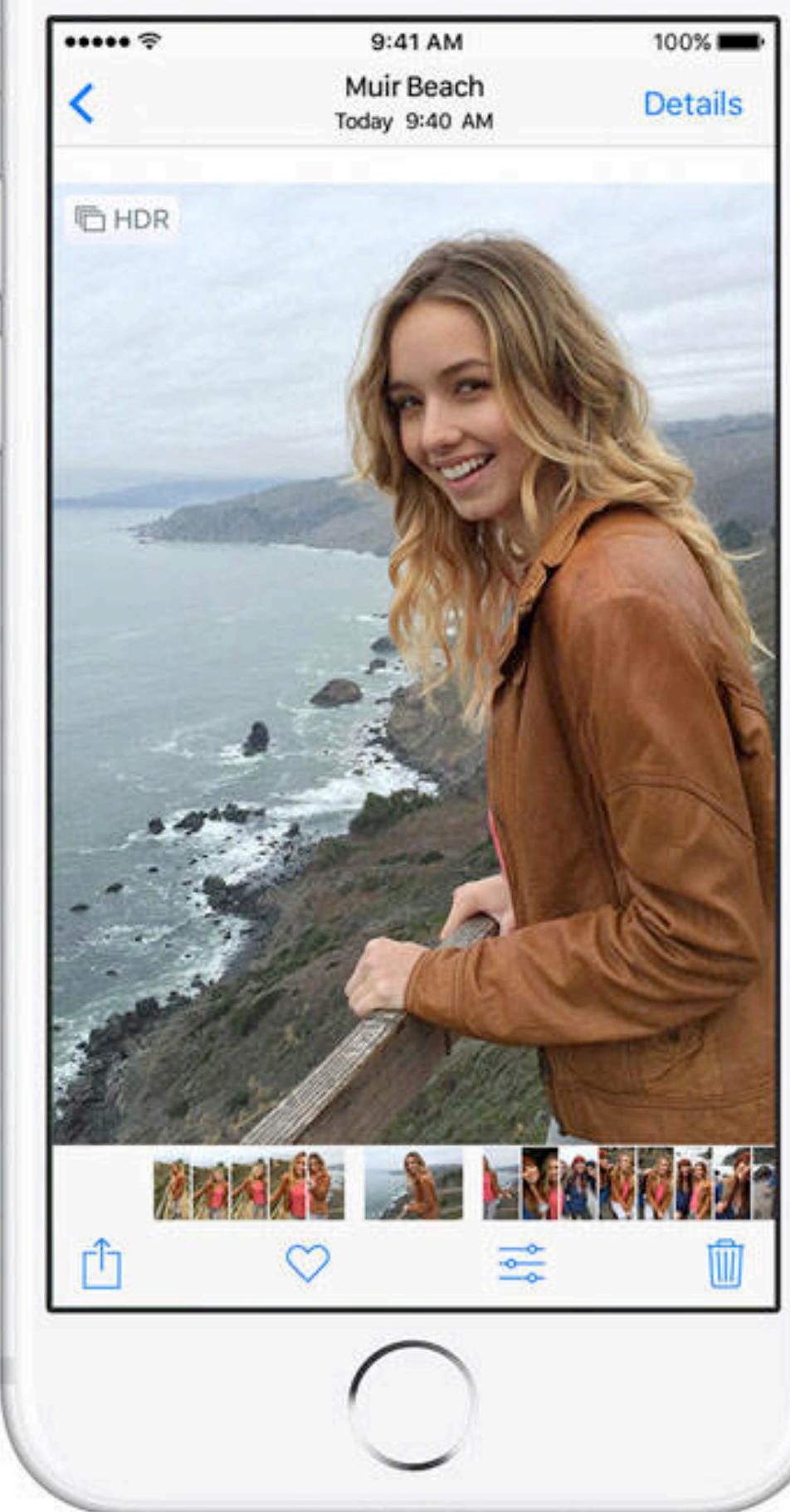
Need an HDR sensor or HDR algorithm.



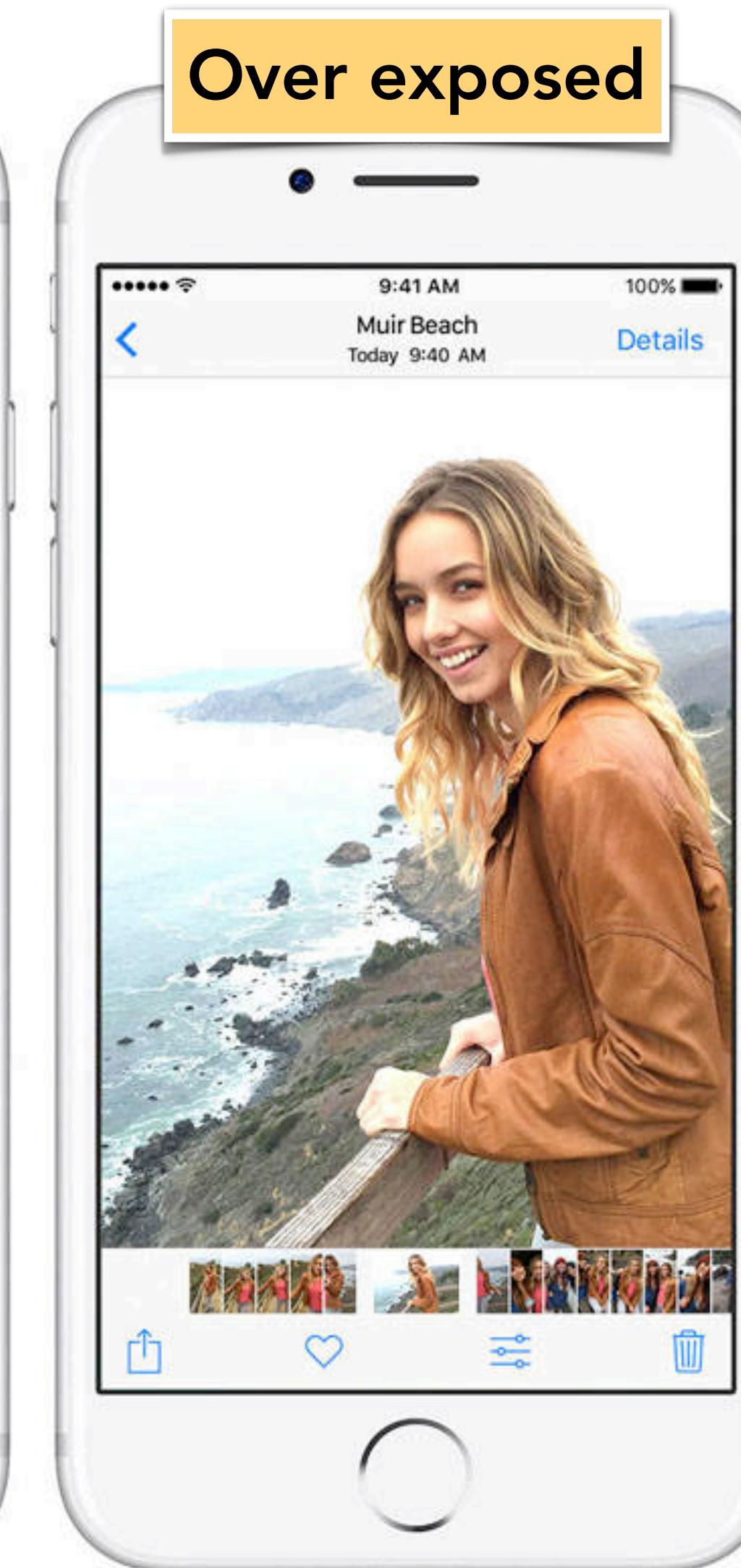
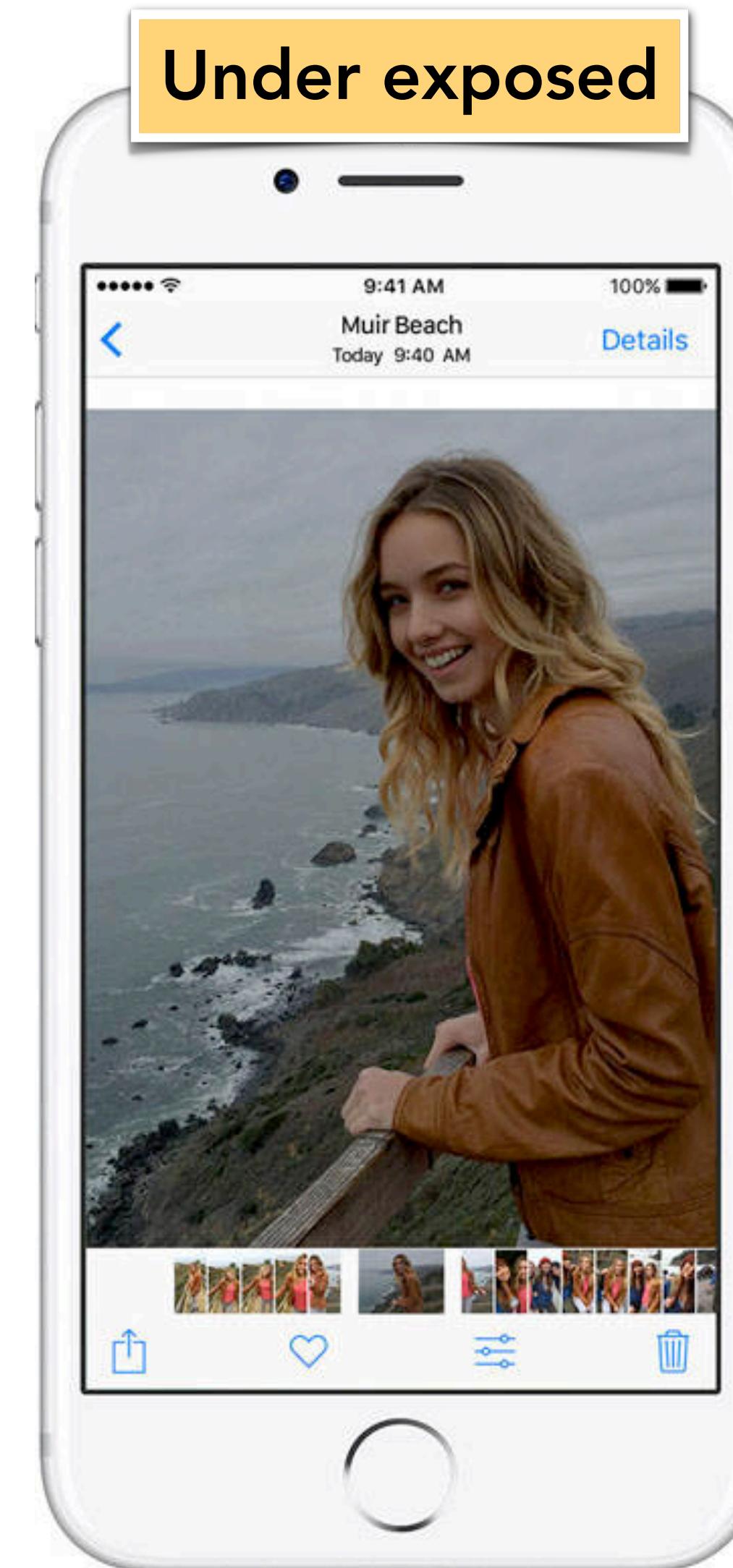
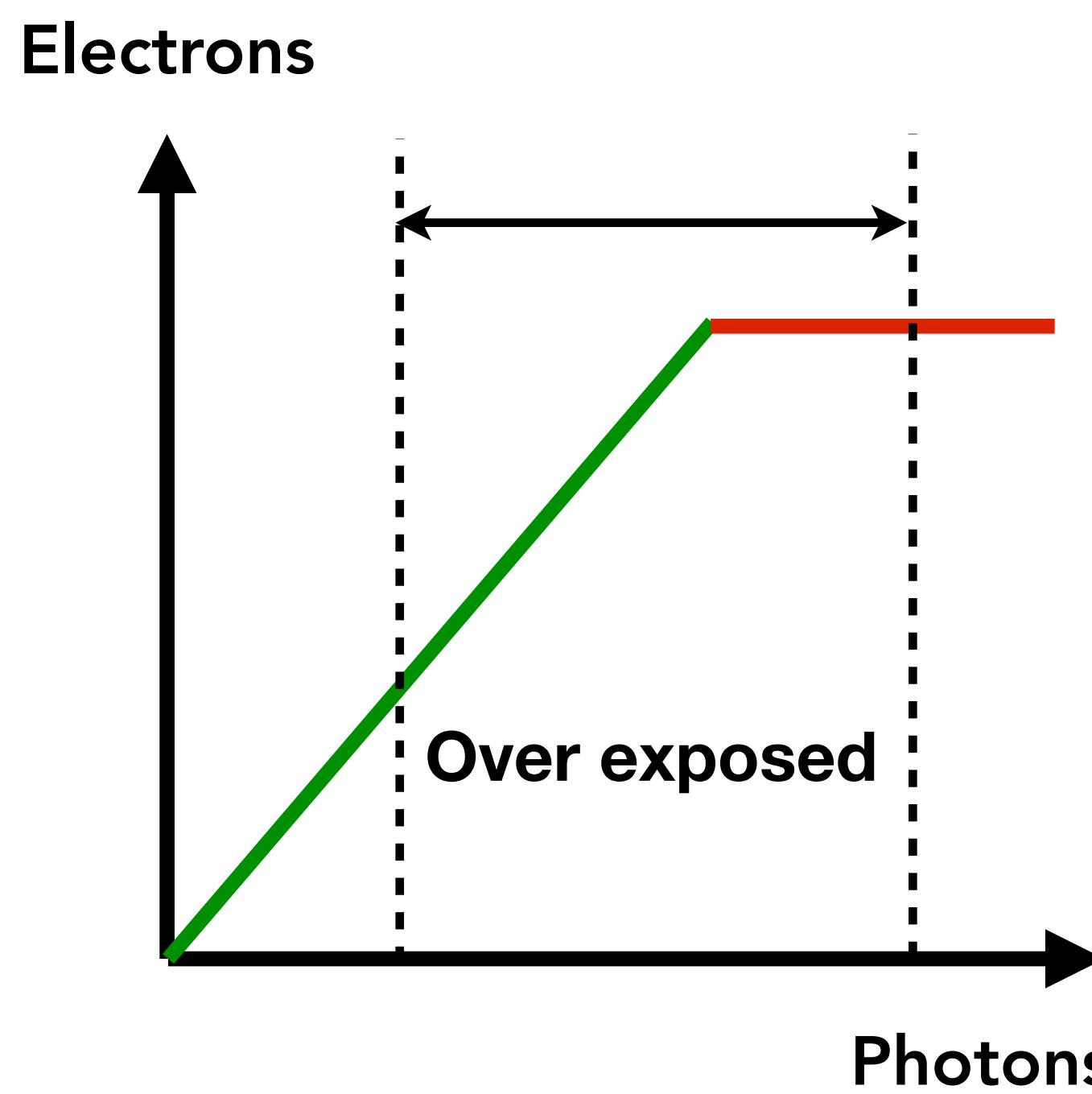
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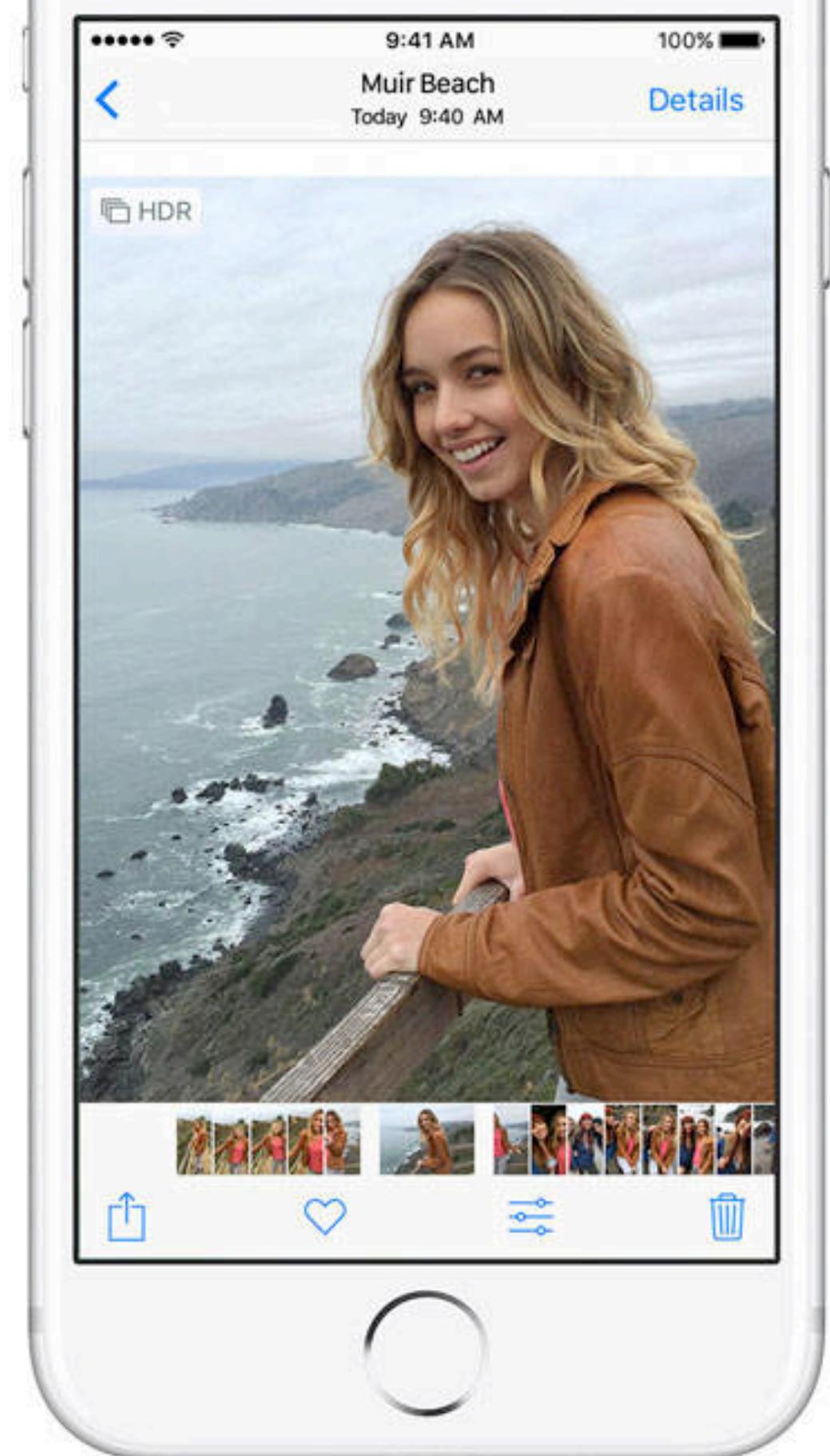
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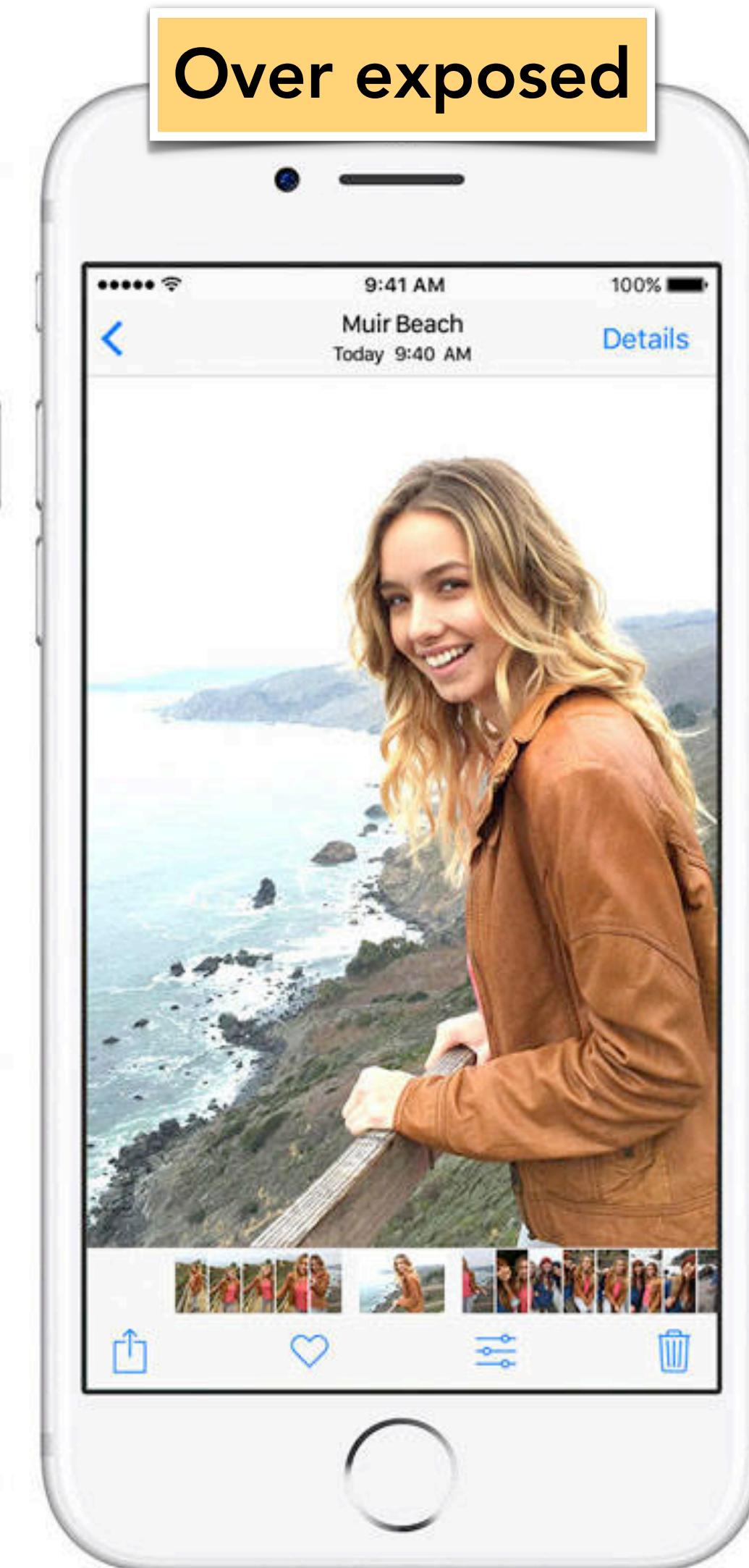
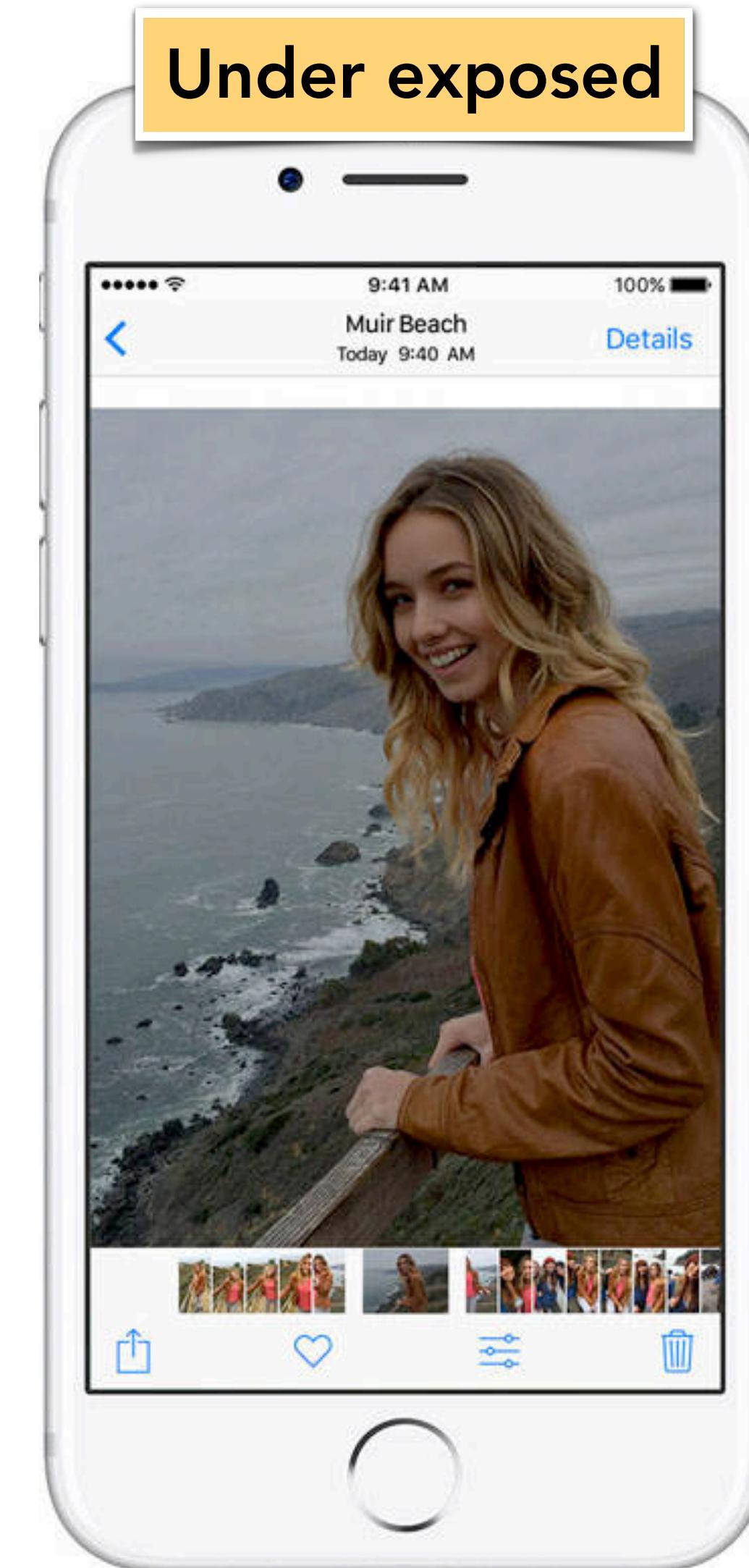
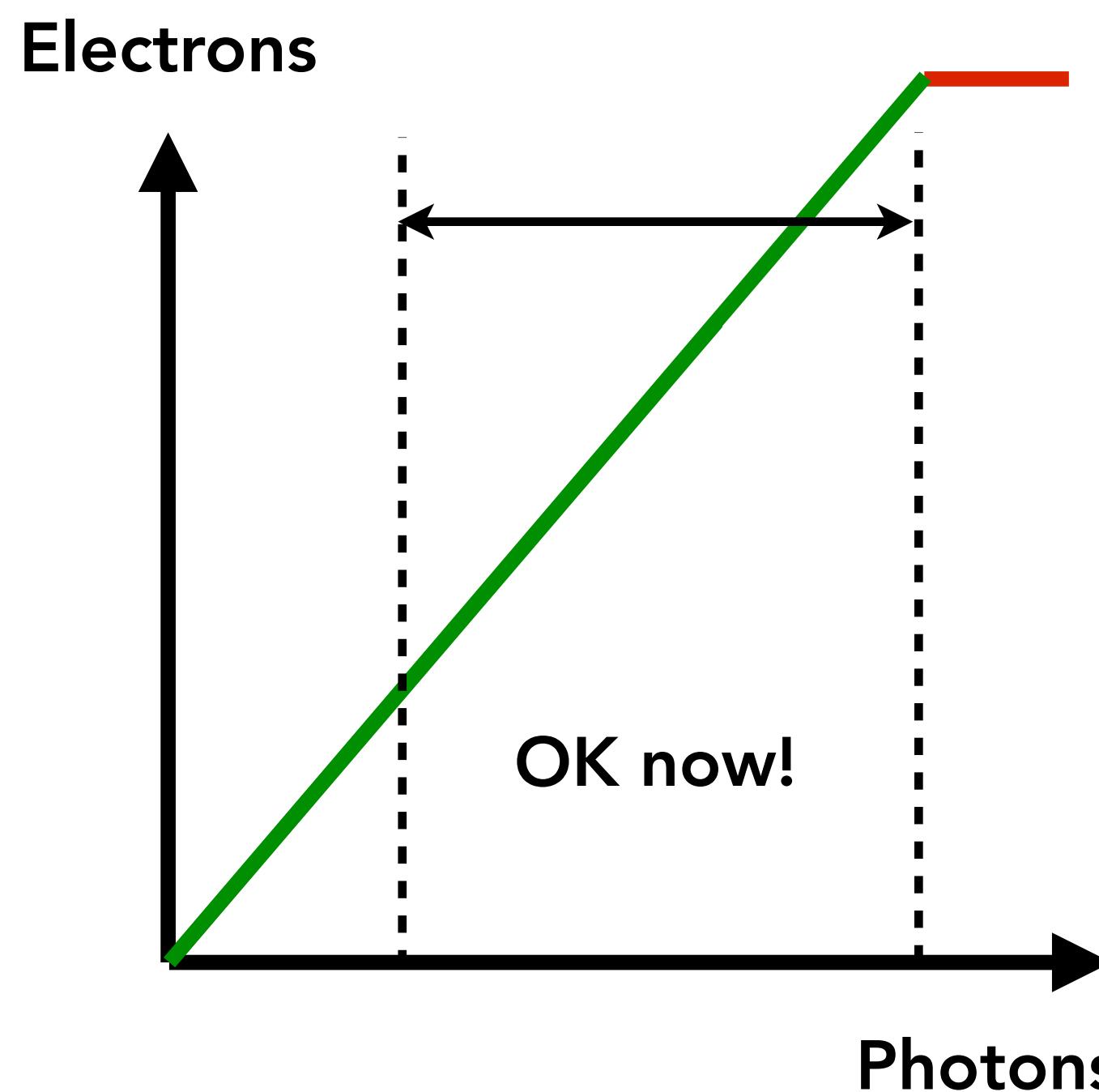
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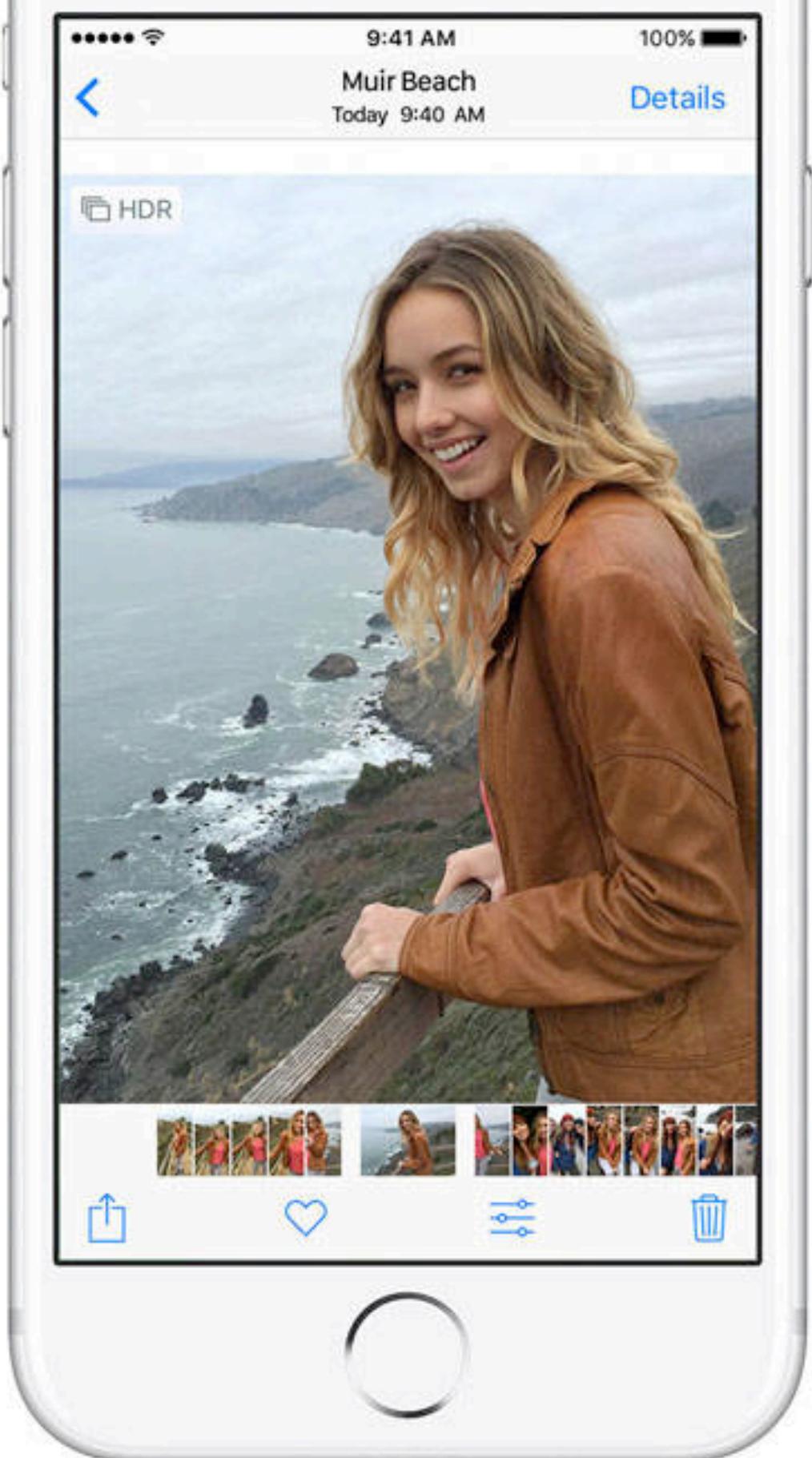
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Dynamic Range (Informal Treatment)



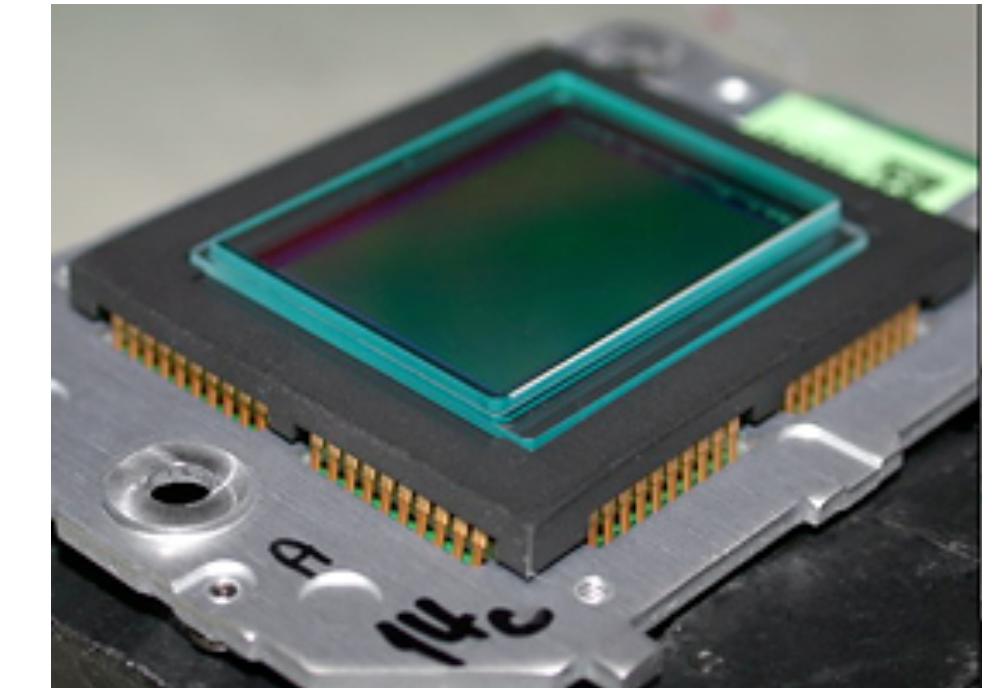
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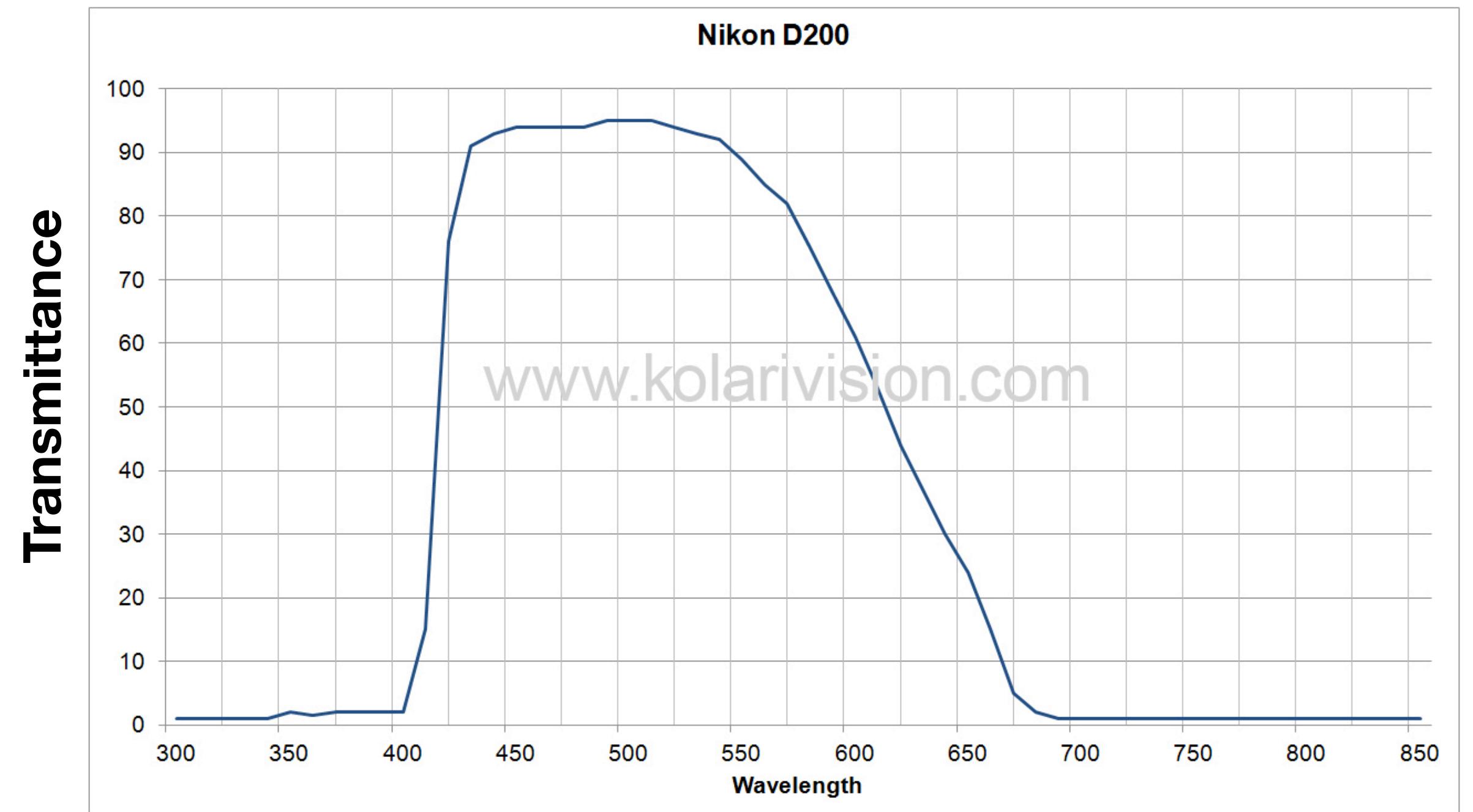
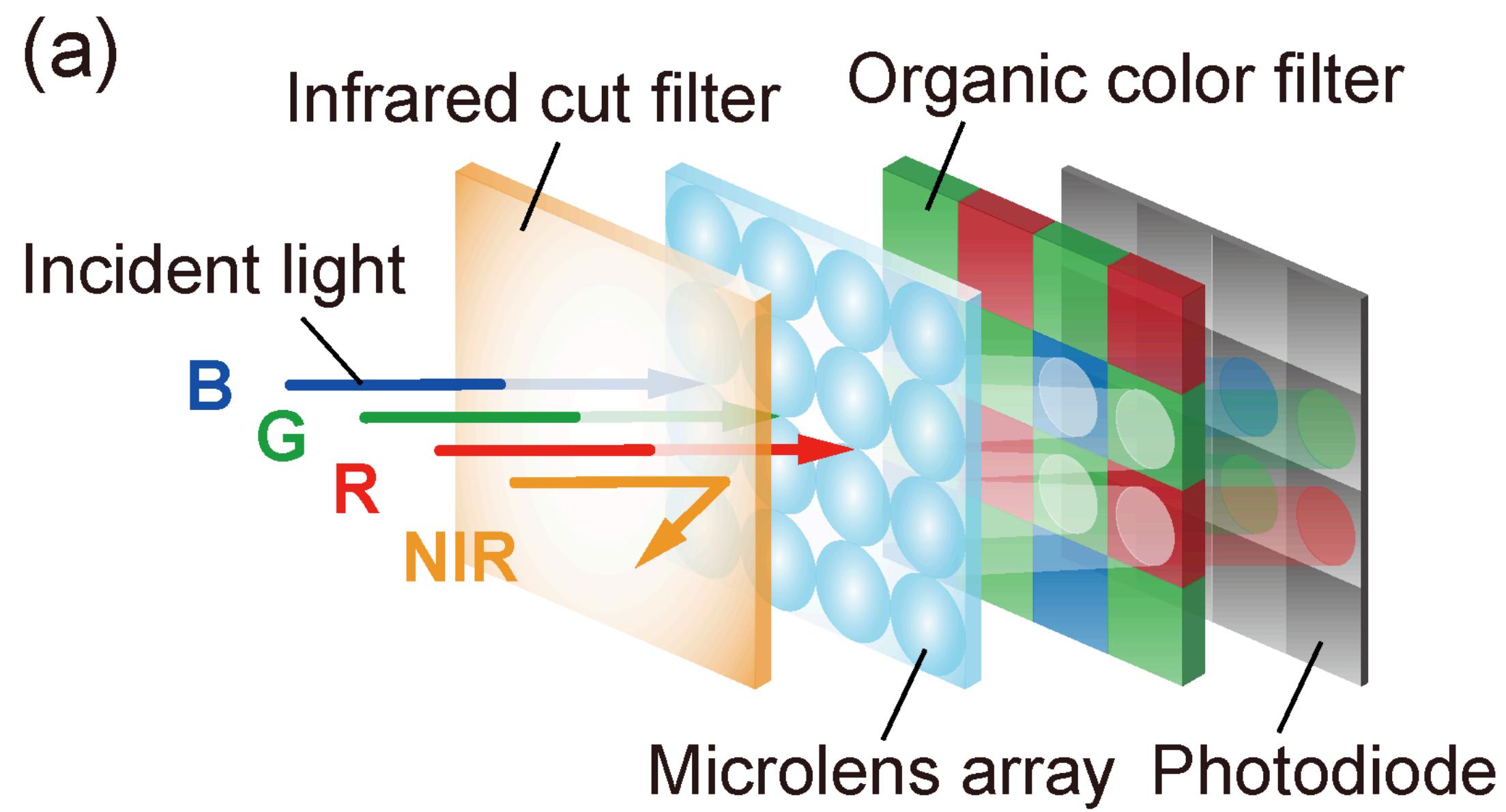
Optics in Sensor

Near IR/UV Filters

Remove IR/UV light. Low transmittance in IR/UV ranges.



Nikon D200



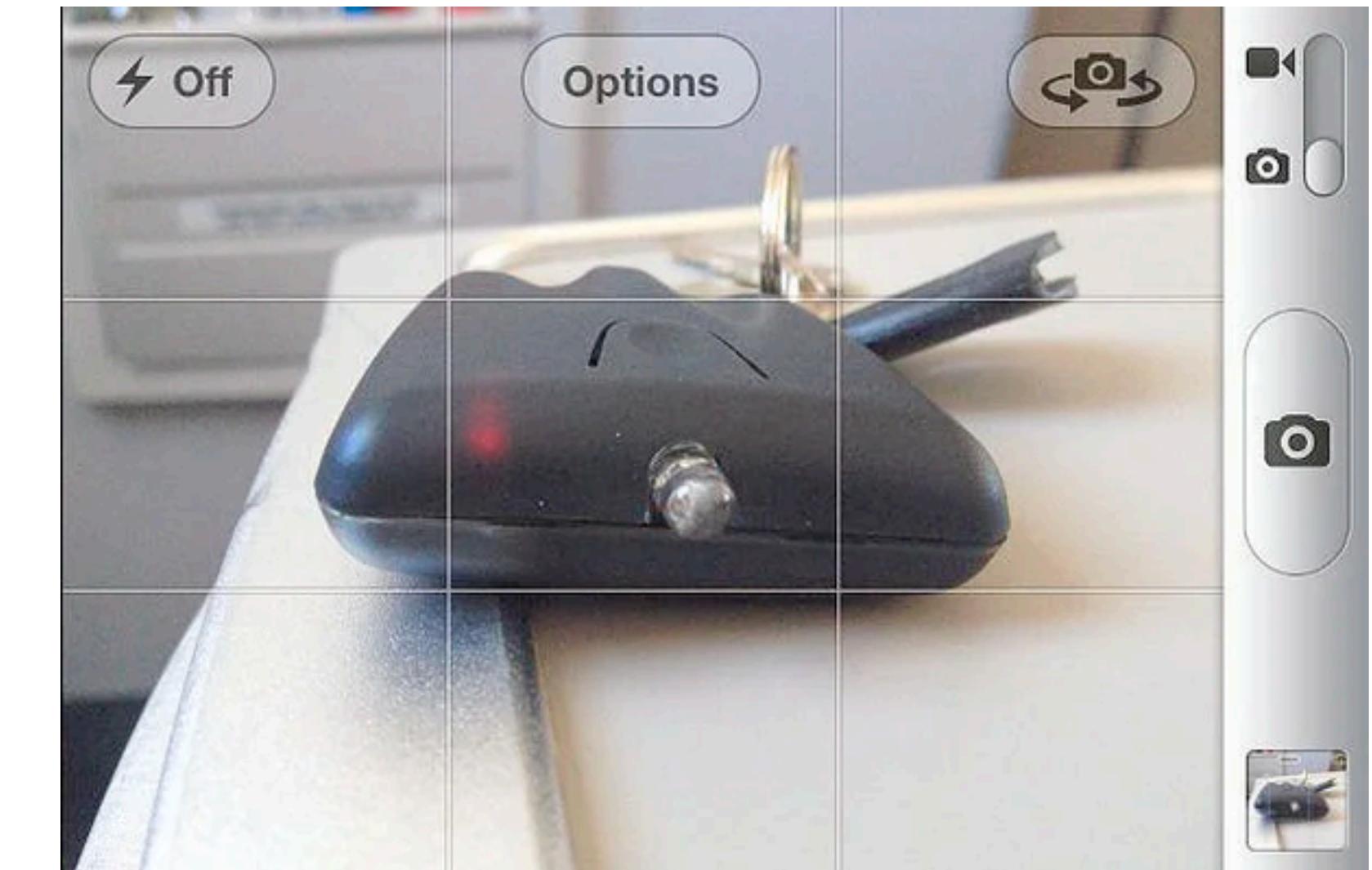
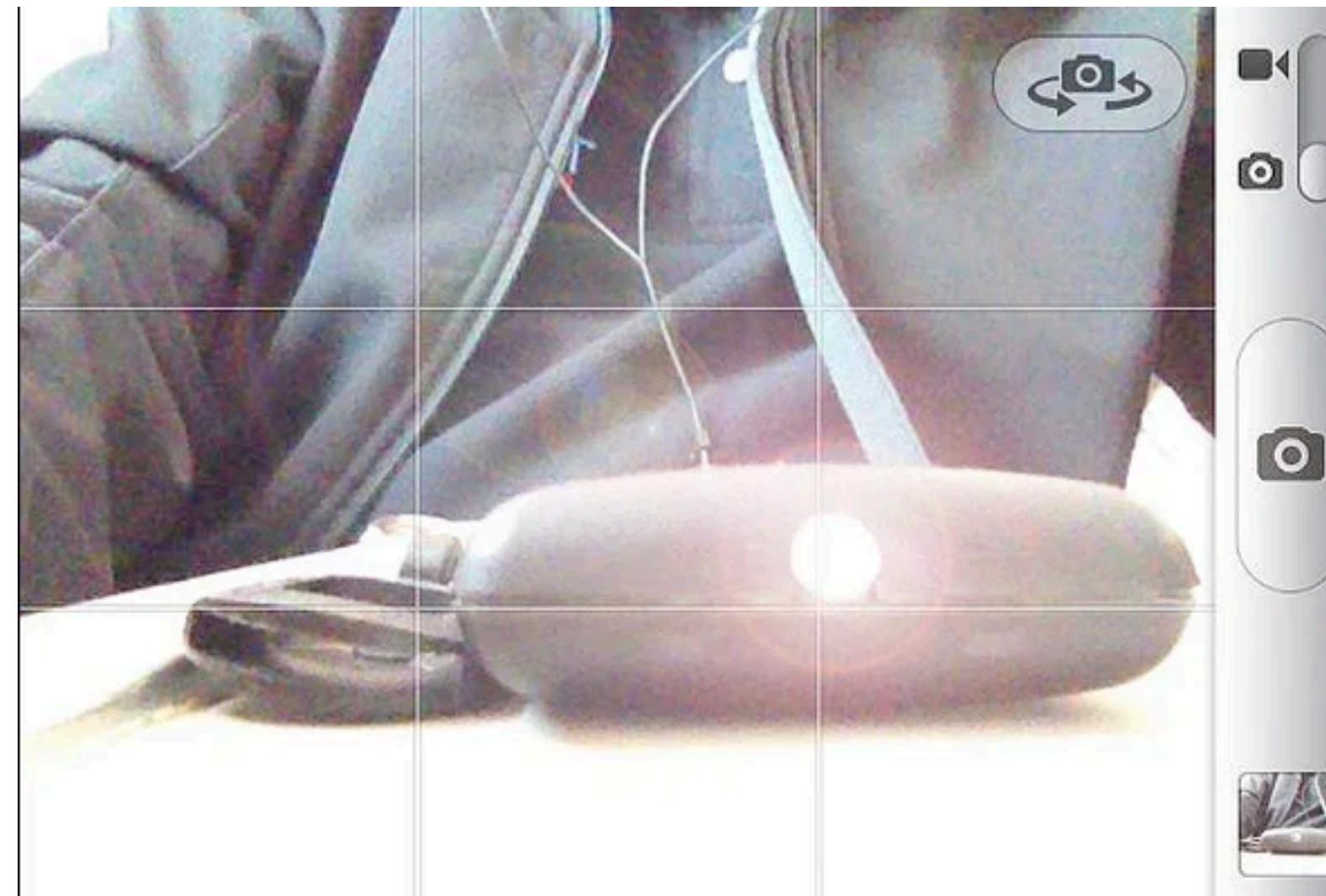
Near IR/UV Filters

Not all cameras do. What happens if you remove the NIR filter?

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Pointing a TV controller to the front and back cameras of iPhone 4.

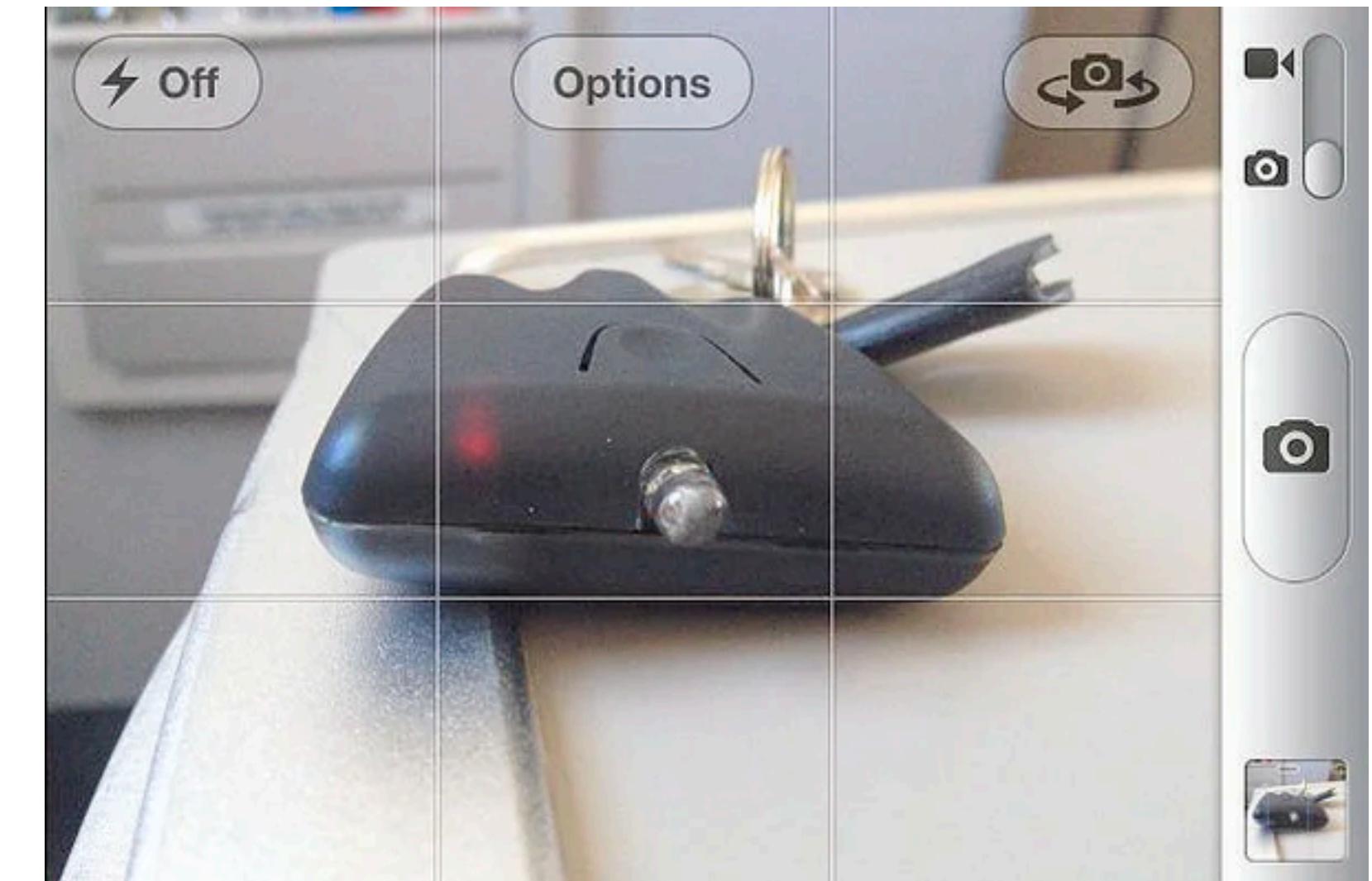
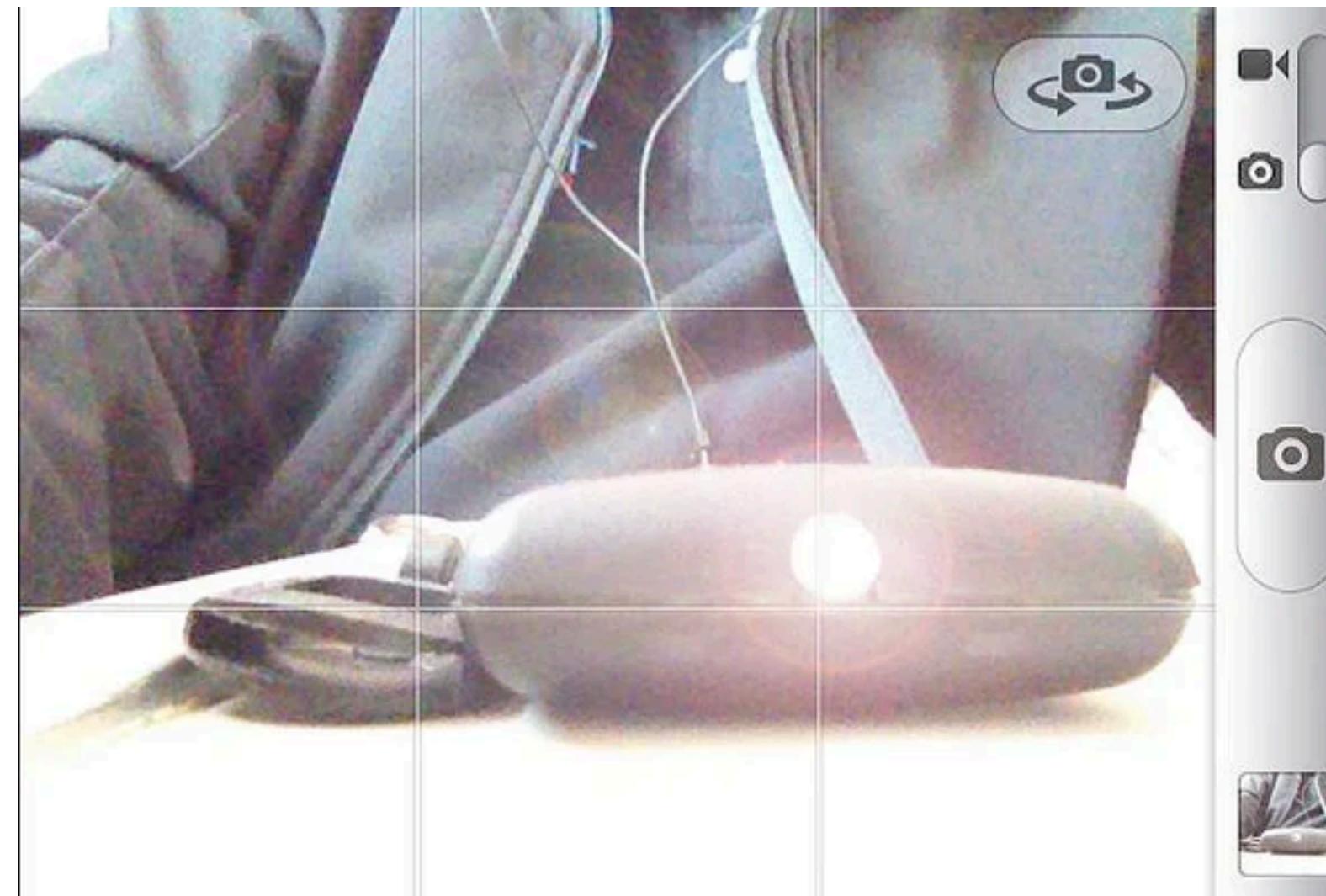


Near IR/UV Filters

Not all cameras do. What happens if you remove the NIR filter?

- See light that human eyes can't see. NIR photography (false color!).

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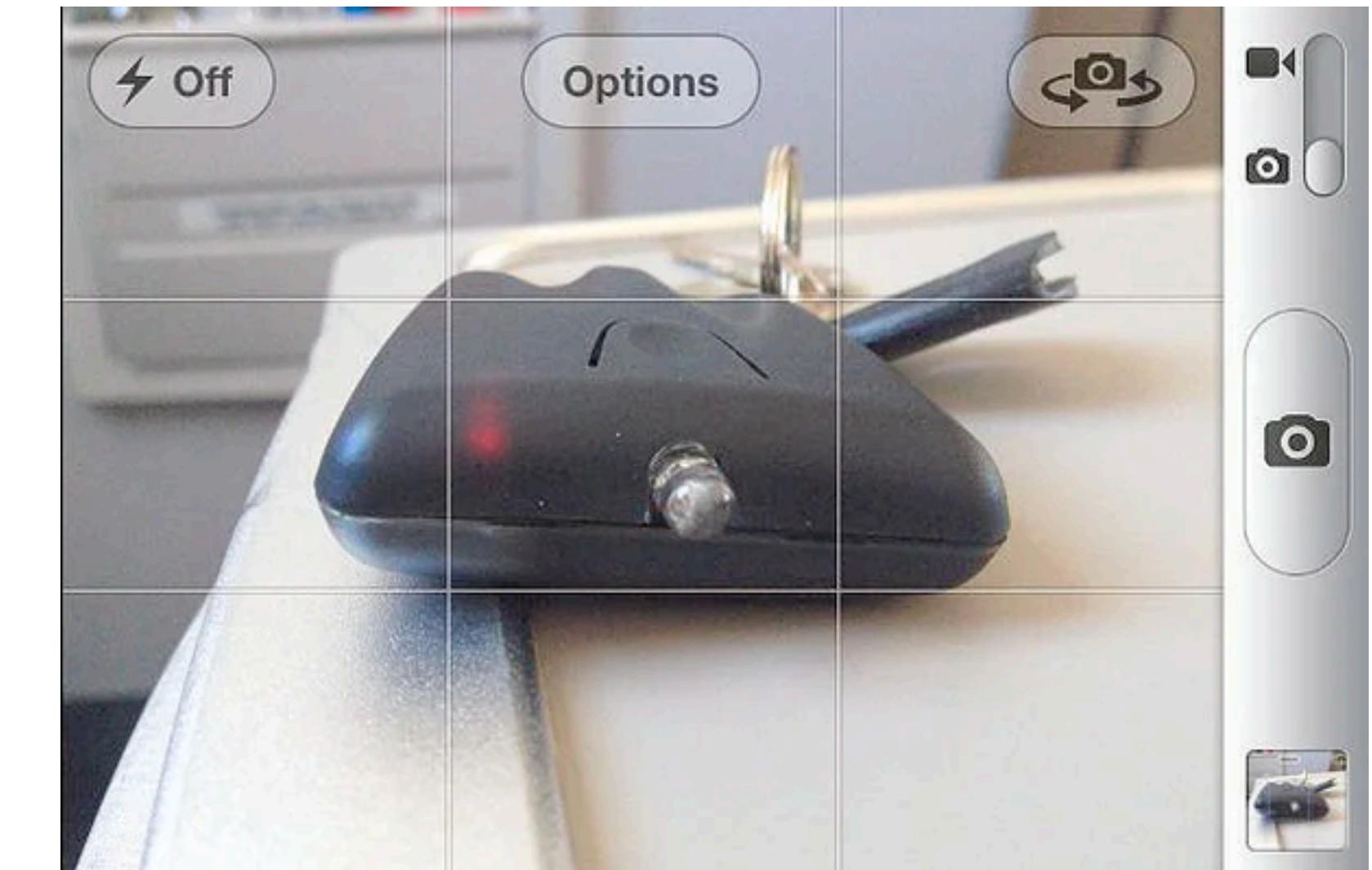
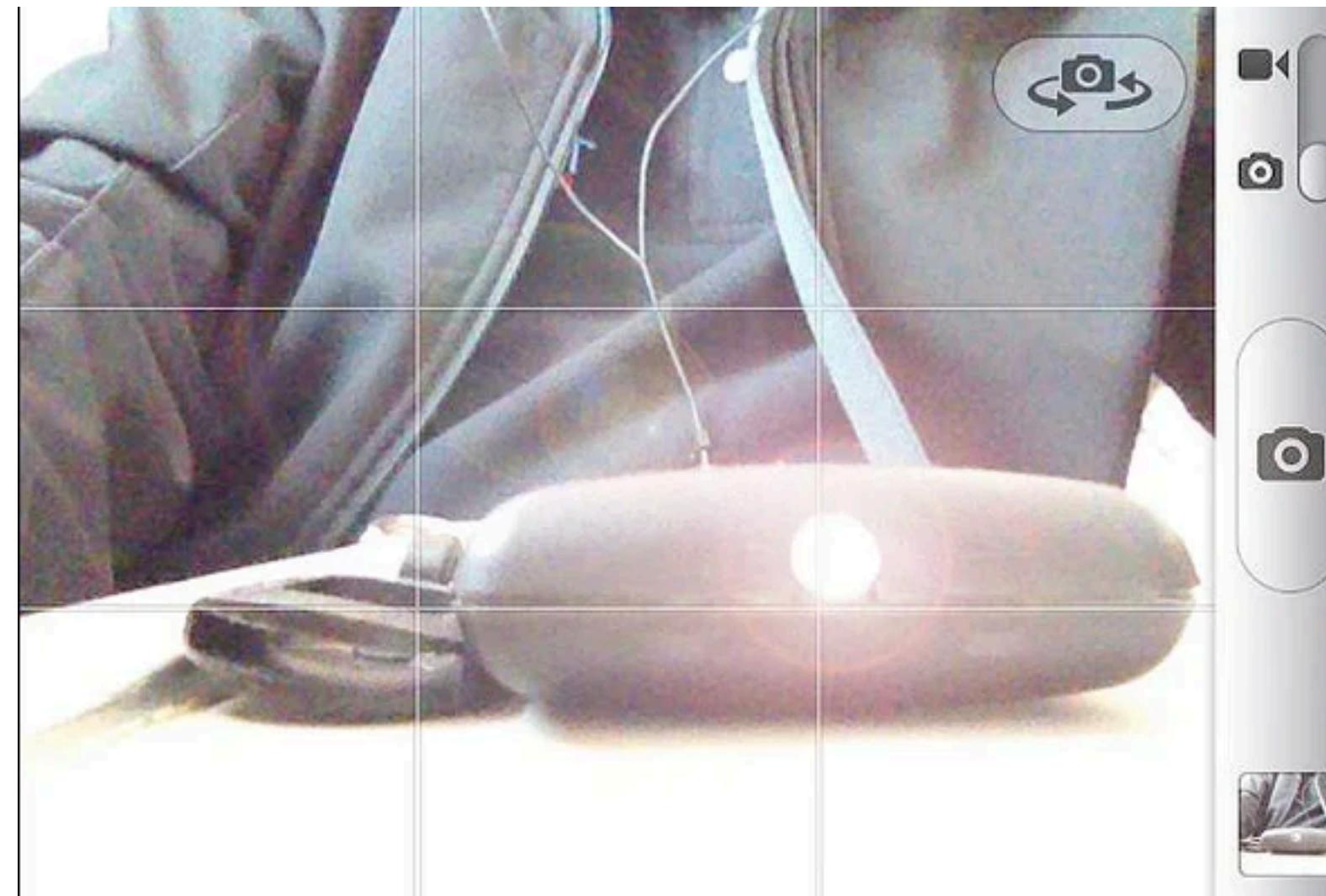


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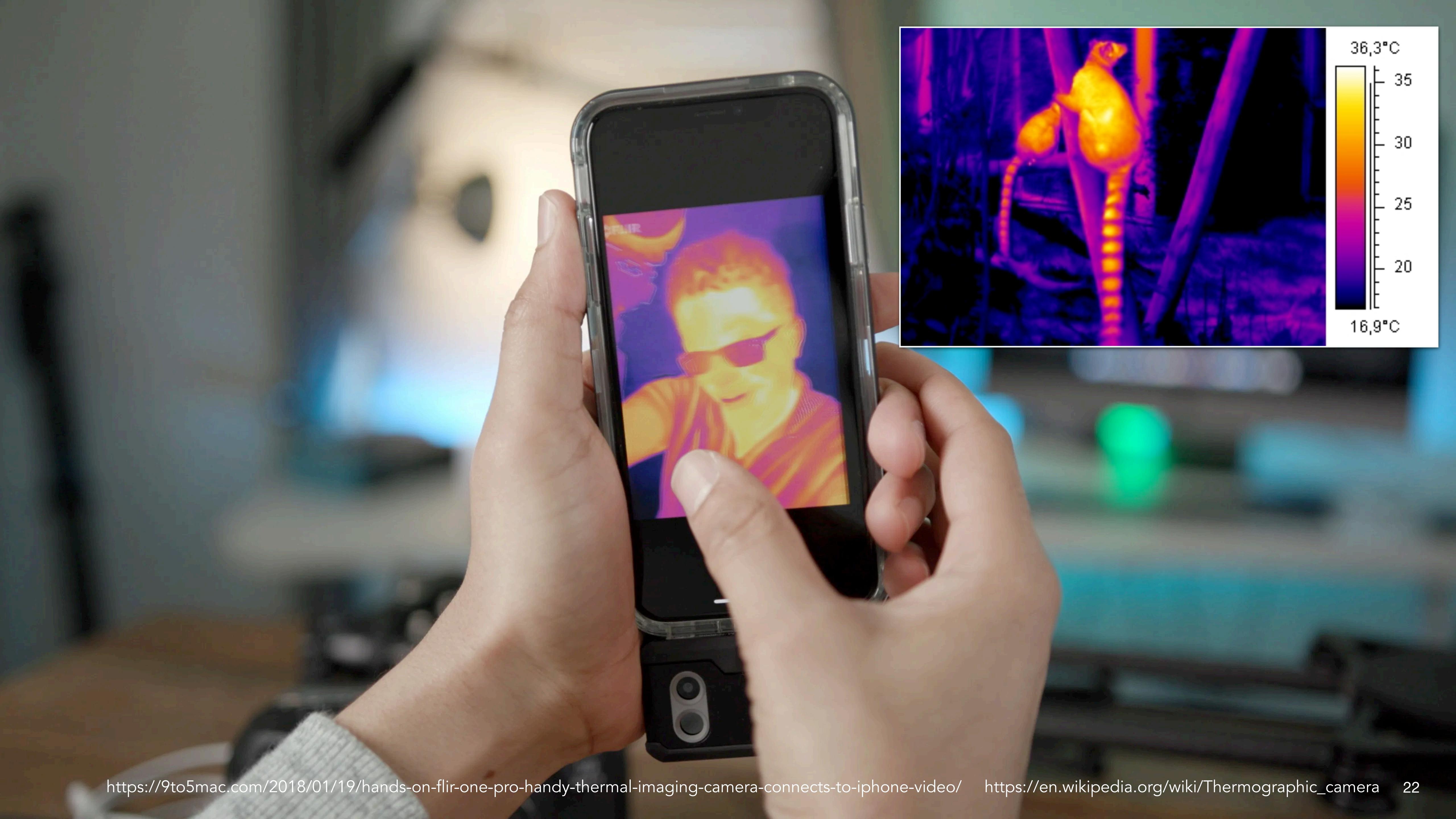
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- Thermographic cameras intentionally sense IR radiations to measure temperature.

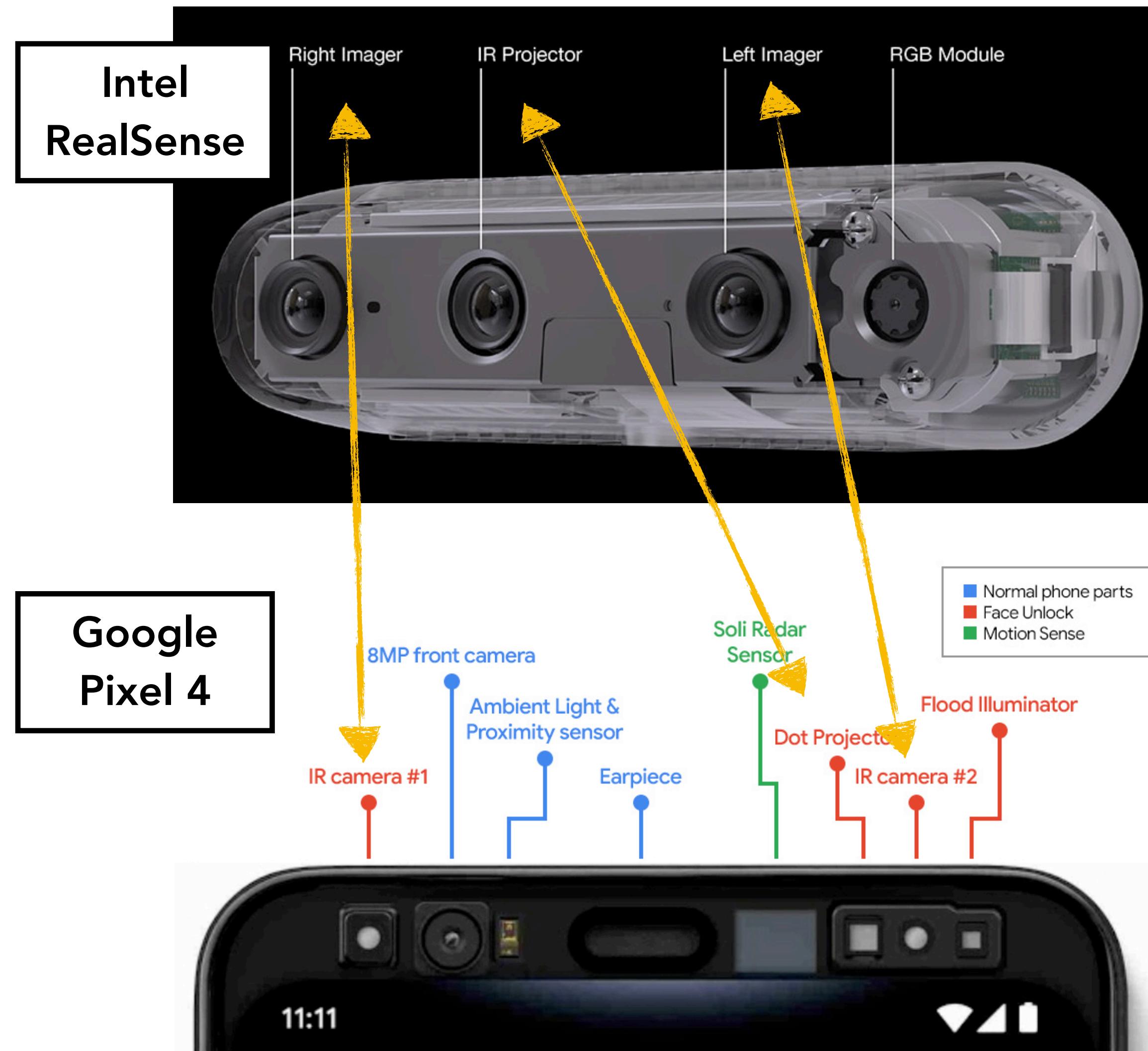
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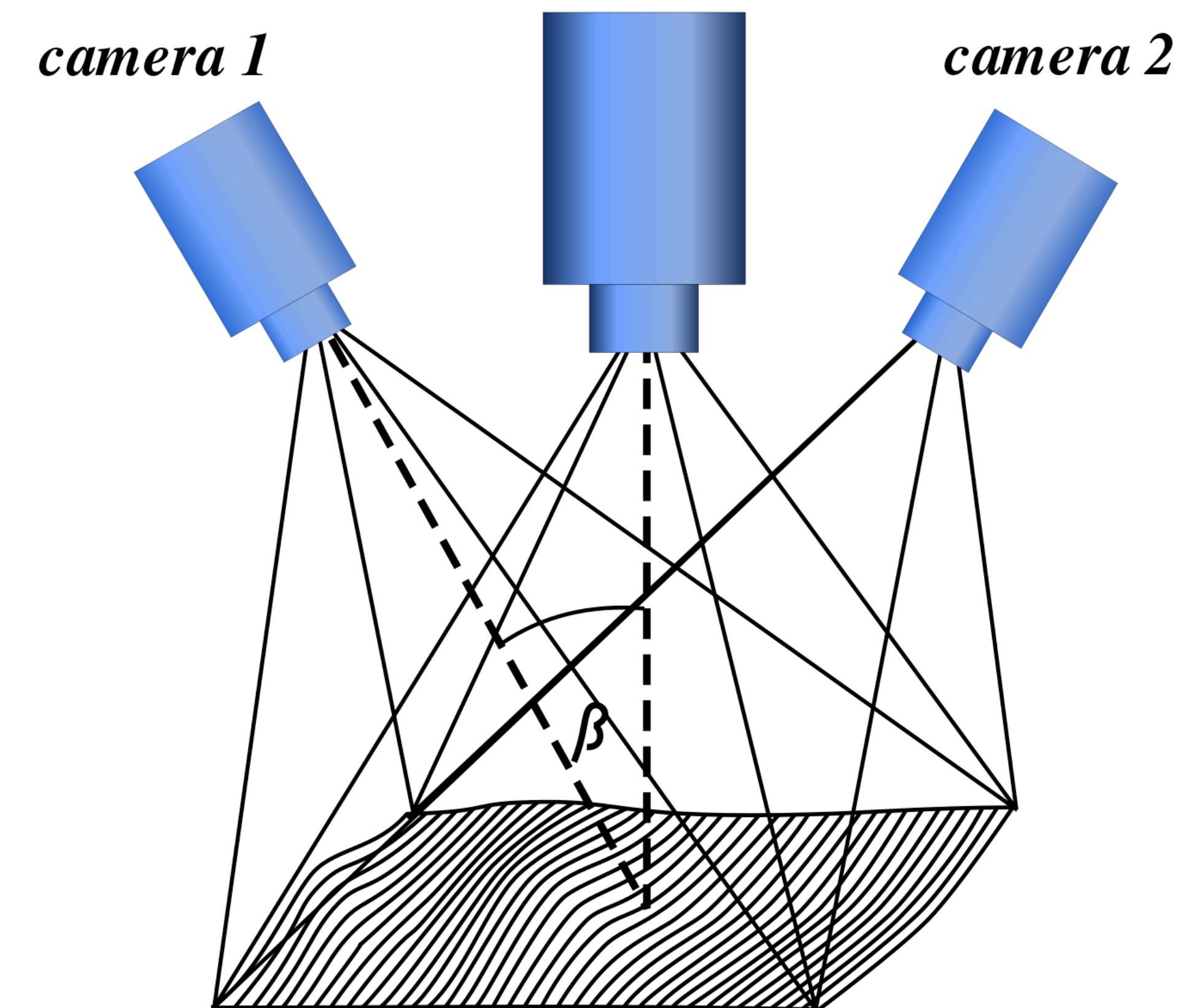




IR Sensor: Proximity and Depth (Later)



Depth from stereo (one depth cue of human eyes)
projector



Fill Factor (FF)

Fill factor is the percentage of the photosensitive area (i.e., photodiode) inside a pixel.

Much of the pixel area is occupied by circuitries other than the photodiodes, e.g., analog to digital conversion, read-out, wires, etc.

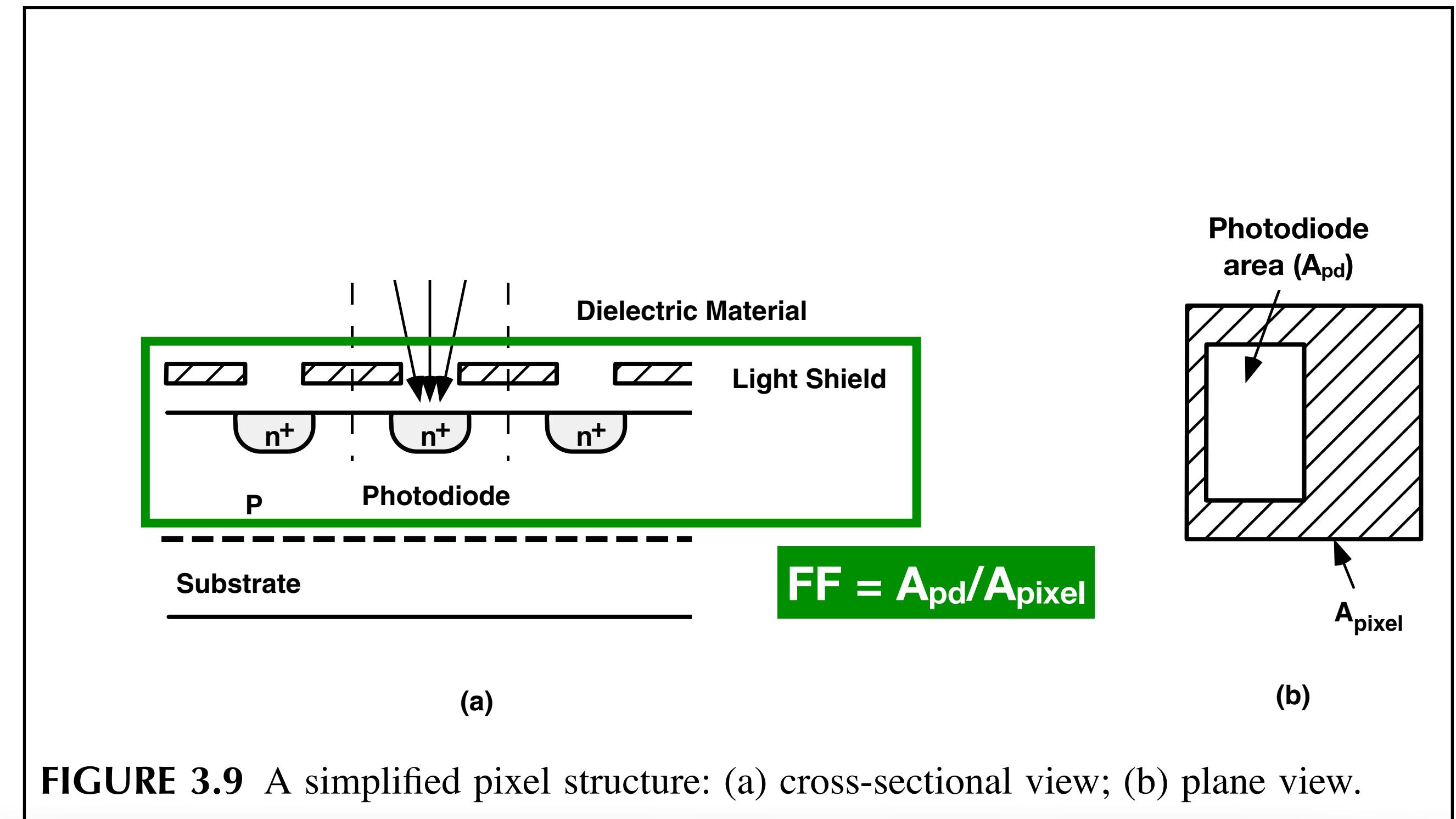


FIGURE 3.9 A simplified pixel structure: (a) cross-sectional view; (b) plane view.

Fill Factor (FF) and Microlenses

Fill factor affects the sensor dynamic range (higher FF leads to “larger” pixels).

Per-pixel microlenses help significantly increase the FF.

Organic PDs can reach almost 100% FF.

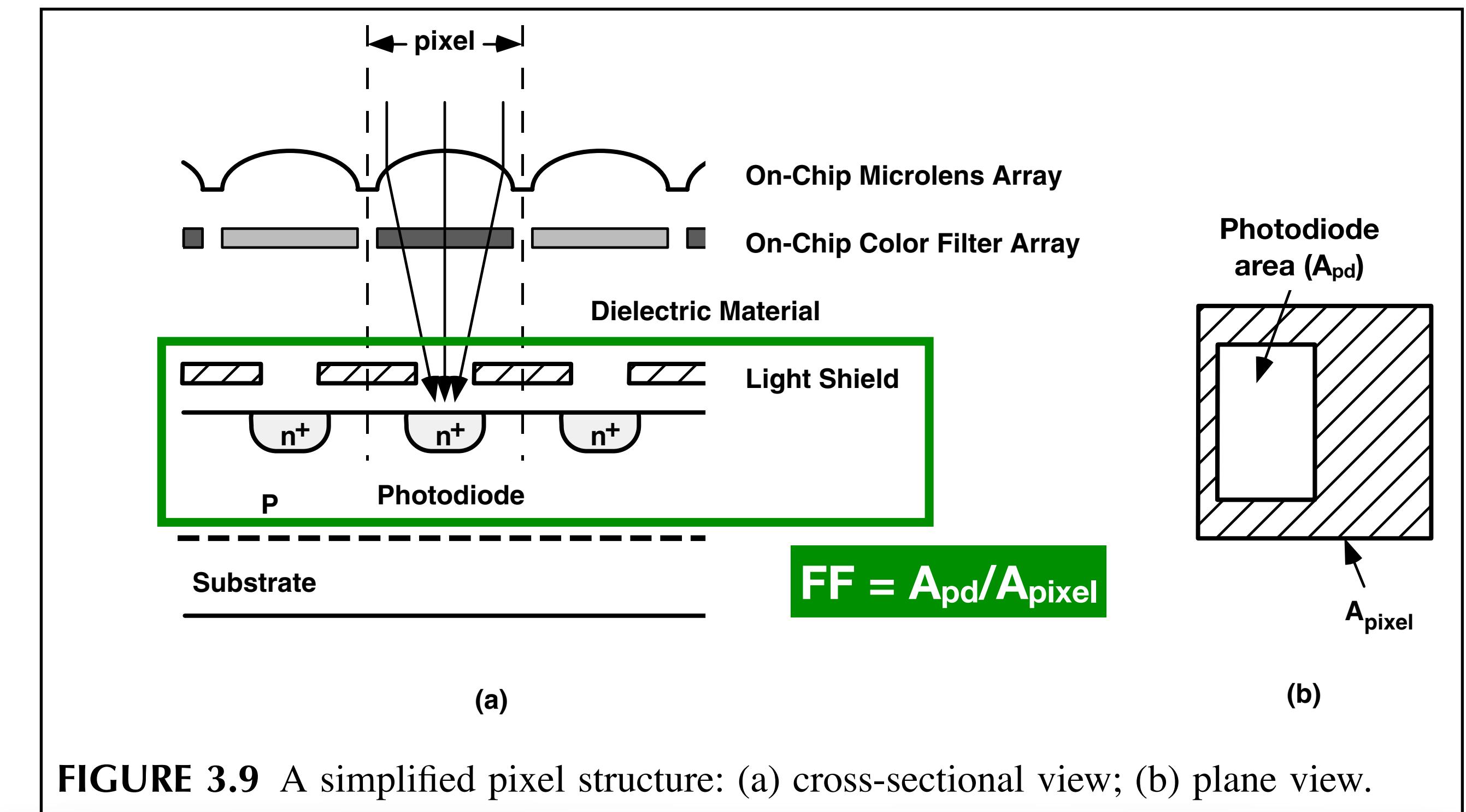
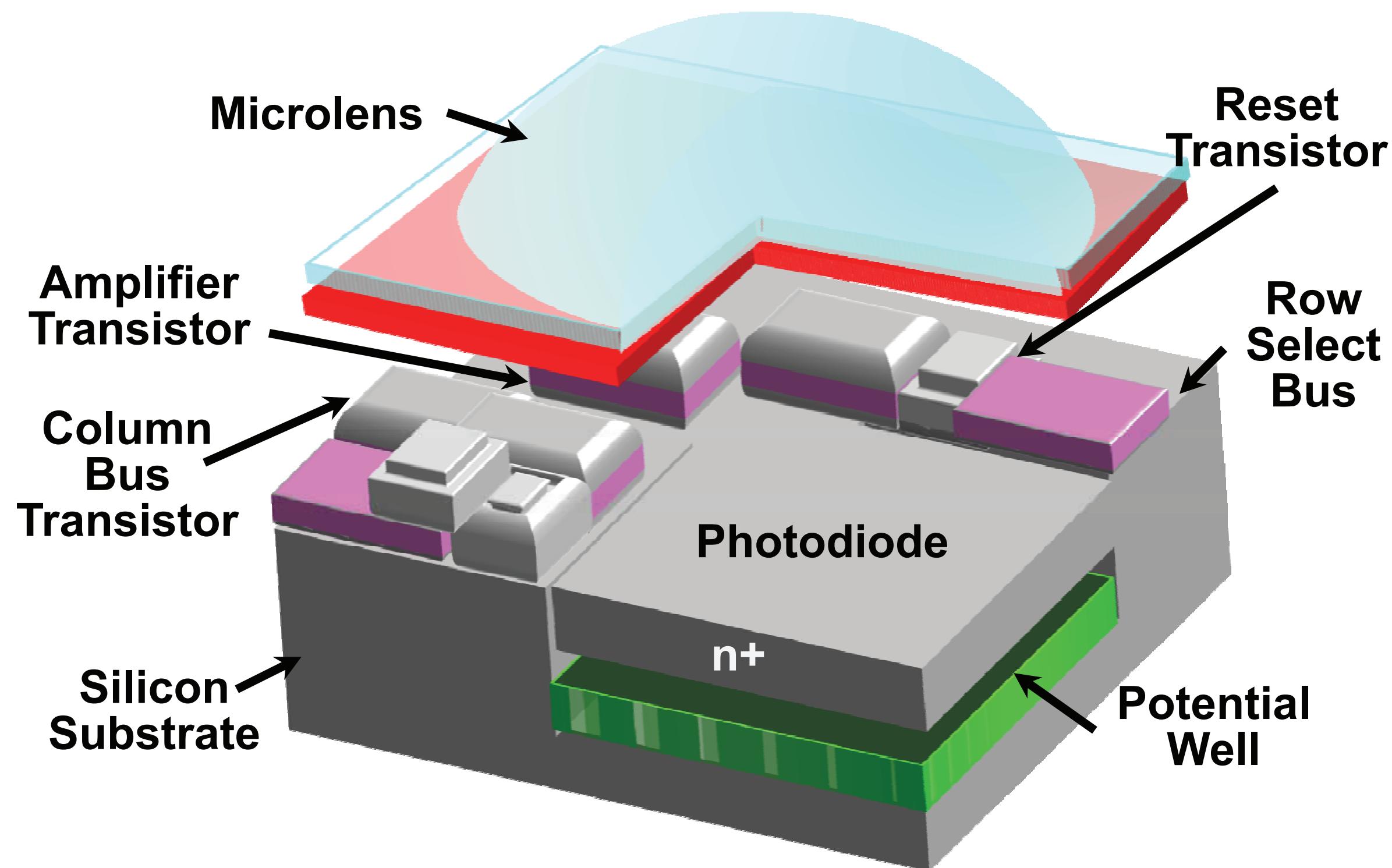


FIGURE 3.9 A simplified pixel structure: (a) cross-sectional view; (b) plane view.

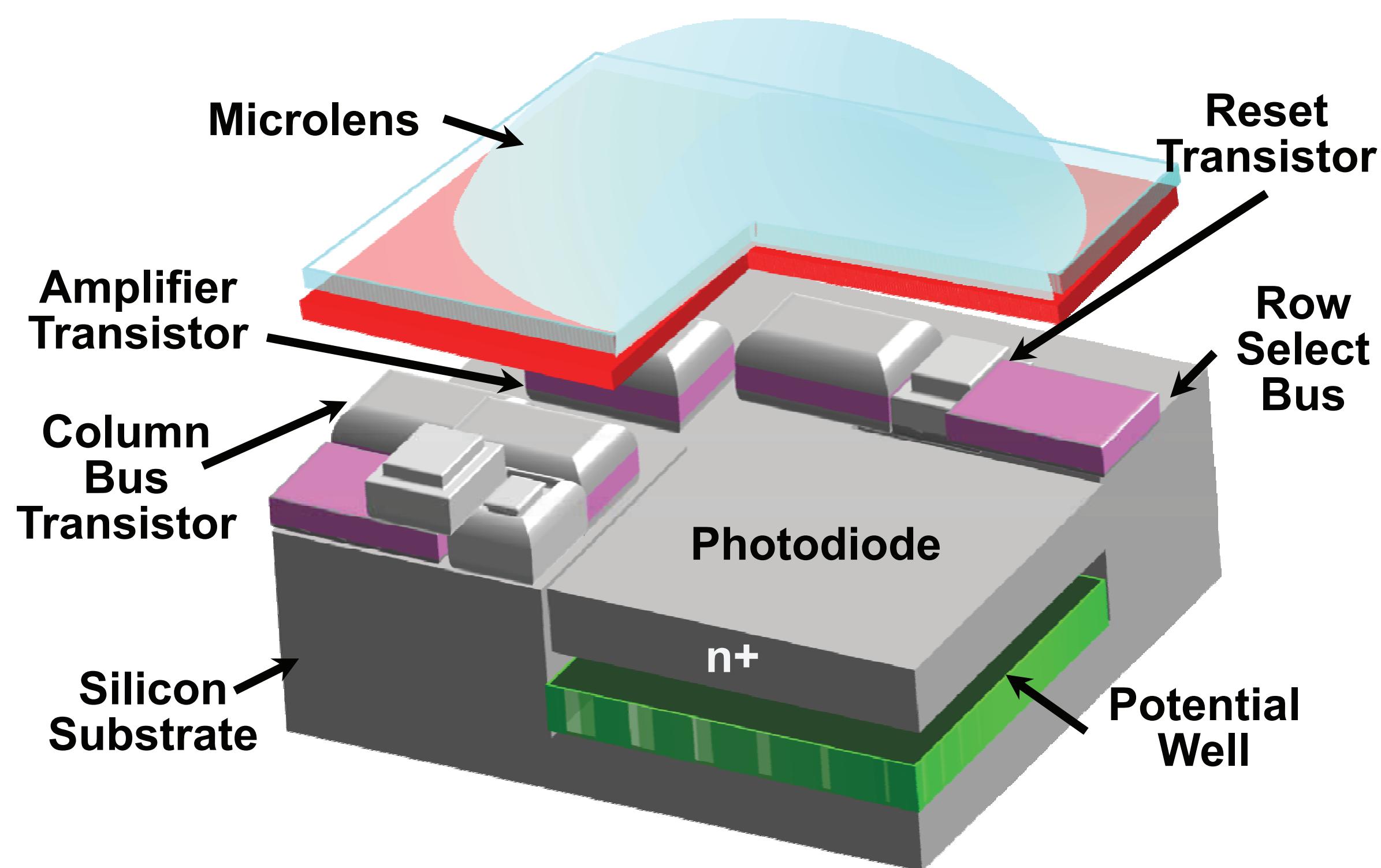
Anti-Aliasing by Micro-lenses and Pixels

Anatomy of the Active Pixel Sensor Photodiode



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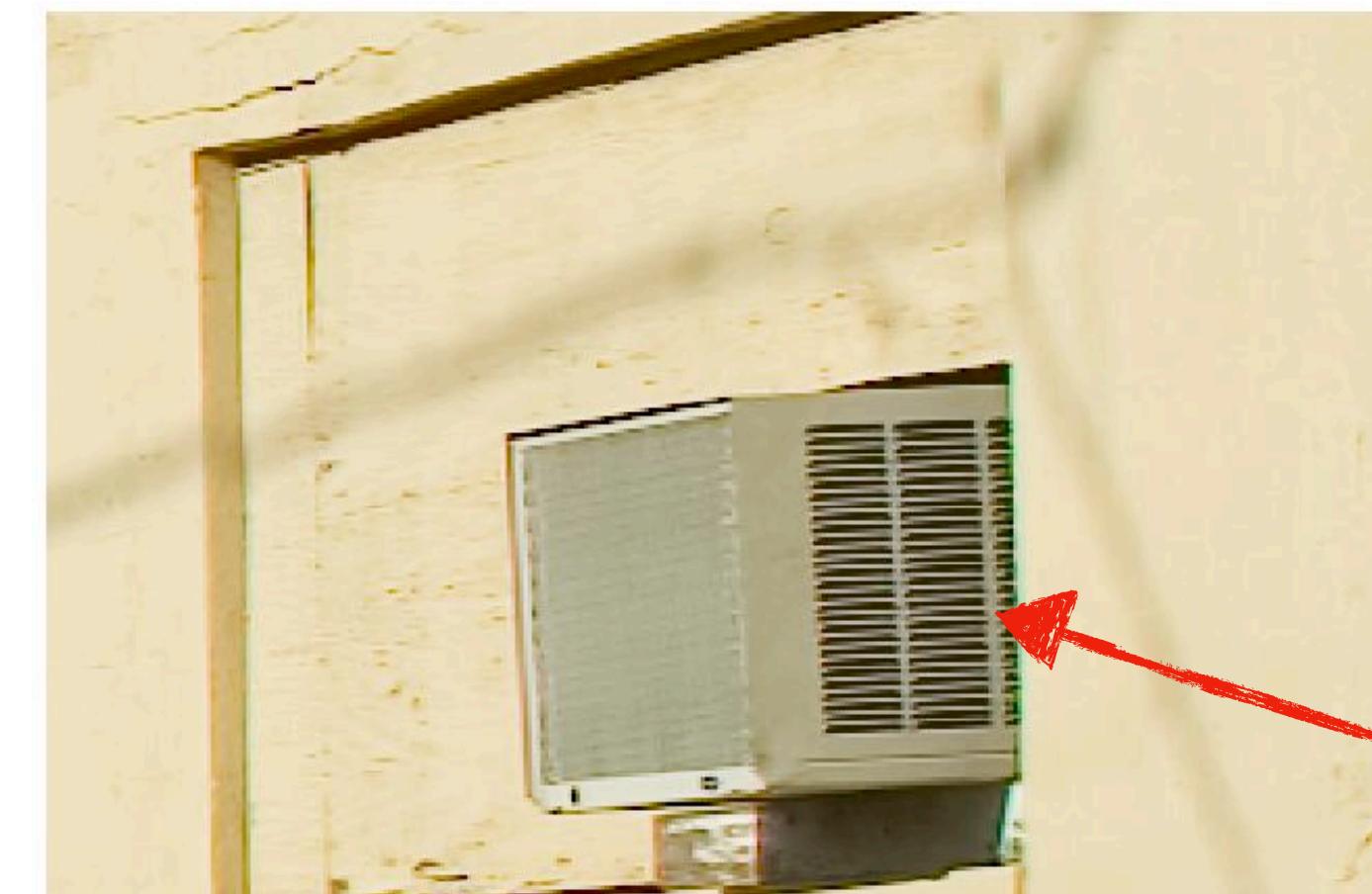


The micro-lenses (and the pixels under) inherently perform a spatial 2D box convolution (which is a low-pass filtering, acting as an anti-aliasing filter) followed by a 2D sampling, where a sample is taken at each pixel's center.

Anti-Aliasing Filter

Pixels perform spatial sampling, which introduces aliasing.

- Anti-aliasing by micro-lenses and pixels is not enough to combat aliasing.



Without AA filter.
Nikon D80e.

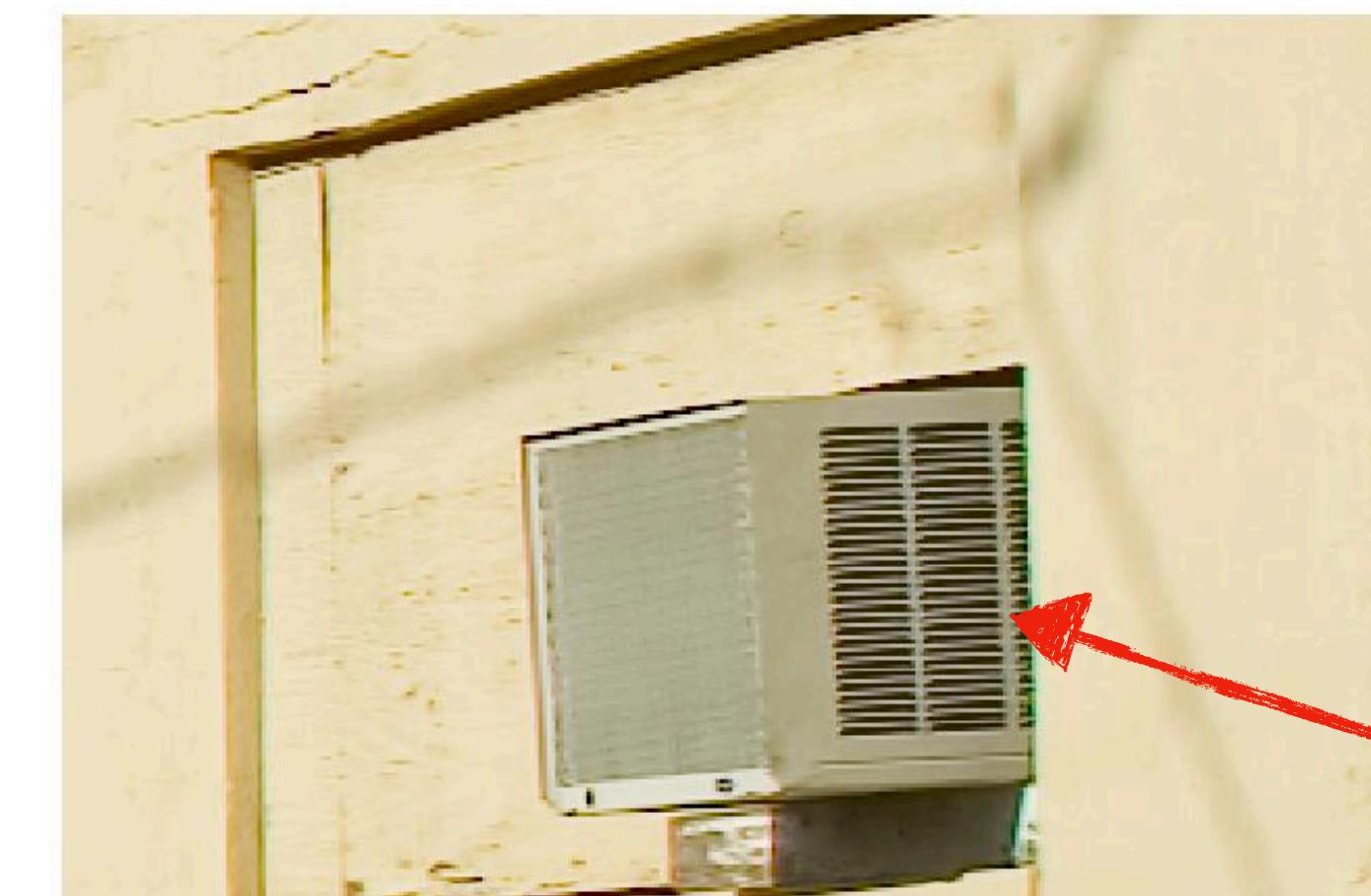
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Use **anti-aliasing filters** (low-pass filter) to remove high spatial-frequency component in light, effectively **blurring** the image.



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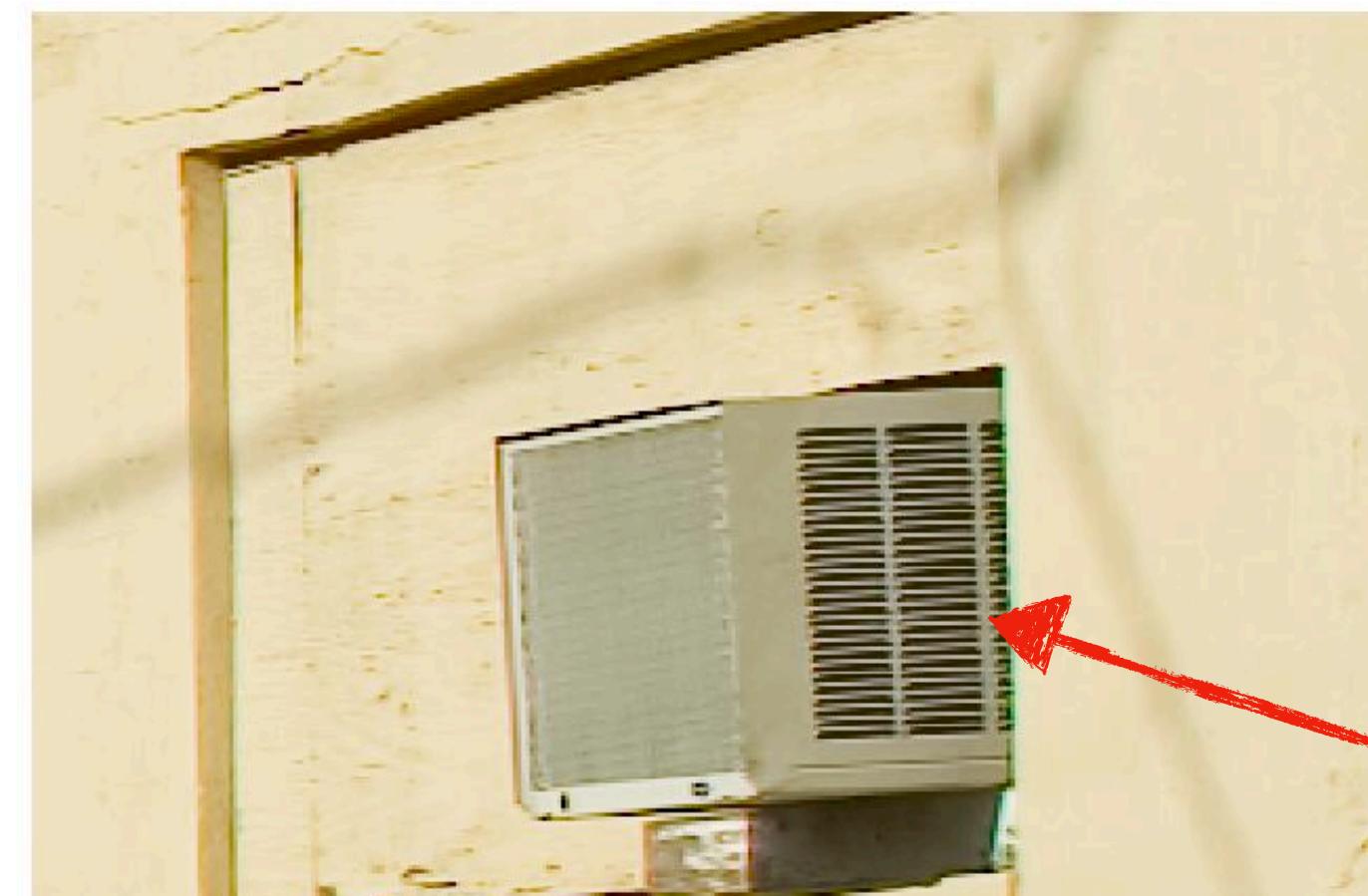
Use **anti-aliasing filters** (low-pass filter) to remove high spatial-frequency component in light, effectively **blurring** the image.

Removing AA filter increases sharpness at the cost of aliasing.



With AA filter.
Nikon D80.

No aliasing



Without AA filter.
Nikon D80e.

Aliasing

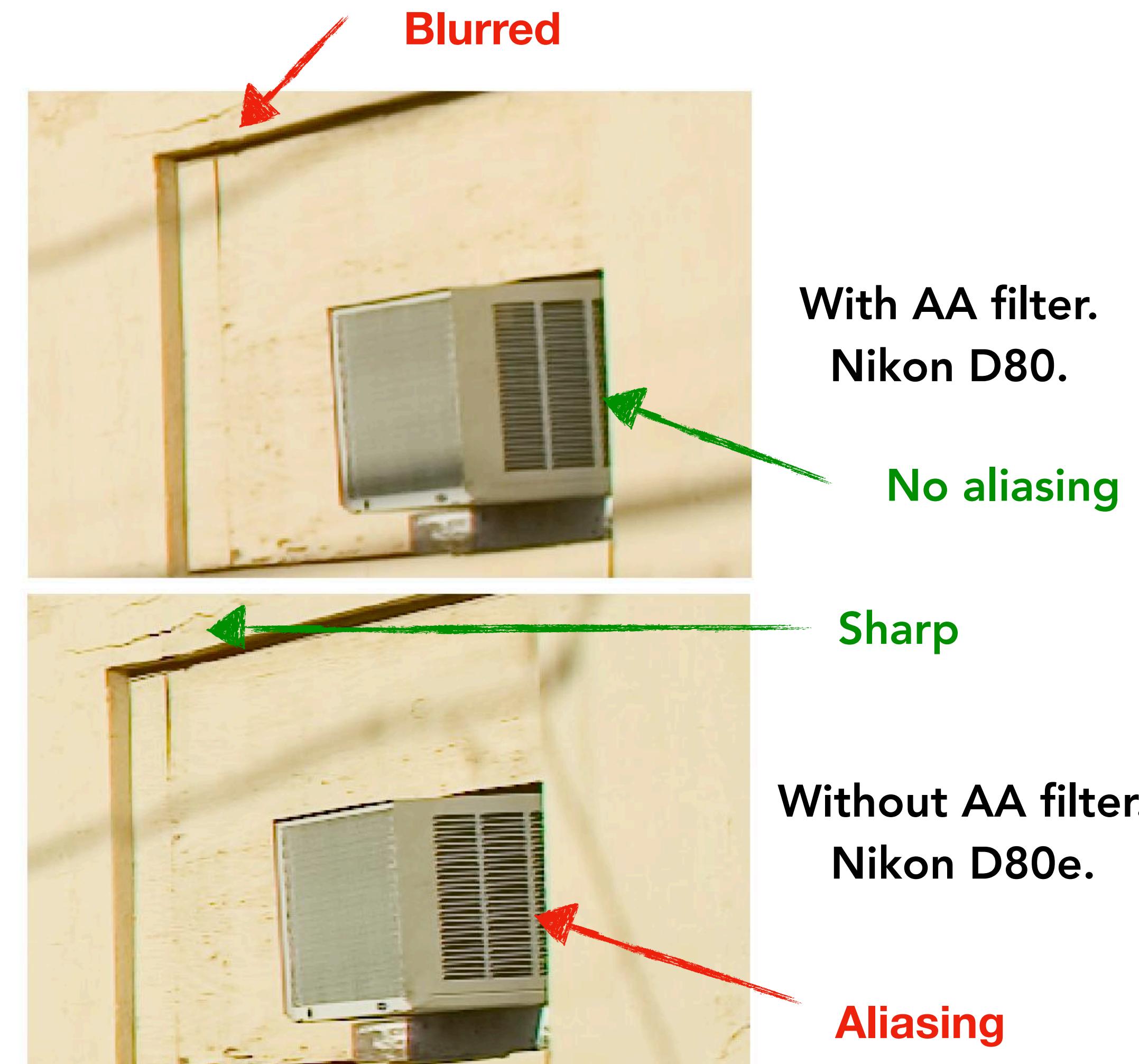
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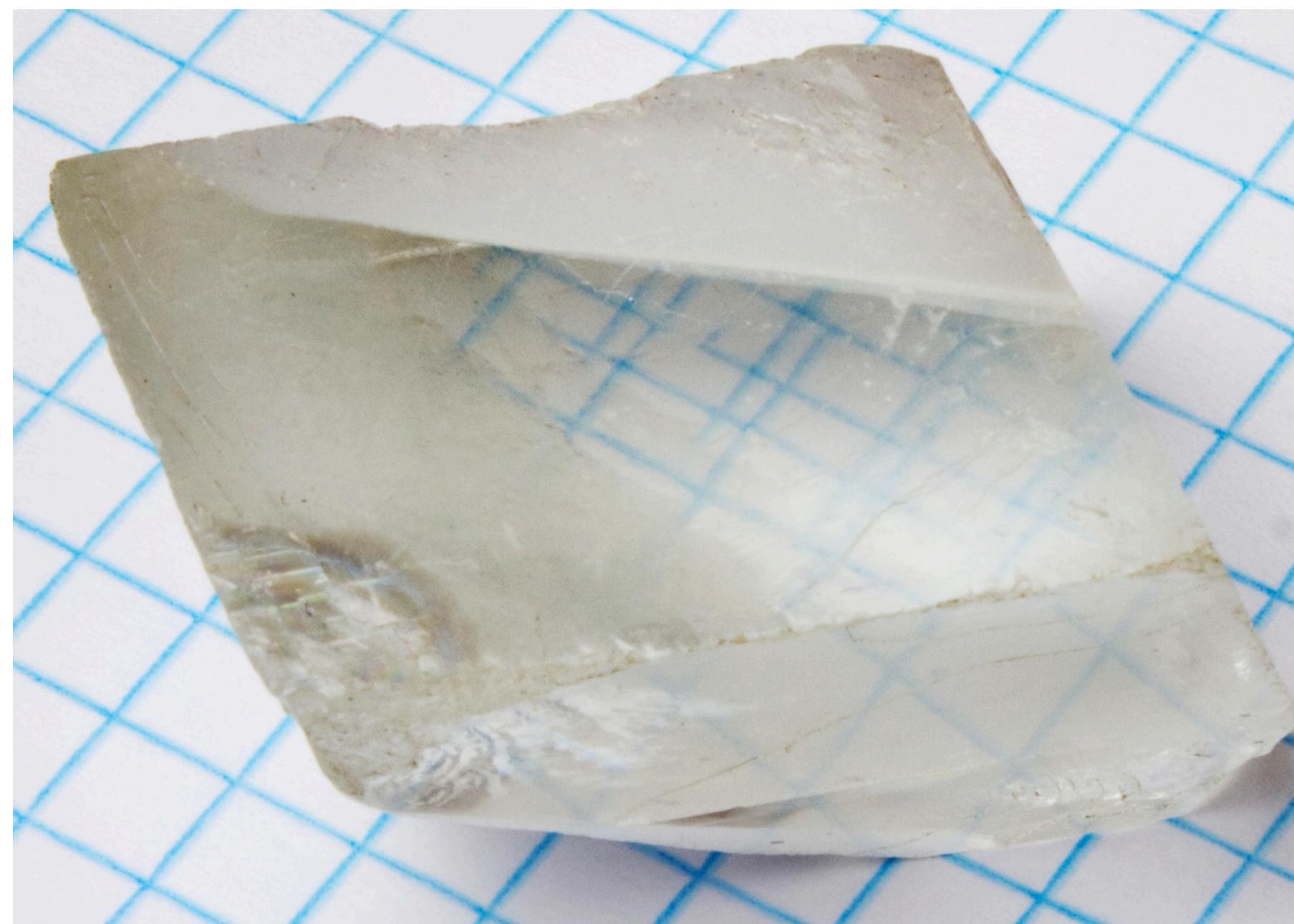
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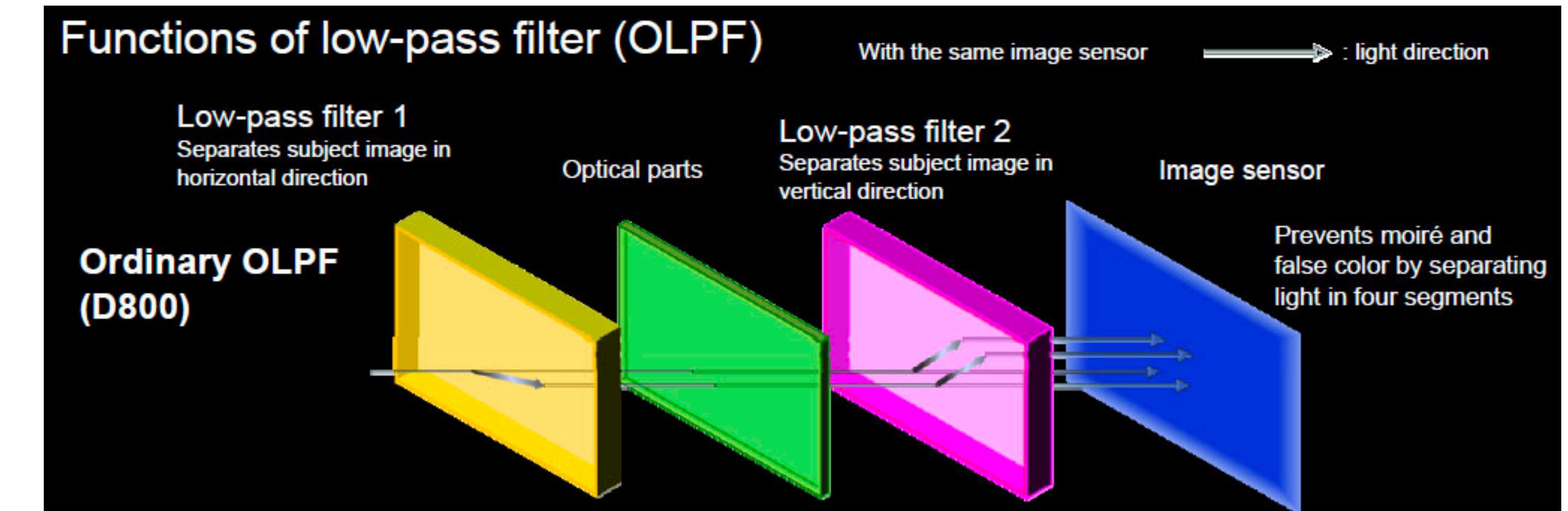
Anti-Aliasing Filter

Two layers of birefringent material separating one point into four pixels.

One birefringent layer



Combining two birefringent layers



From Charges to Digital Values

From Electrons to Pixel Values

Ideally, a pixel's value should reflect the incident light intensity (luminance). So we need to count the number of photons striking each pixel.

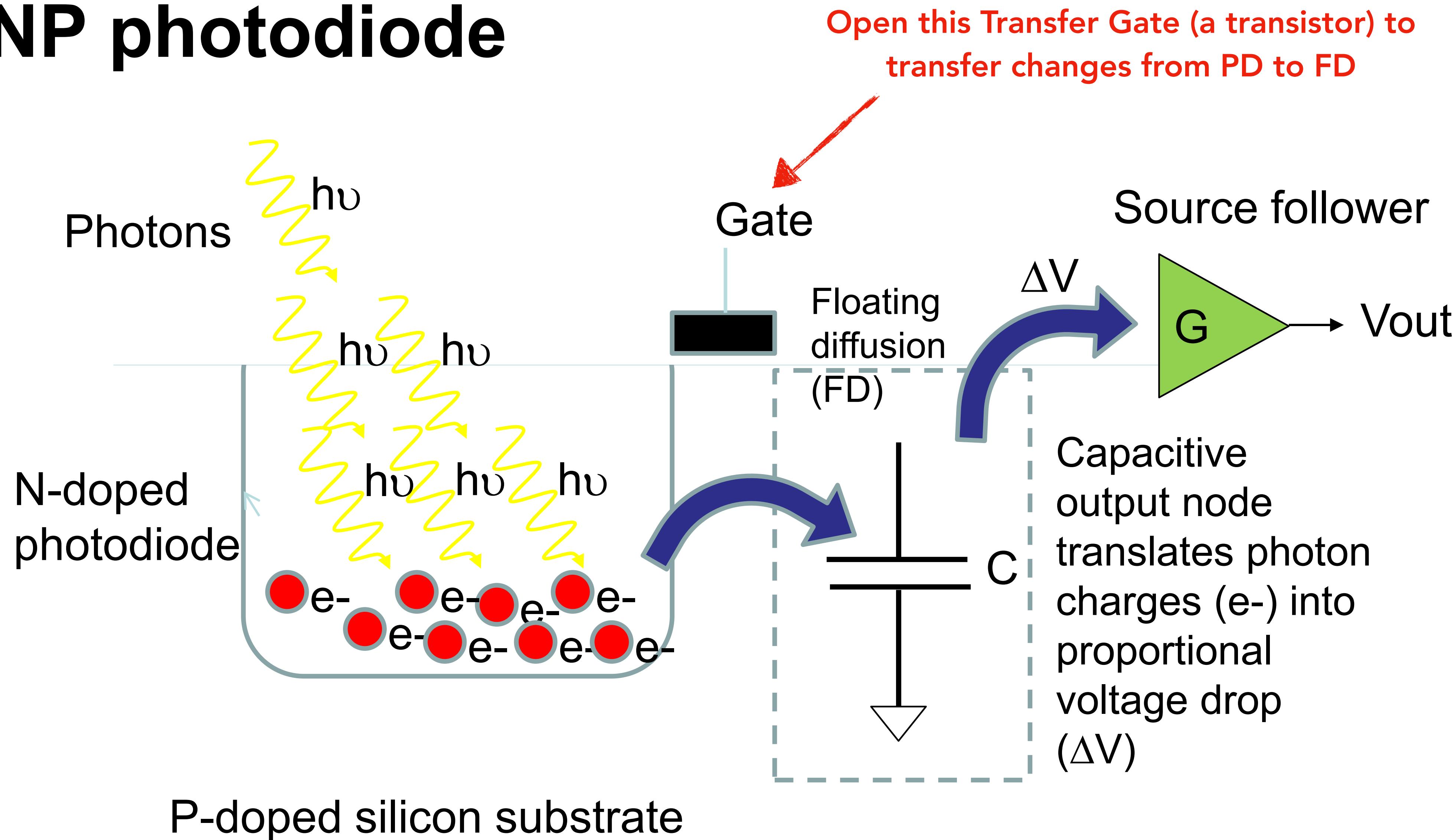
Pixel wells accumulate electrons. The number of electrons is proportional to the number of incident photons.

So counting photons is equivalent to counting electrons.

Count electrons in two steps (implementations differ):

- Convert electron charges to voltage potentials
- Convert voltage potentials to digital values

NP photodiode



Charge to Voltage Conversion

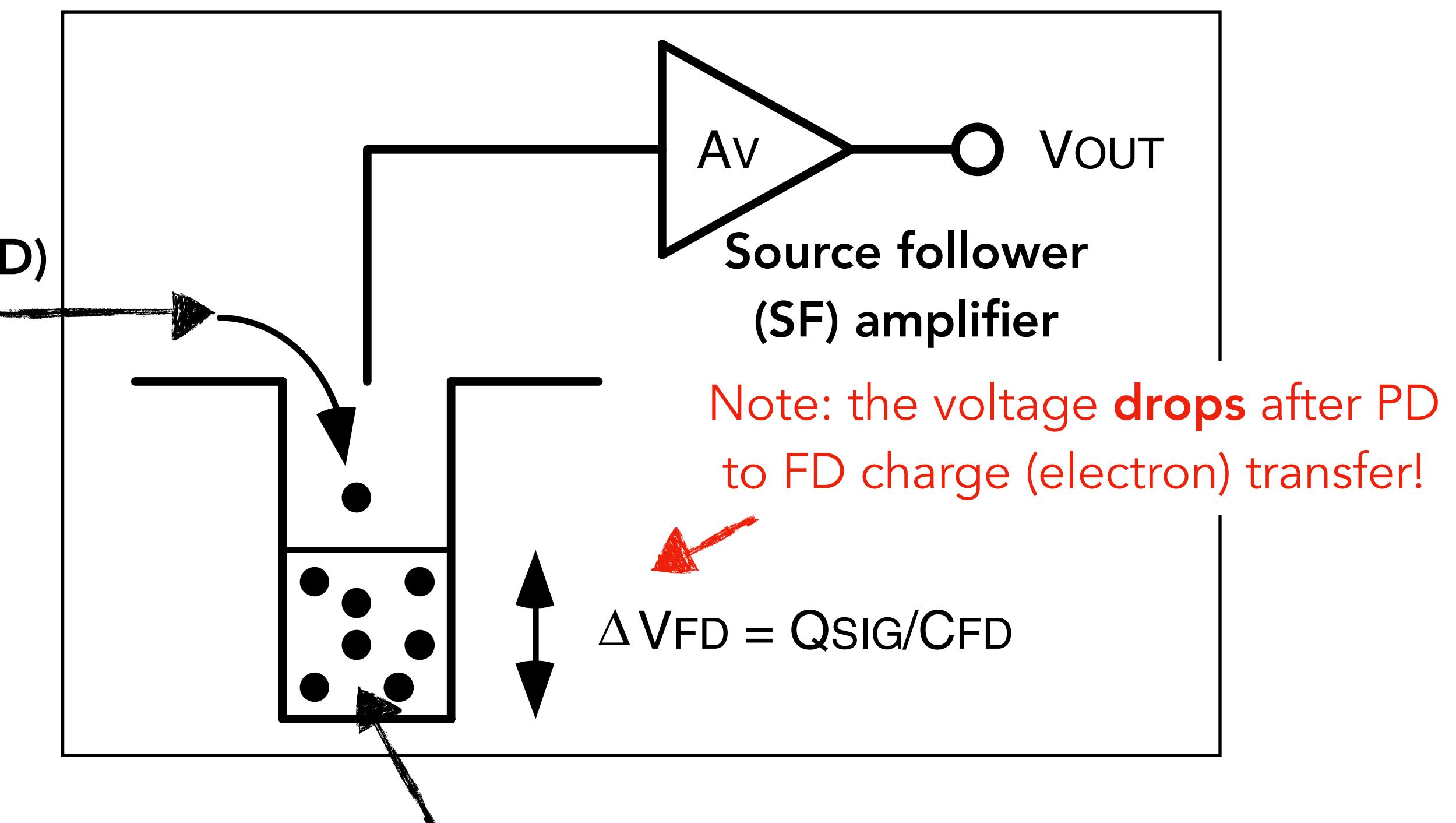
Charge in the signal

$$\Delta V = \frac{Q_{SIG}}{C_{FD}} \times g$$

Capacitance
Voltage gain
from SF

Charges from
Photodiodes (PD)

* The source follower acts as a voltage buffer that allows the voltage to be read. The SF has an inherent amplification (~1).



The capacitor is implemented
as a Floating Diffusion (FD)

Electronic Shutter

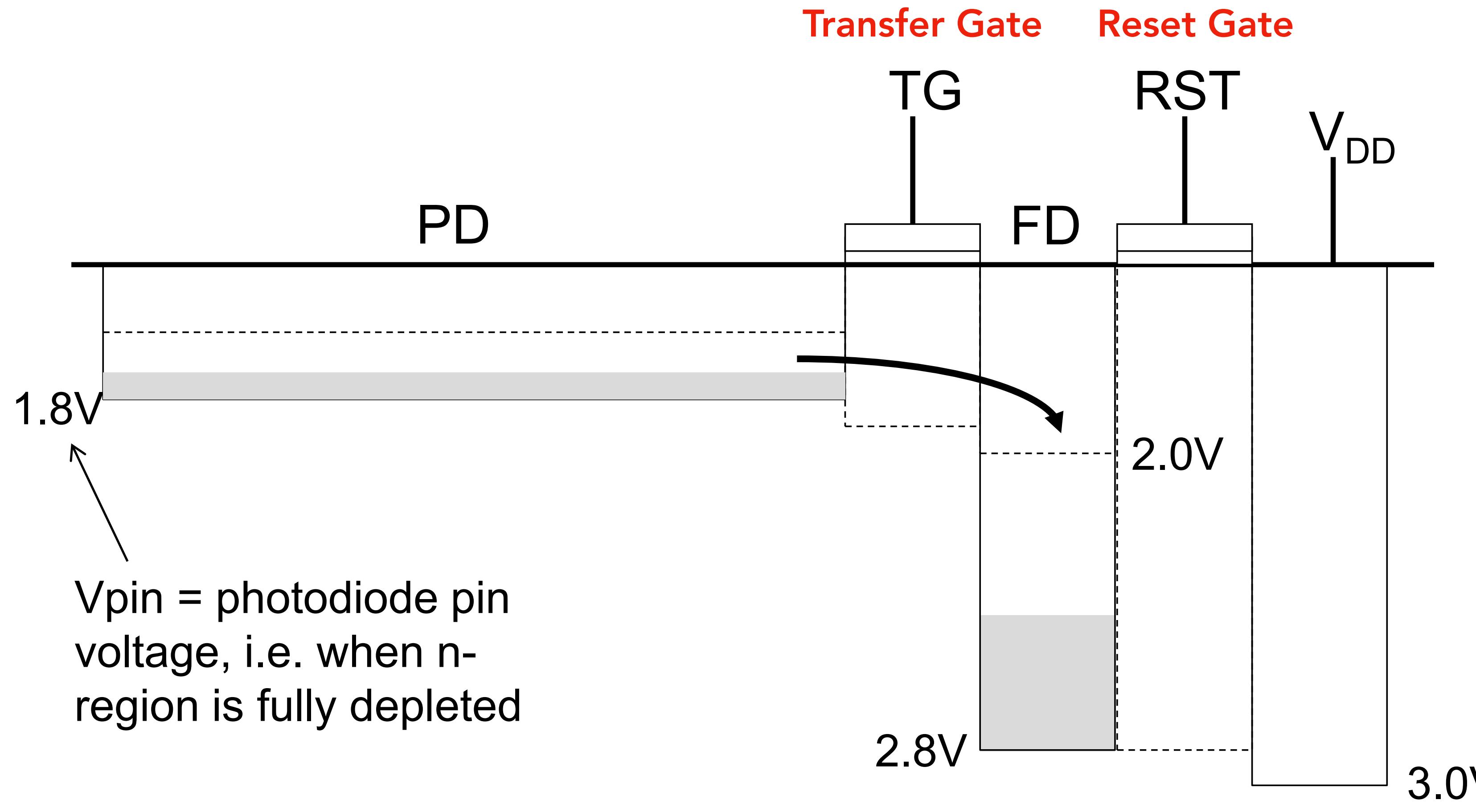
Ideally when we are not capturing the photodiodes should not be exposed to lights. Mechanical shutters do so by physically blocking lights.

With electronic shutters, we expose photodiodes to lights all the time, and when are ready to capture we “reset” the photodiodes.

Reset drains (depletes) the charges accumulated by the photodiode thus far and so prepares it for the actual exposure.

- Change the photodiodes reset time to control actual exposure time.

Electronic Shutter: Two Resets



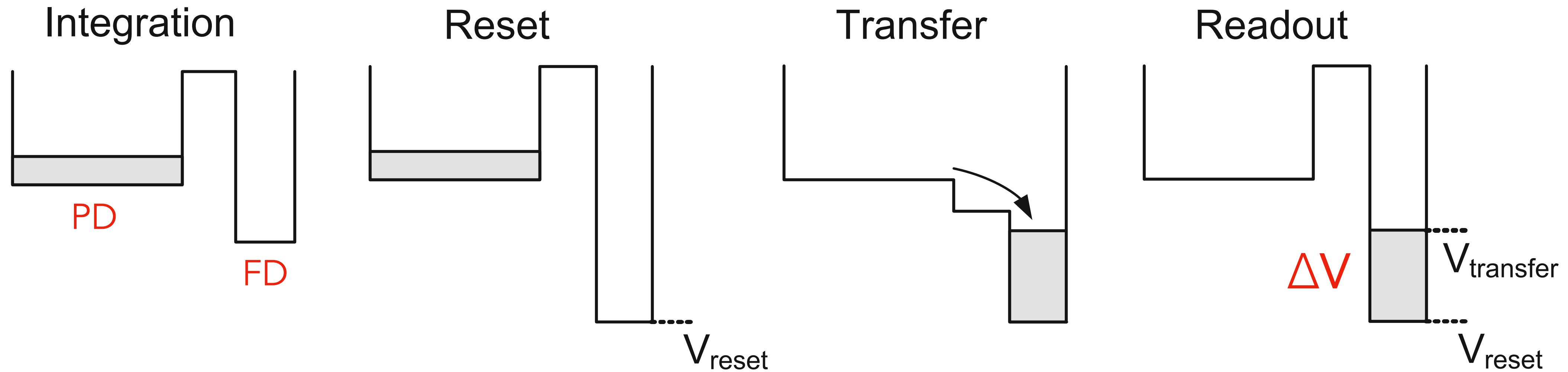
Before exposure, open TG and RST together to **reset the PD to V_{dd}**

- FD will naturally be reset too but it's of no functional use.

After exposure and before read-out, open RST to **reset FD**.

- Then PD to FD transfer.

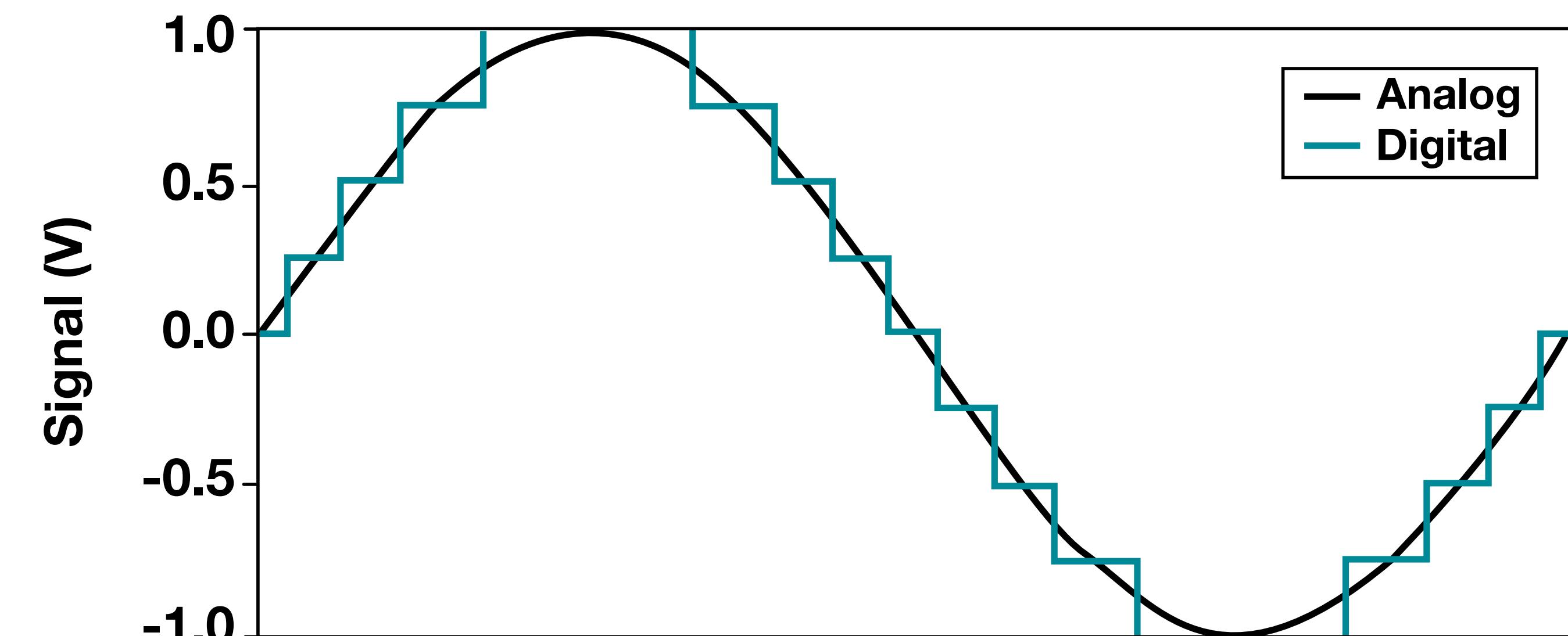
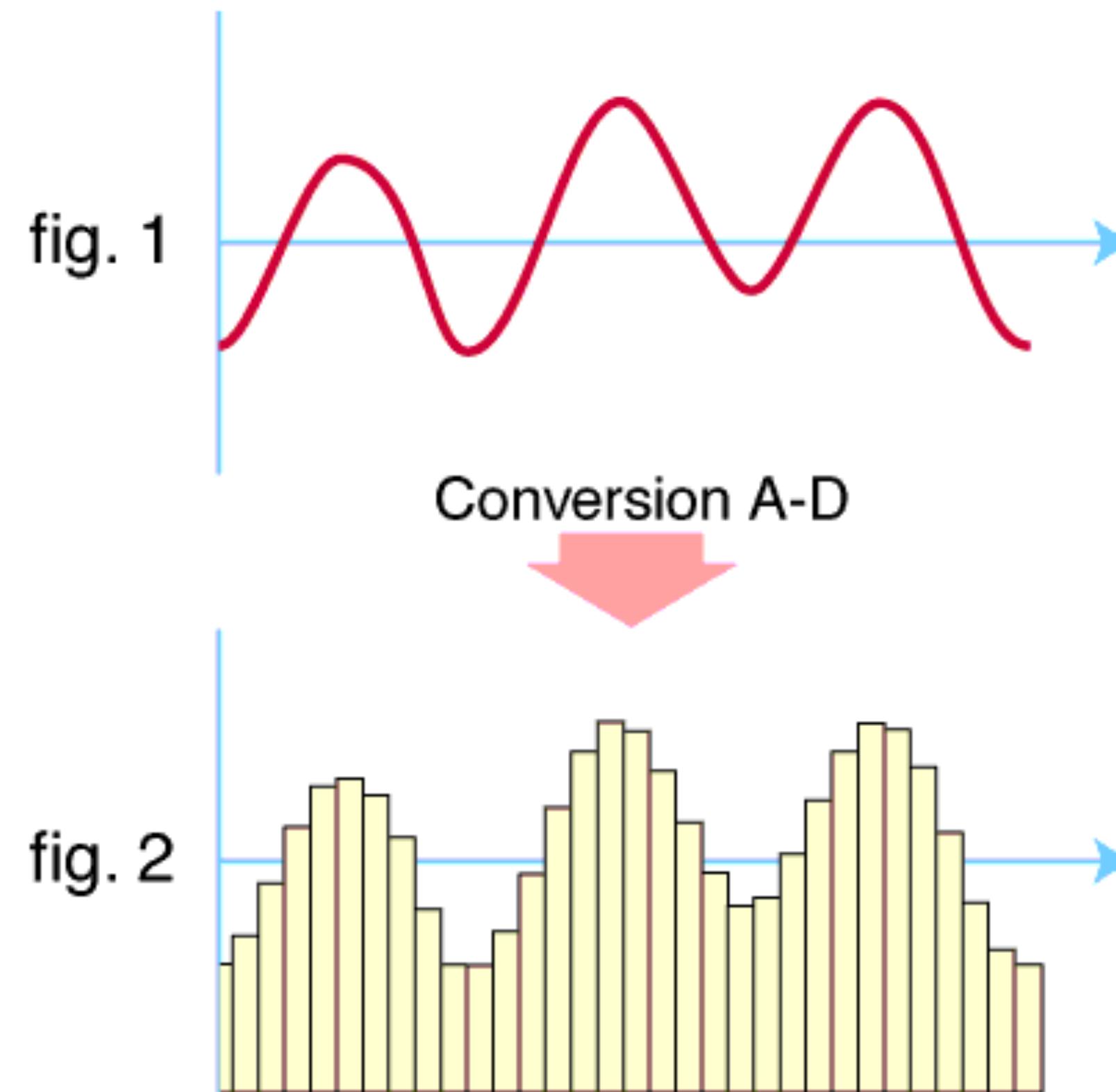
FD Reset



Conceptually, ΔV is used to generate raw pixel values; implementations vary:

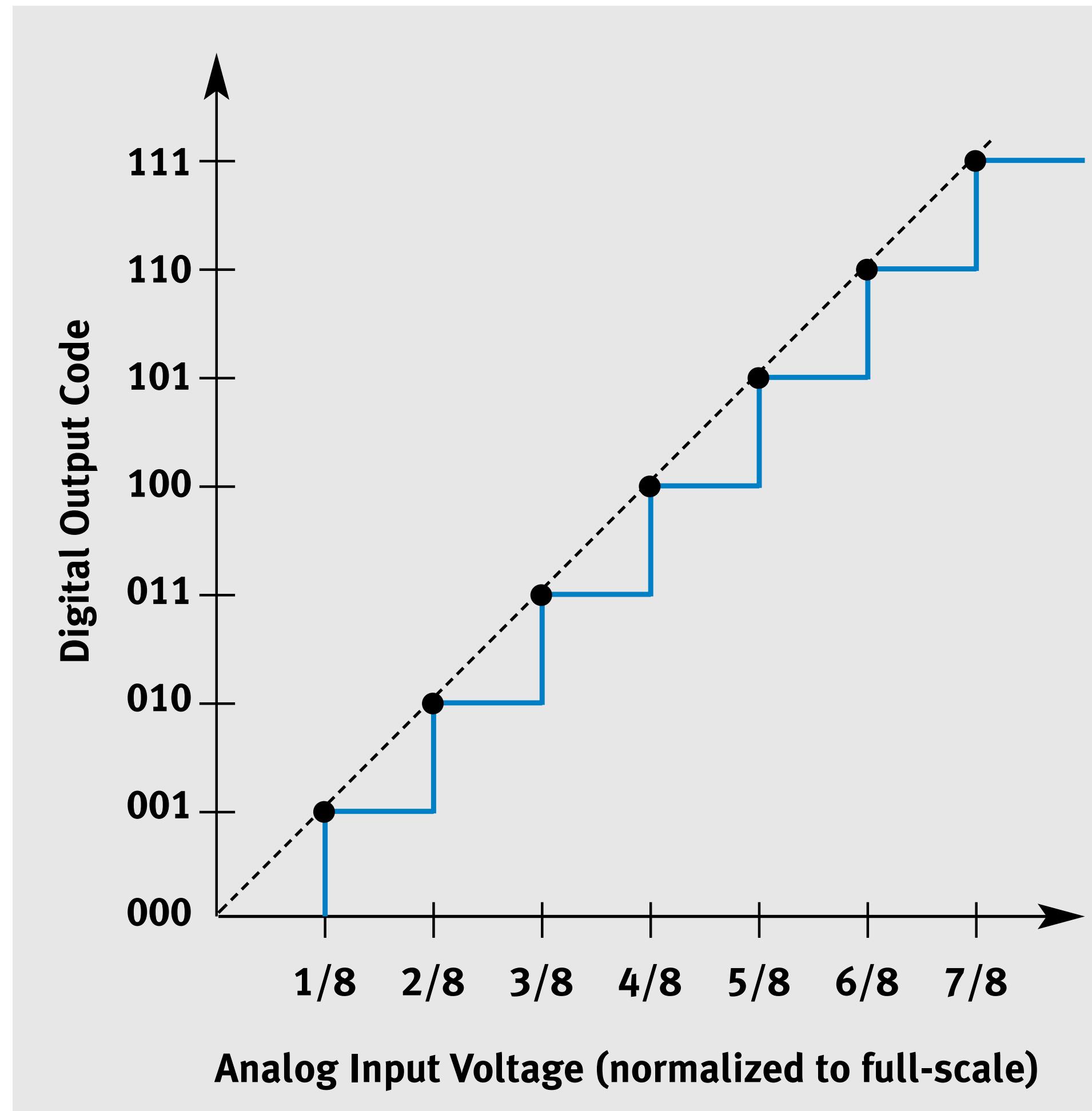
- With Correlated Double Sampling (CDS; next lecture), both $V_{transfer}$ and V_{reset} are read, and the difference ΔV is quantized by ADCs. CDS reduces noises.
- Without CDS, $V_{transfer}$ directly enters the ADC, whose design needs to, effectively (by properly setting its reference voltage), subtract V_{reset} .

Analog to Digital Conversion (ADC)

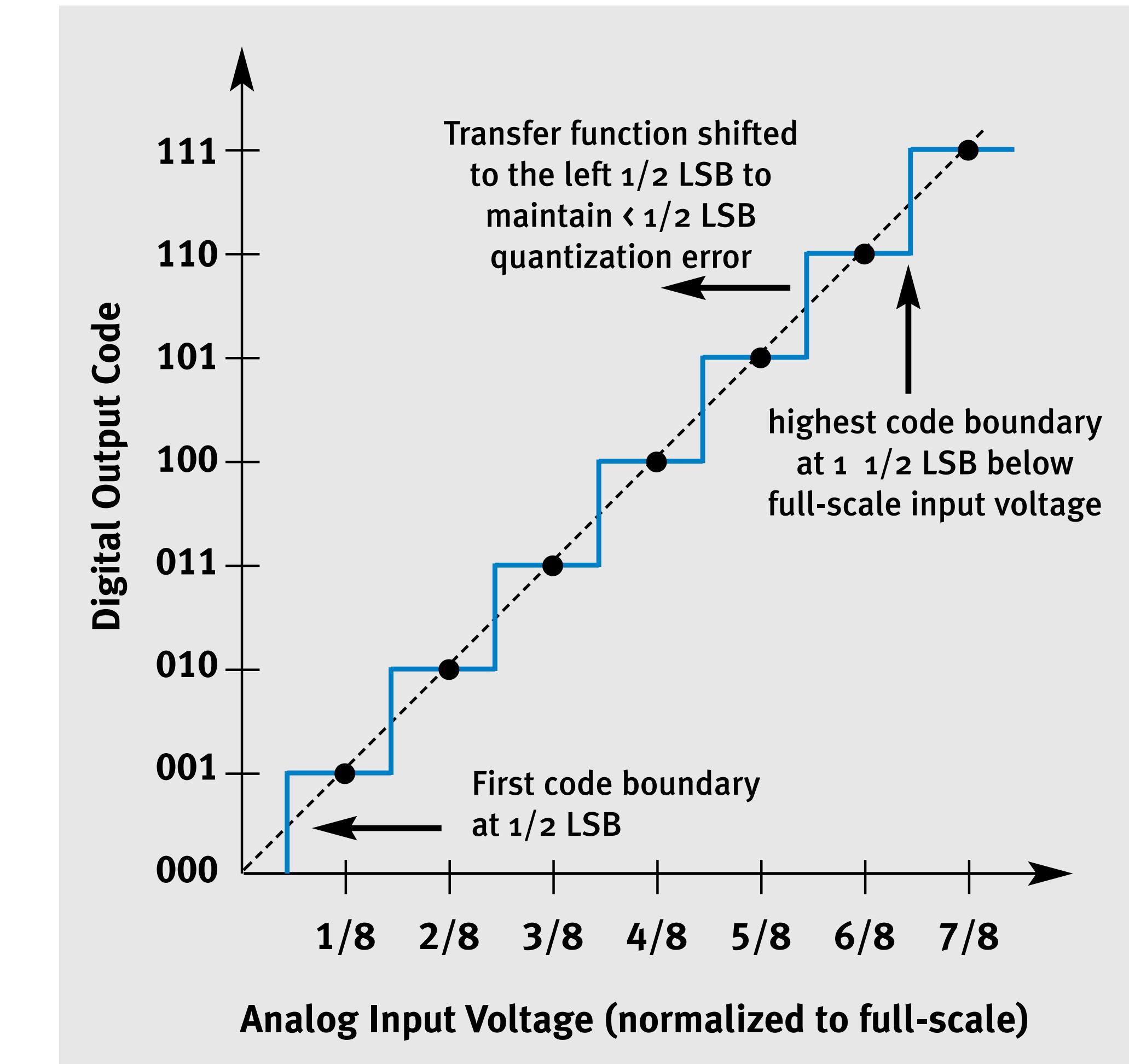


Transfer Function

Ideal Transfer Function of a 3-bit ADC

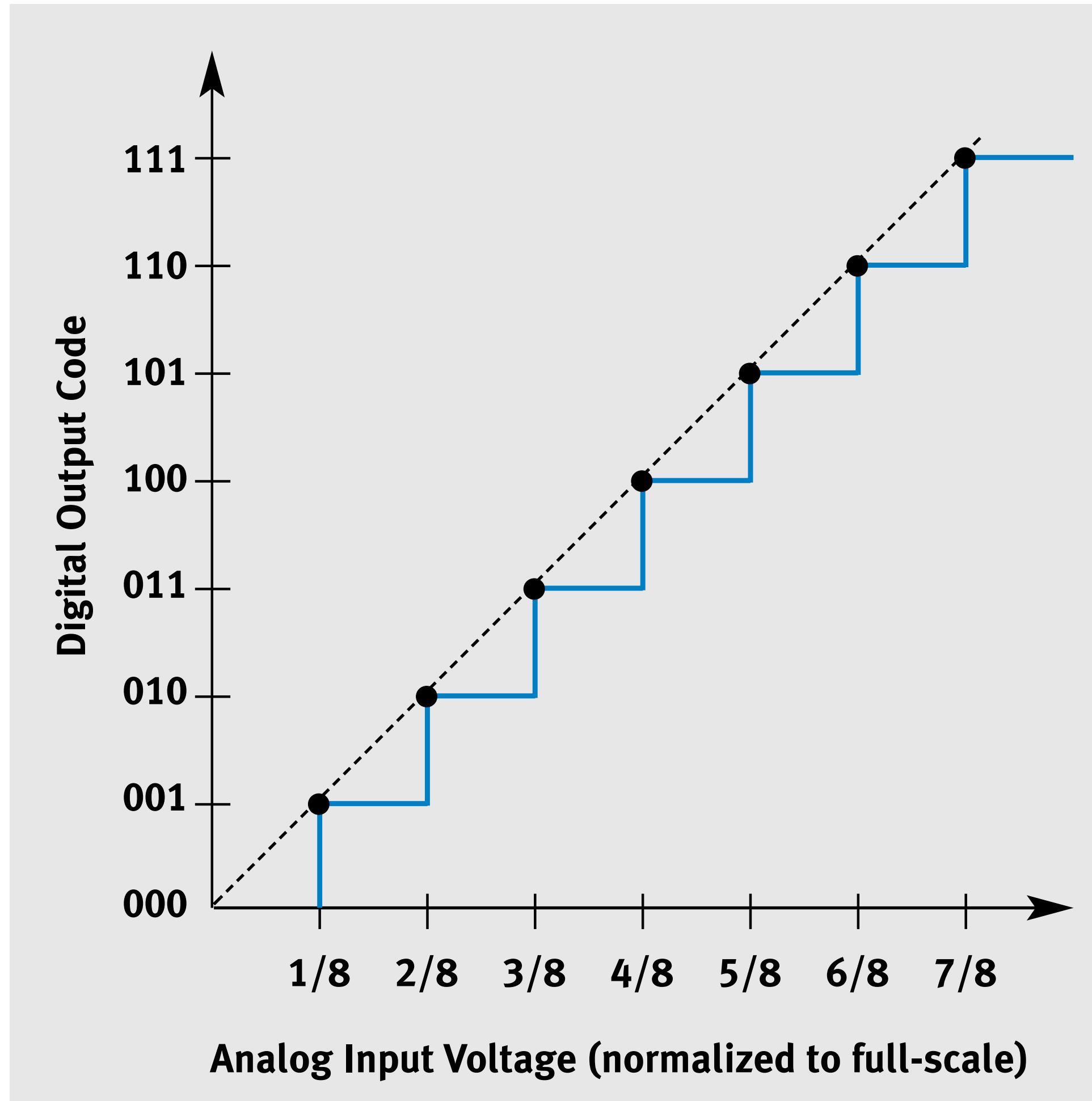


Another (more common) Transfer Function



Analytical Model

Ideal Transfer Function of a 3-bit ADC



Full-scale range

Output
digital value

$$\text{FSR} = V_{max} - V_{min}$$

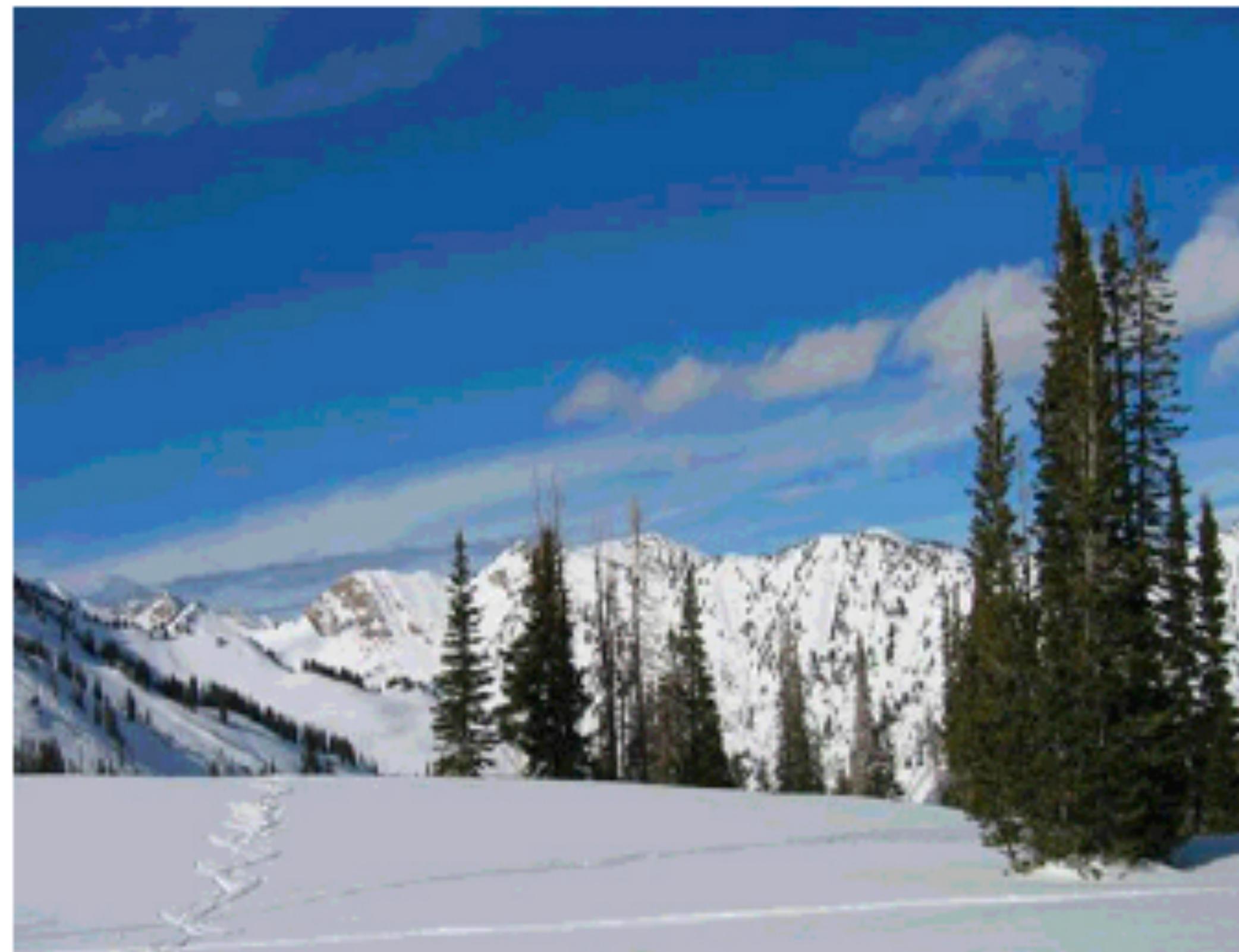
Upper extreme

Lower extreme (usually 0)

$$n = \lfloor \frac{V_{in} - V_{min}}{\text{FSR}} (2^N - 1) \rfloor$$

Contouring From Aggressive Quantization

Lower ADC resolution;
smaller image size (in theory)



Higher ADC resolution; larger image size



A Monochromatic, Noise-Free Sensor Model

$$Q(x, y) = \int_t \int_{\lambda} \int_y^{y+v} \int_x^{x+u} Y(x, y, \lambda, t) QE(\lambda) q \, dx dy d\lambda dt$$

of incident photons at pixel (x, y);
varies with λ and t.

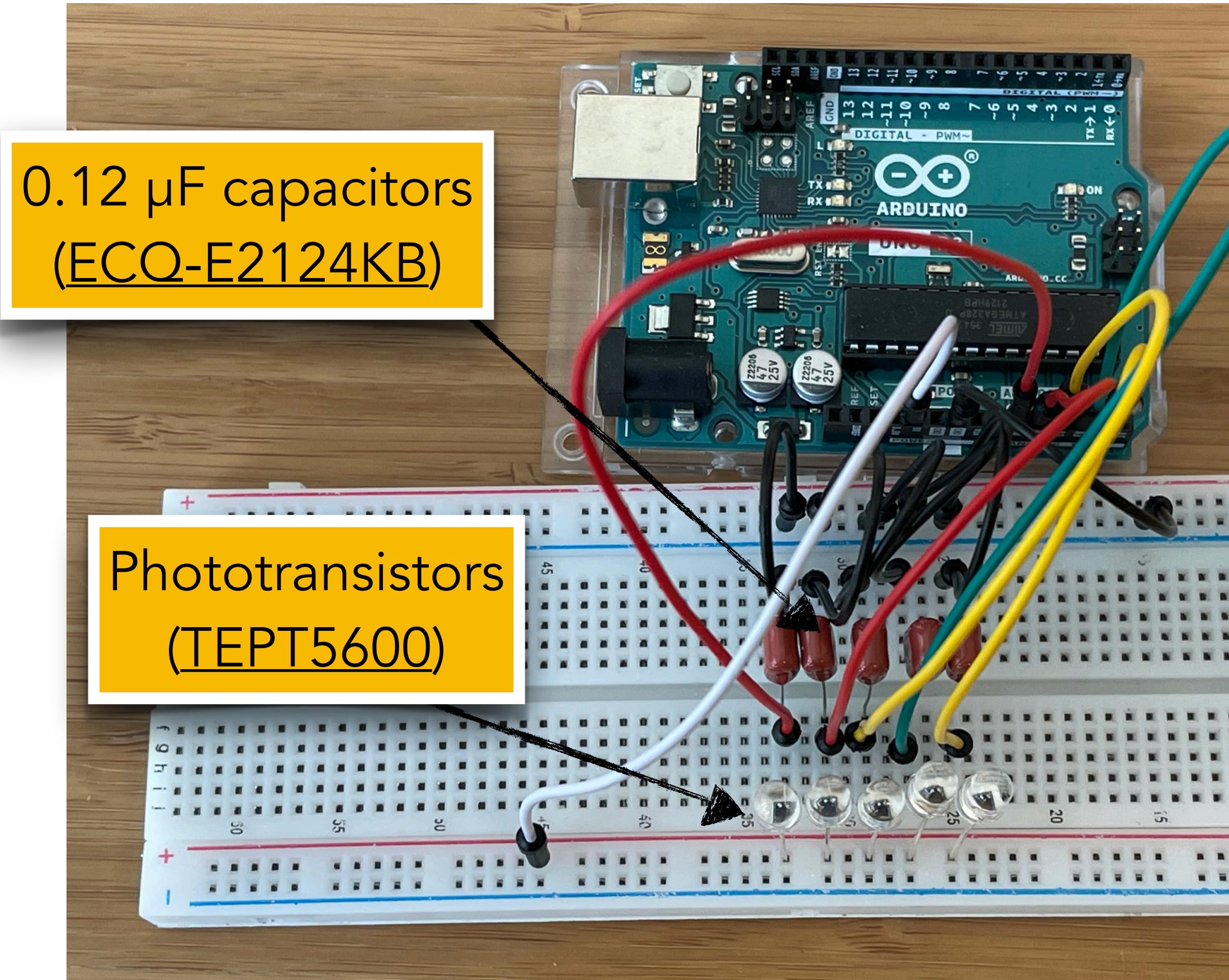
$$\Delta V(x, y) = \frac{Q(x, y)}{C} g$$

$$n(x, y) = \lfloor \frac{\Delta V(x, y)}{V_{max}} (2^N - 1) \rfloor$$

Raw pixel value

Max voltage corresponding to
max raw value (assuming $V_{min} = 0$)

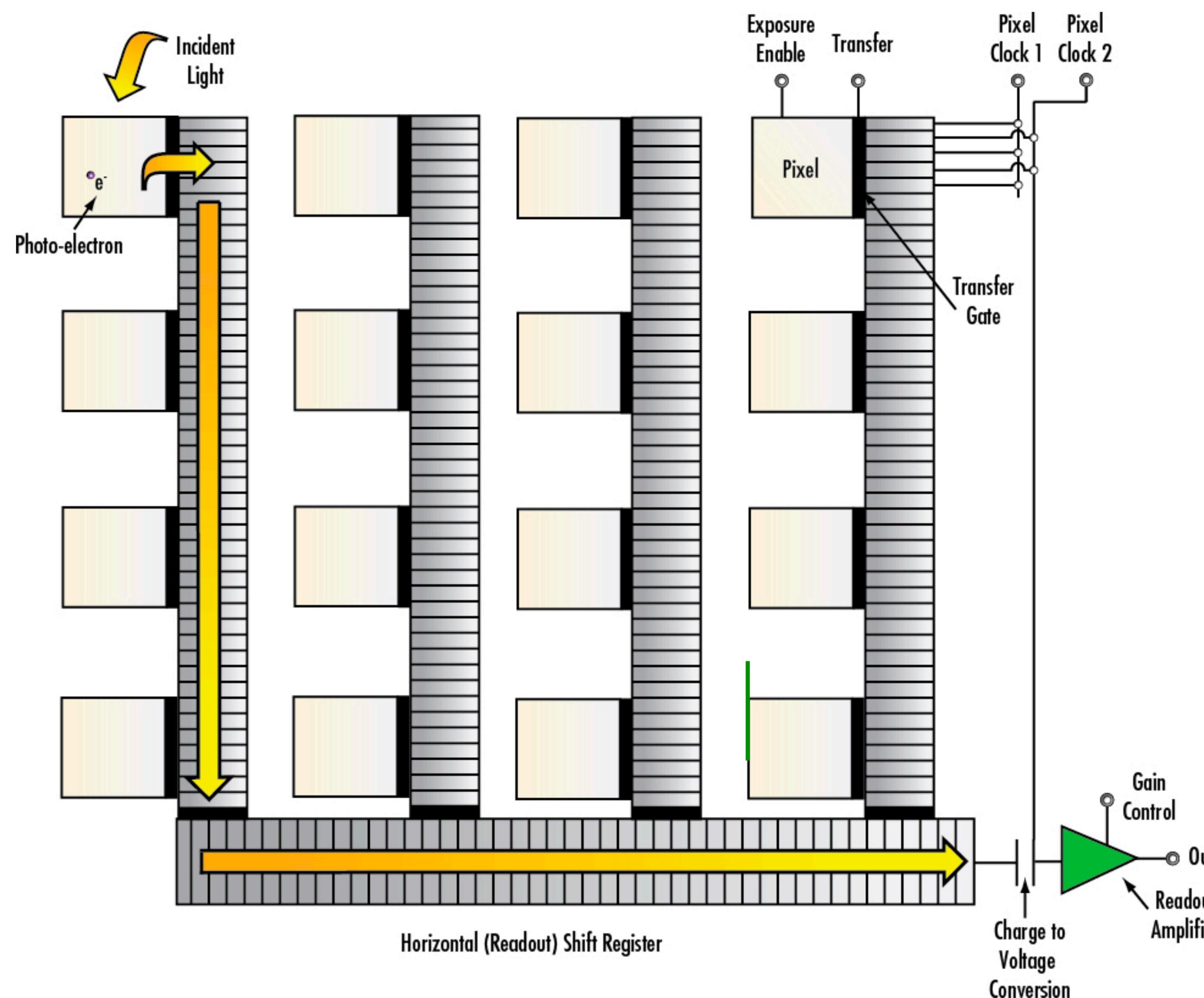
Demo



```
// set pins to high-impedance for sensing  
pinMode(A0, INPUT);  
pinMode(A1, INPUT);  
pinMode(A2, INPUT);  
pinMode(A3, INPUT);  
pinMode(A4, INPUT);  
  
// exposure time  
delayMicroseconds(6000);  
  
// read pixel values.  
int values[5];  
for (int i = 0; i < 5; i++) {  
    values[i] = analogRead(i);  
}  
  
// set pins to low voltage to discharge capacitors  
pinMode(A0, OUTPUT);  
pinMode(A1, OUTPUT);  
pinMode(A2, OUTPUT);  
pinMode(A3, OUTPUT);  
pinMode(A4, OUTPUT);  
digitalWrite(A0, LOW);  
digitalWrite(A1, LOW);  
digitalWrite(A2, LOW);  
digitalWrite(A3, LOW);  
digitalWrite(A4, LOW);
```

Different Sensor Designs

CCD Sensor



Exposure all pixels simultaneously.

Shifting charges row by row. When shifting, naturally no pixel can be exposed, a.k.a., global shutter.

- A good introduction of CCD [here](#).

Convert charges to voltage and then to digital values in the end.

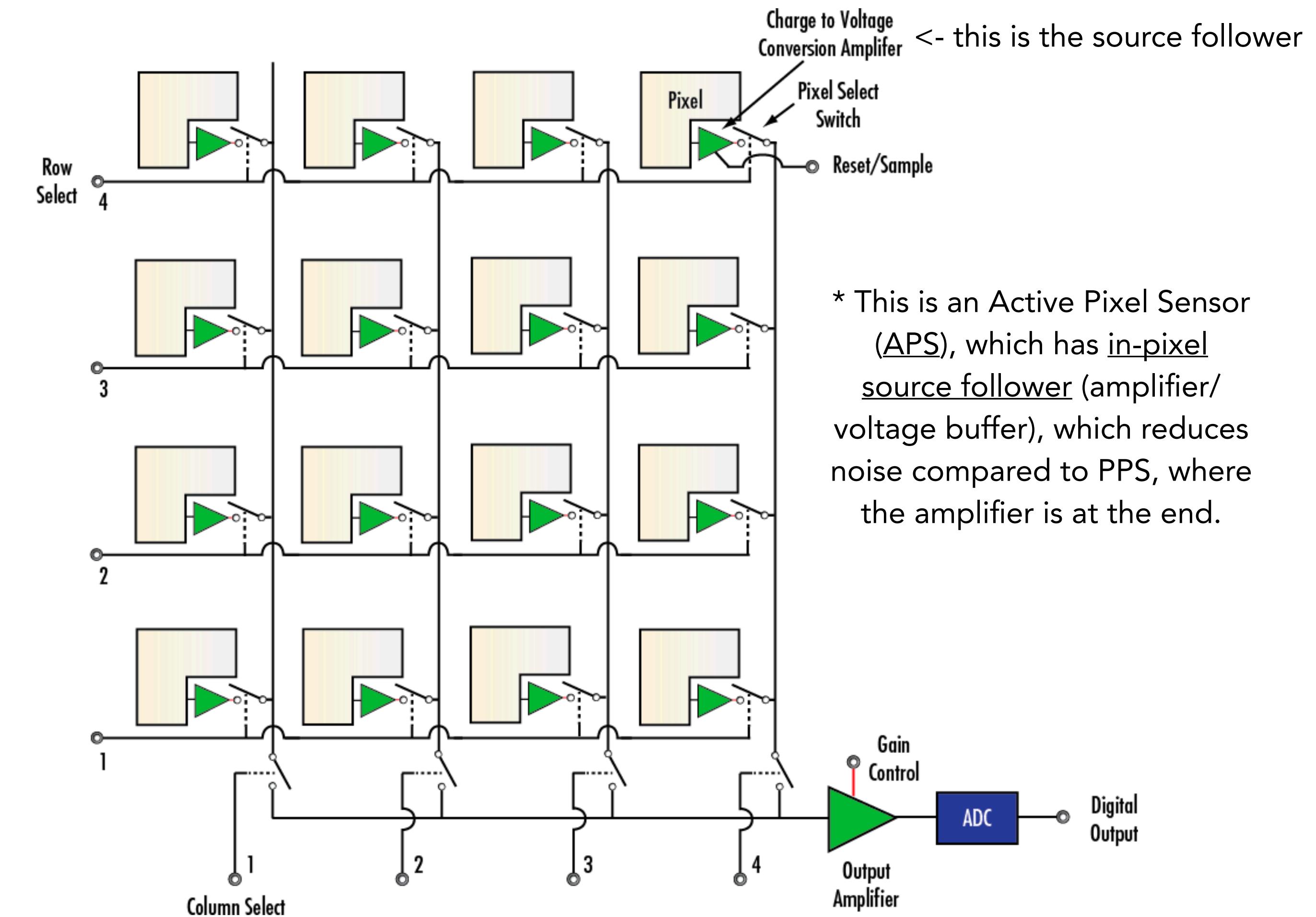
CMOS Sensor

Charge to voltage conversion takes place within the pixel. Instead of shifting charges, directly read the voltages.

- but still row by row.

Pixels are now exposed row by row, a.k.a., rolling shutter.

- because voltages in each row must be read out immediately (no buffer).
- an artifact; not something we want.



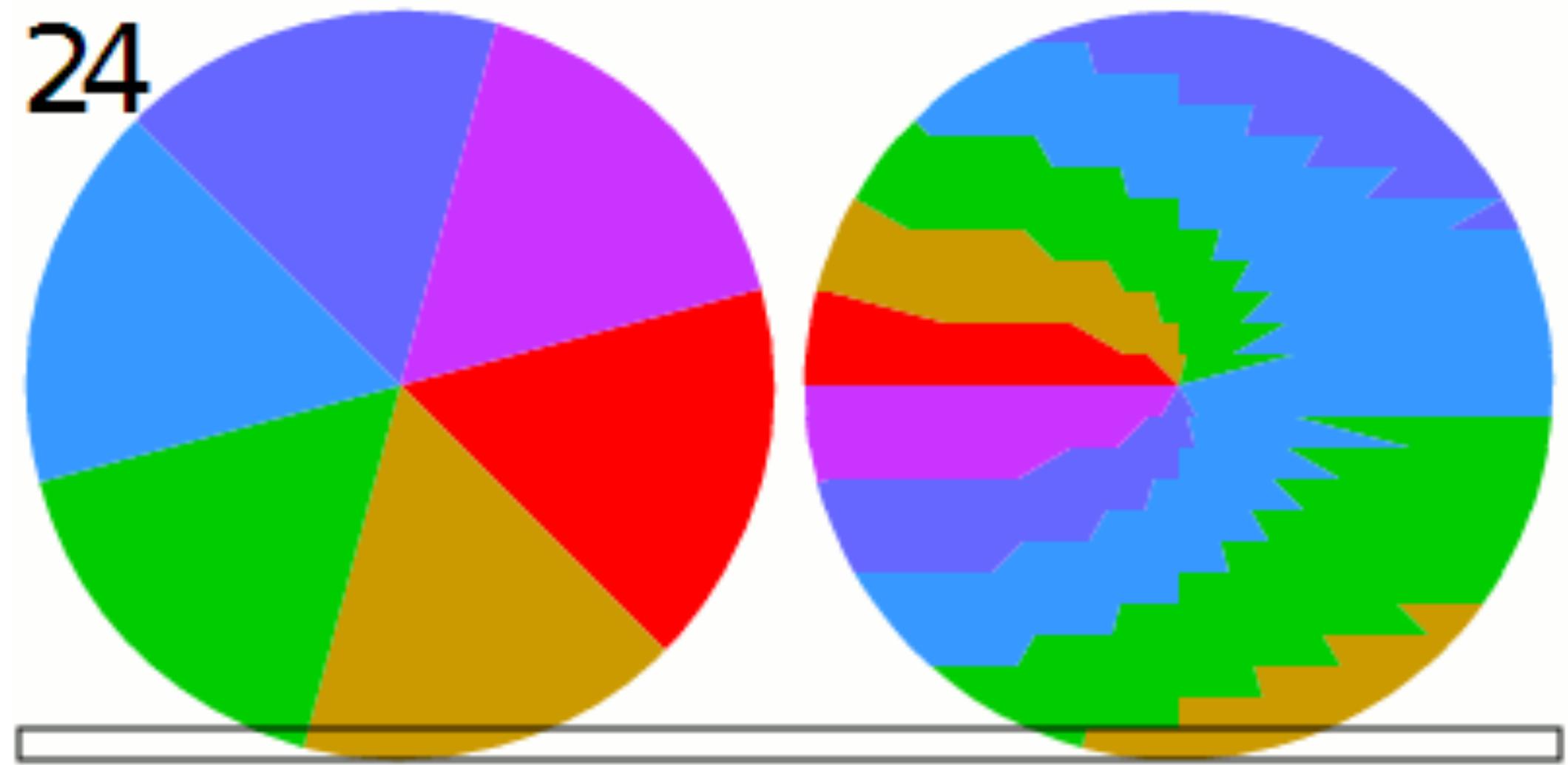
Rolling Shutter Operation



Rolling Shutter Operation



Rolling Shutter Artifact

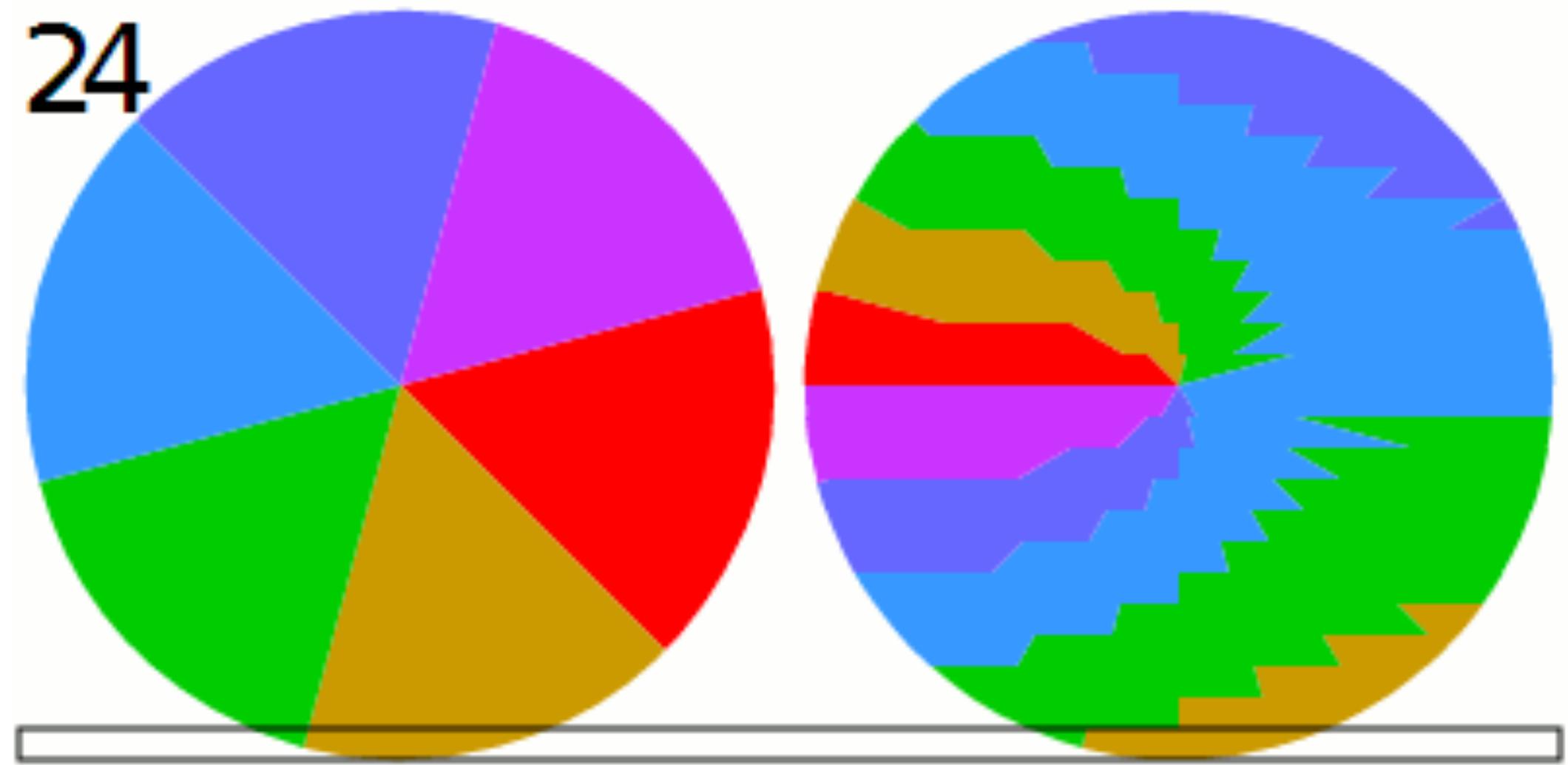


https://en.wikipedia.org/wiki/Rolling_shutter

https://www.reddit.com/r/interestingasfuck/comments/en3lap/rolling_shutter_effect_of_chopper_blades/

<https://www.bhphotovideo.com/explora/video/tips-and-solutions/rolling-shutter-versus-global-shutter>

Rolling Shutter Artifact

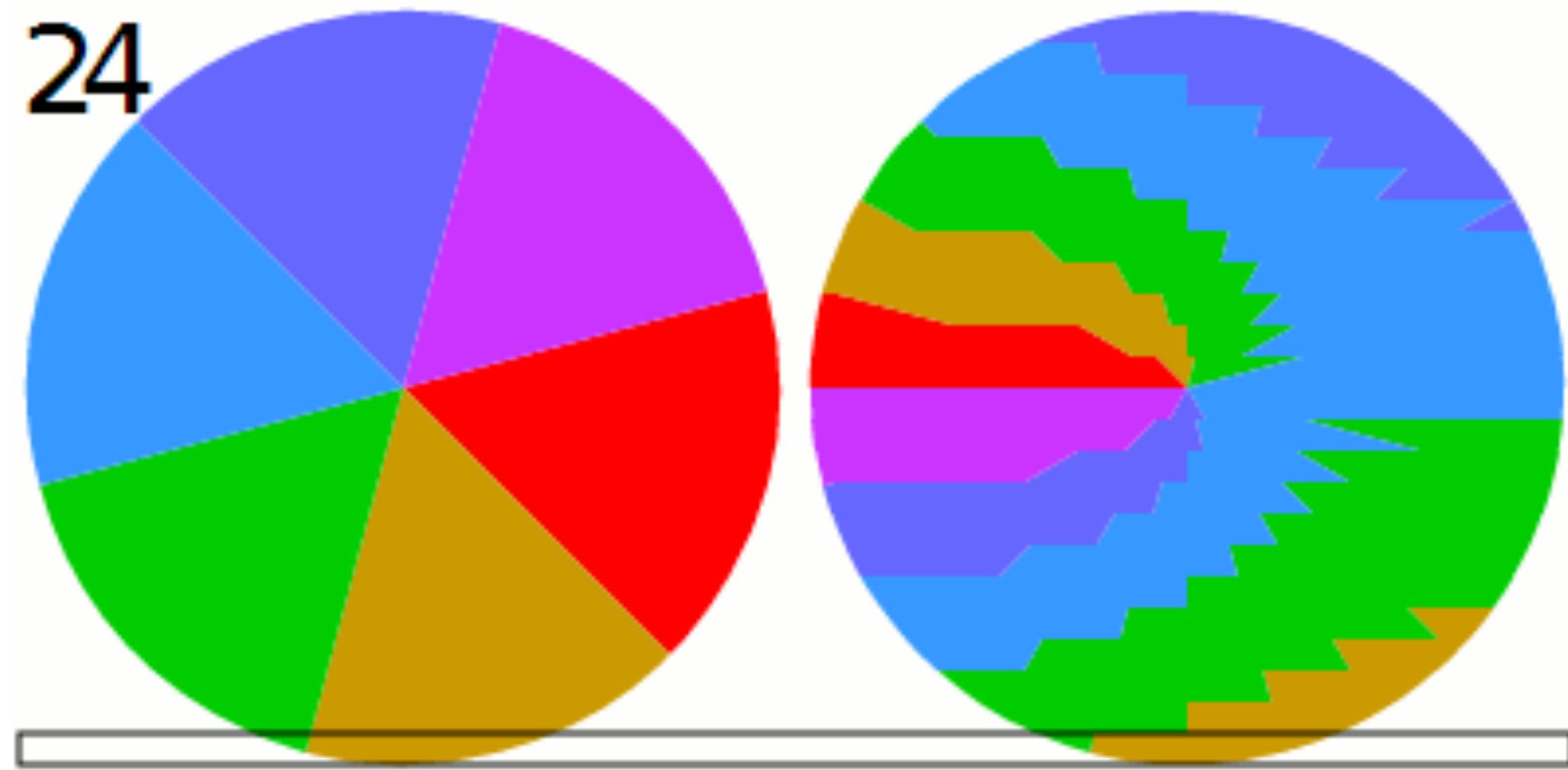


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Rolling Shutter Artifact

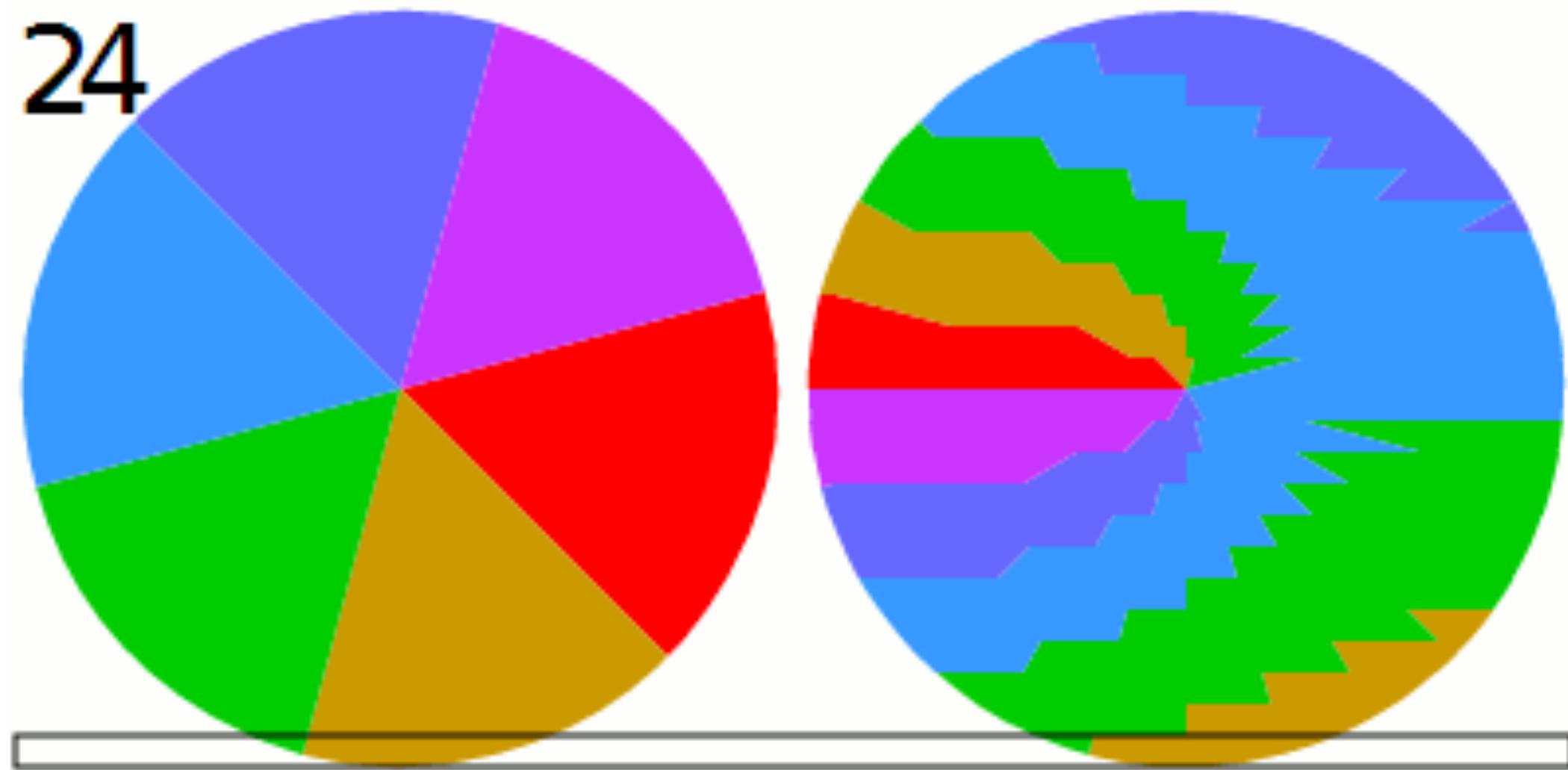


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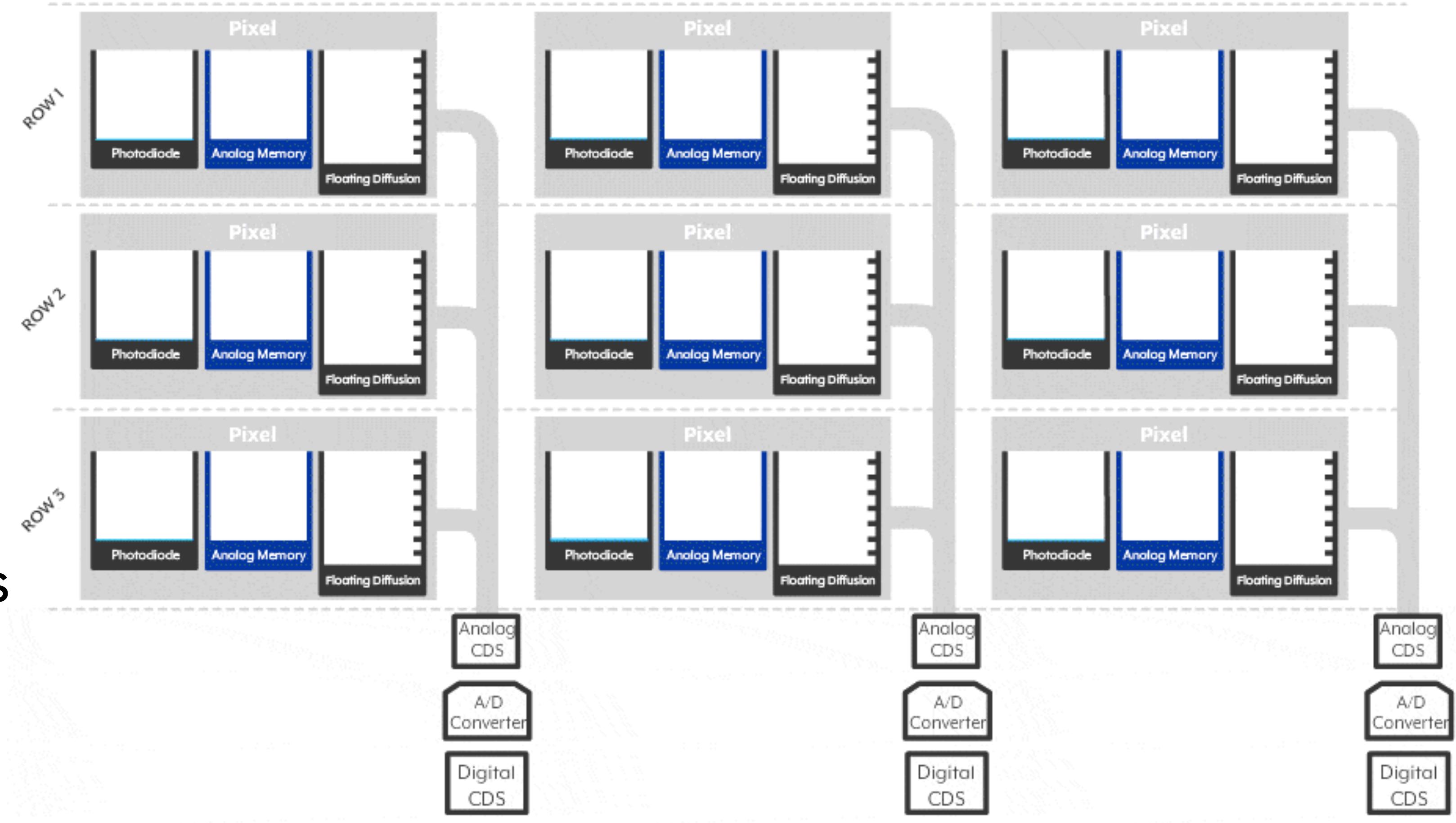
<https://www.bhphotovideo.com/explora/video/tips-and-solutions/rolling-shutter-versus-global-shutter>



Global Shutter

CCD naturally uses global shutter, since no pixel can be exposed during read-out.

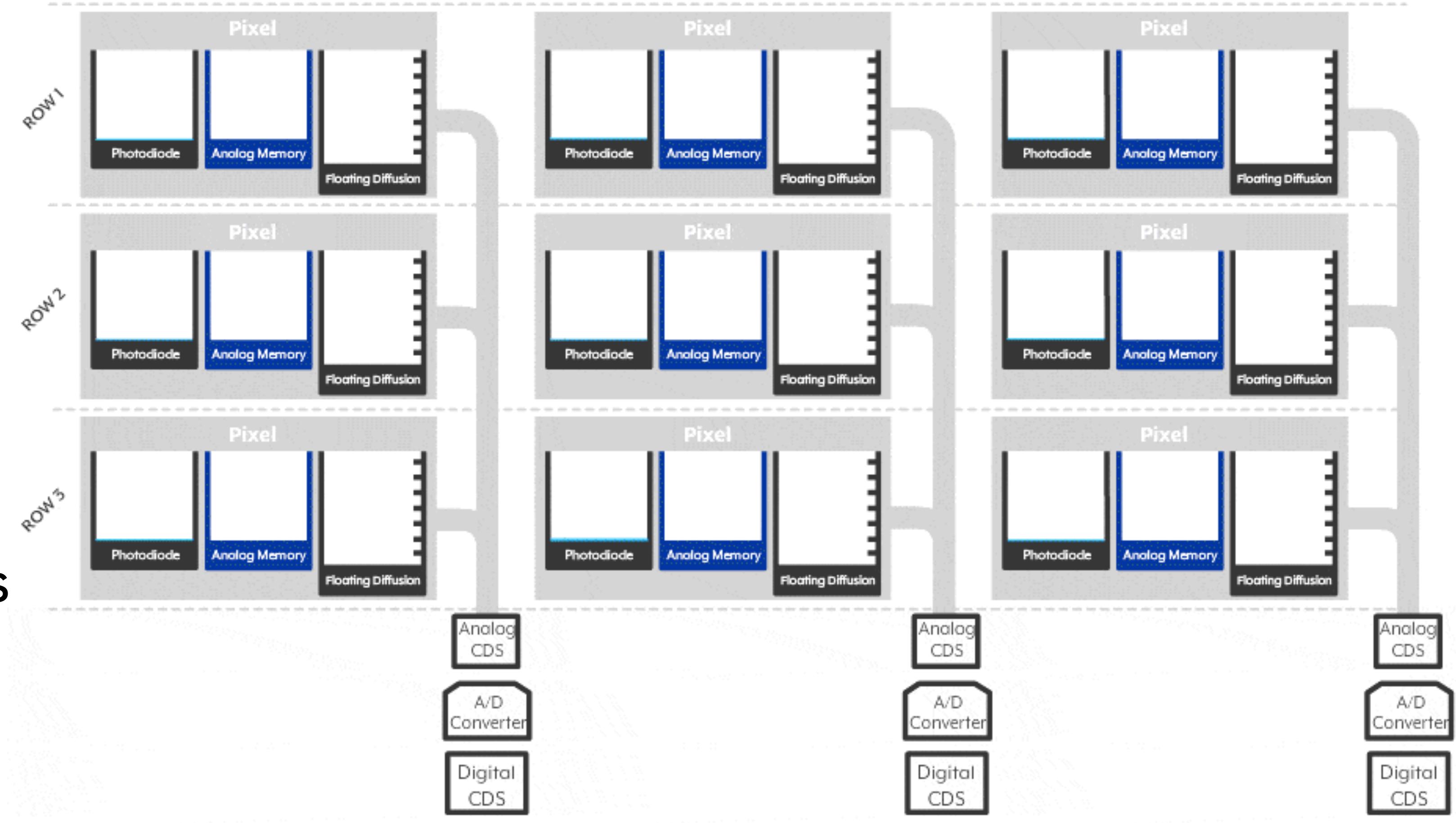
To implement global shutter for CMOS sensors, each pixel needs to have a temporary storage space (analog voltage buffer).



Global Shutter

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To implement global shutter for CMOS sensors, each pixel needs to have a temporary storage space (analog voltage buffer).



CMOS Global Shutter Read-Out

Expose all pixels at the same time, but readout is still line by line.

Why not read all the pixels at the same time?

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Does global shutter avoid motion blur?

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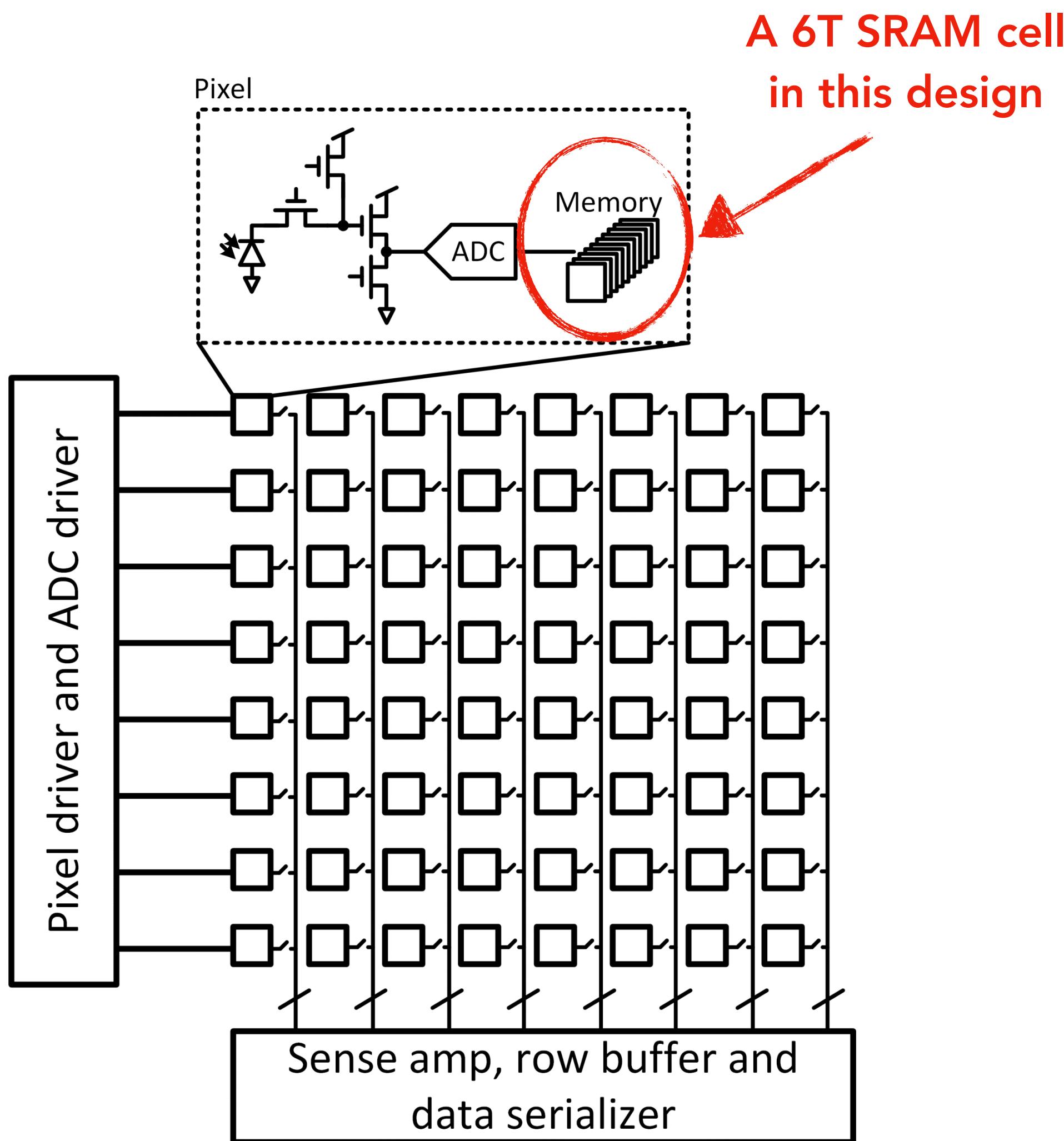
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- A “solution” that avoids analog memory in global shutter is to expose later lines longer and still read line by line, but spatially non-uniform exposure is clearly undesirable.

Does global shutter avoid motion blur?

- No

Digital Pixel Sensors



- Each pixel contains an ADC and digital memory
- Pixel data is stored in digital memory and readout as digital bits
- ADC circuit has to be small enough to keep pixel size reasonable
- Now you can treat the pixel array as your frame buffer memory!
- DPS opens new possibilities, we will demonstrate one example in next section

Usually the ADC and digital memory is on a separate layer different from the pixel array layer (later)

CCD vs. CMOS

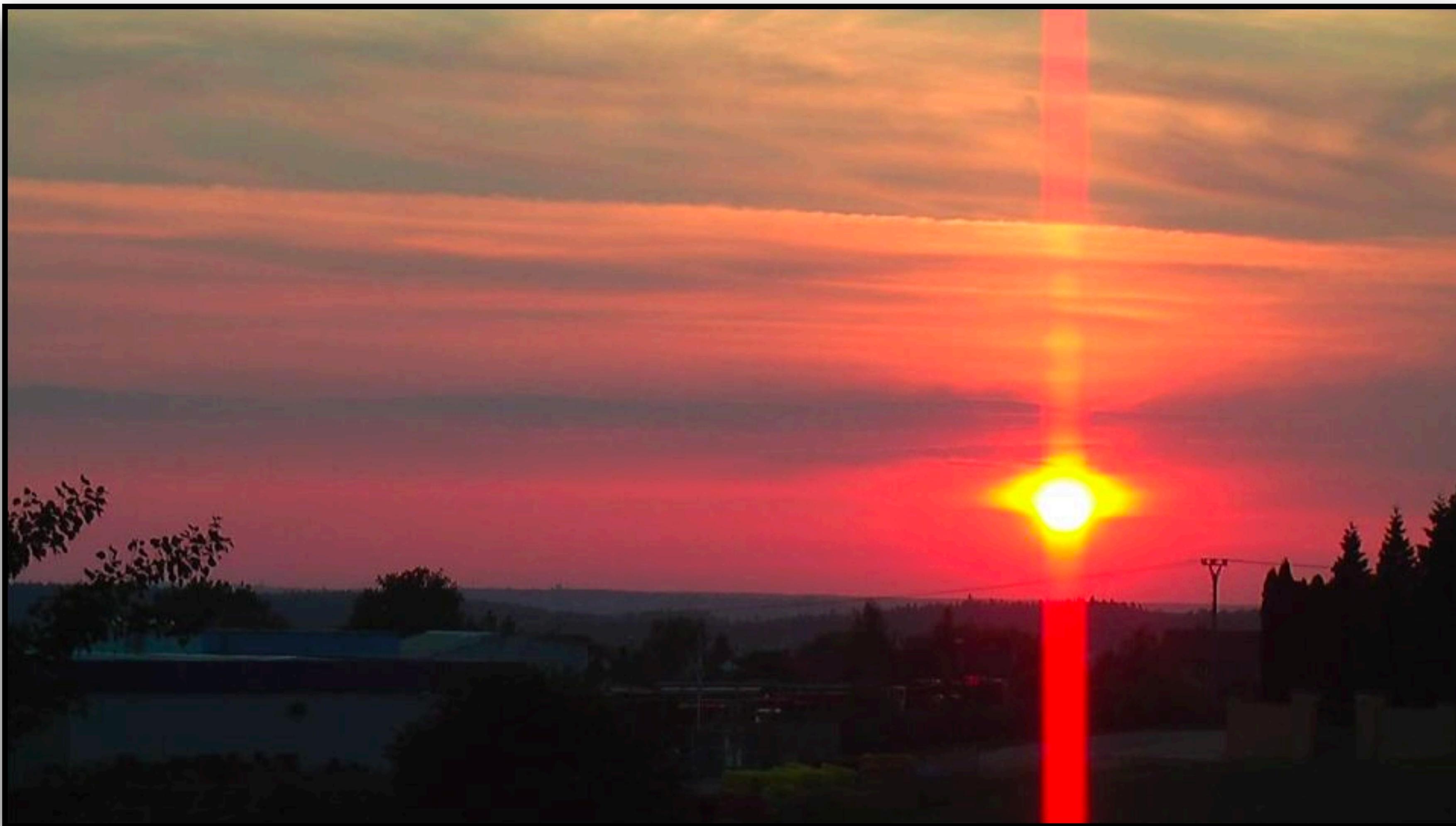
CCD Sensors

- Higher quality (FF higher), expensive
- Slower, higher power (circuitry needs precise timing control)
- Astrophysical imaging (e.g., telescopes) still prefers CCD sensors

CMOS Sensors

- Dominate the consumer photography market now, cheaper
- Same fabrication technology as digital microprocessors, enabling "camera on a chip"
- Faster and lower-power (can easily read just a small window of pixels)
- More noisy (e.g., each pixel has amplifier and/or ADC), but getting better

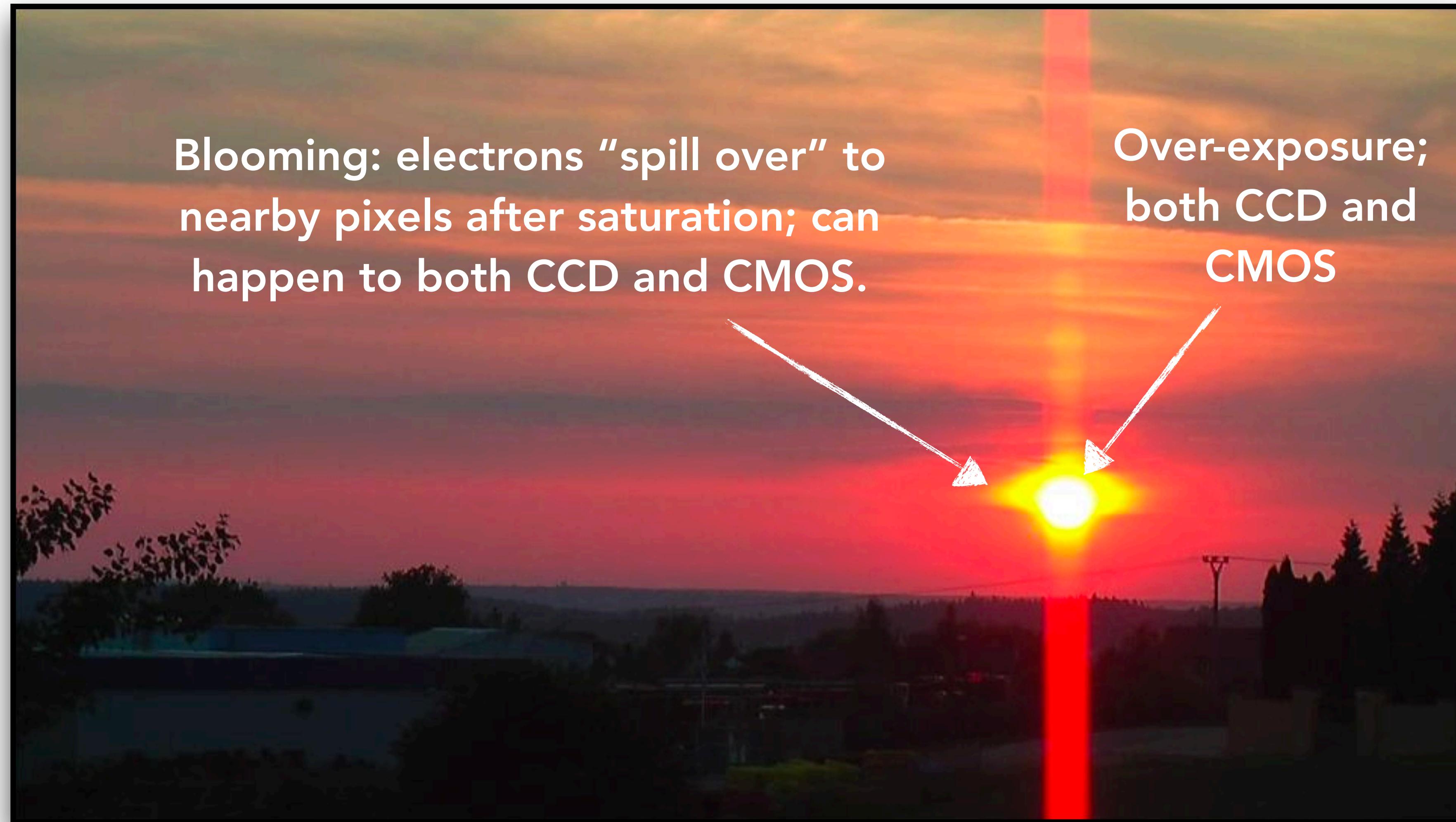
Over-Exposure, Blooming, Smearing



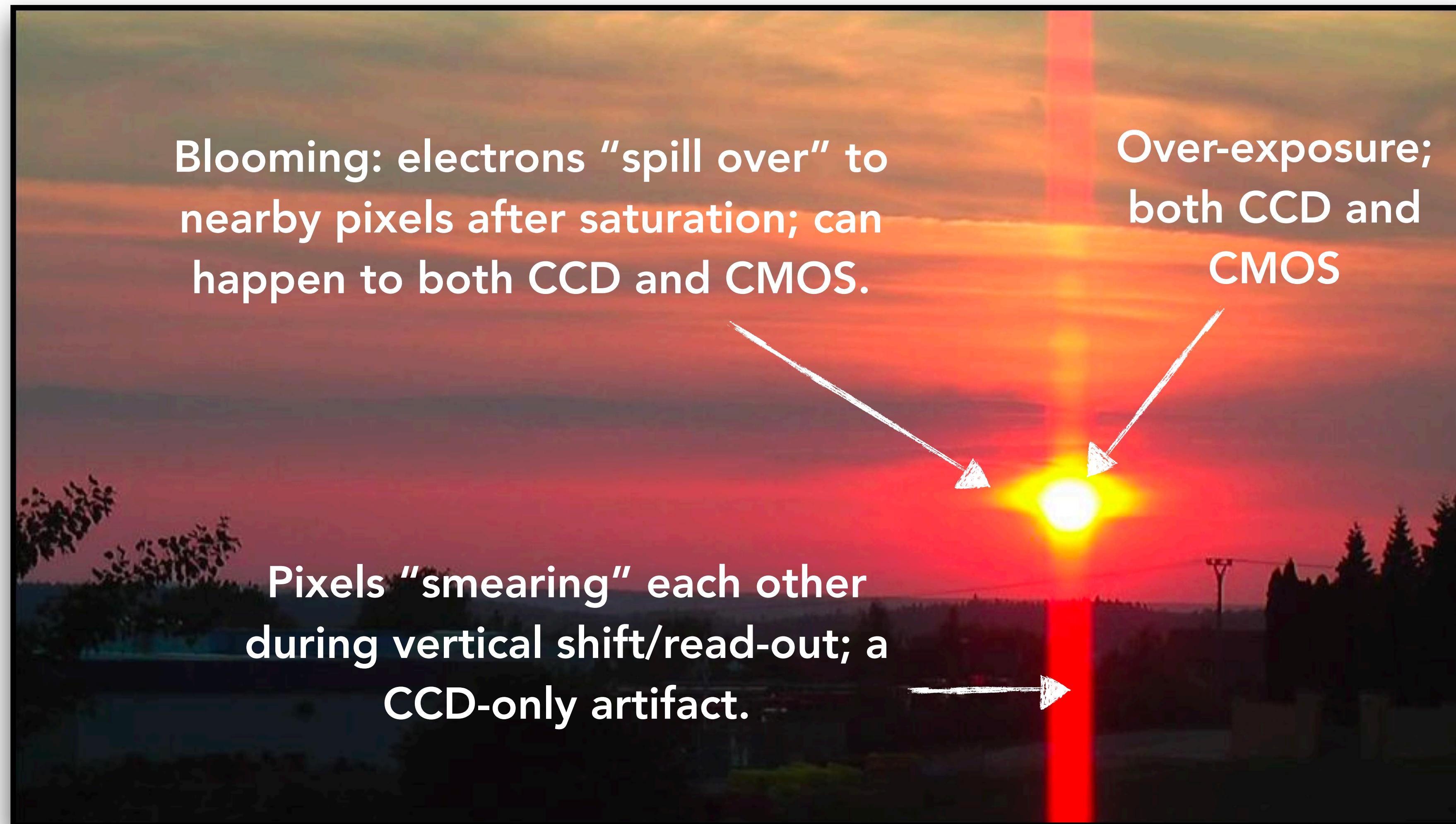
Over-Exposure, Blooming, Smearing



Over-Exposure, Blooming, Smearing



Over-Exposure, Blooming, Smearing



Time Delay Integration (TDI) CCD Sensor

CCD uses global shutter, but still doesn't avoid motion blur.

Long exposure introduces motion blur, but many application scenarios require a long exposure time, e.g., astrophysical imaging.

TDI is a clever sensor design that mitigates motion blur under long exposure.

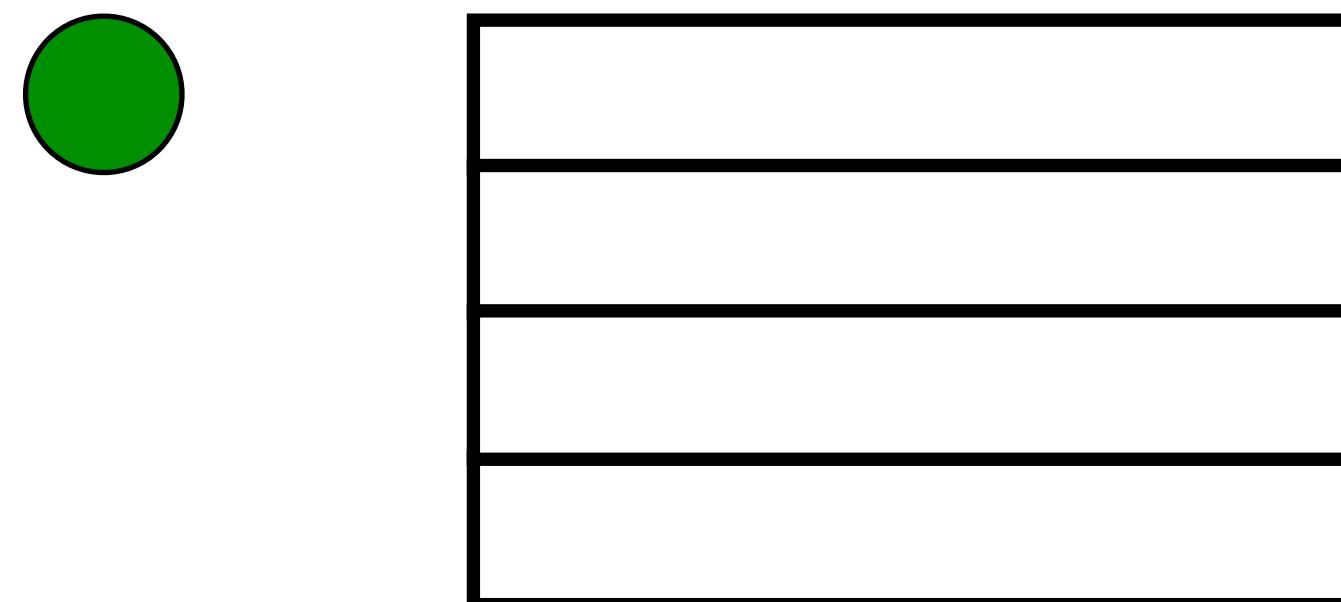
Conventional CCD sensor: shift pixel rows after exposure.

TDI CCD: shift rows during exposure and accumulate charges for each shift.

TDI Operation

The shift is in sync with object movement. Effectively capture a moving object N times, once per row, increasing the effective exposure time.

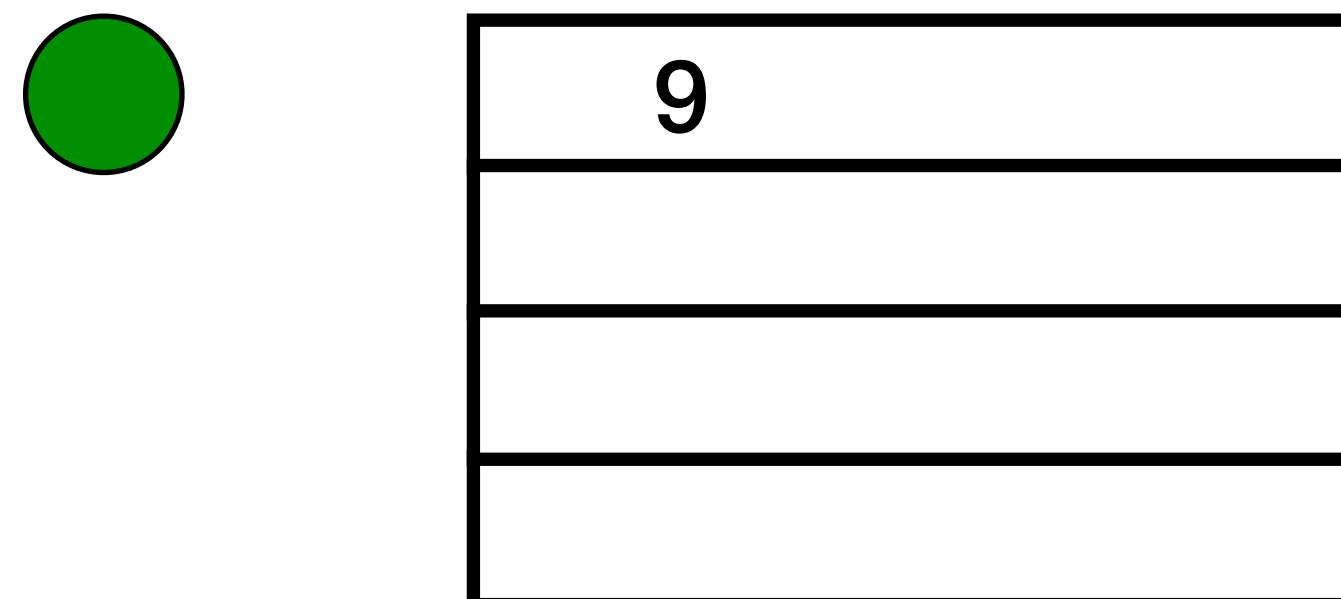
Object movement within a pixel doesn't matter (pixels integrate anyways).



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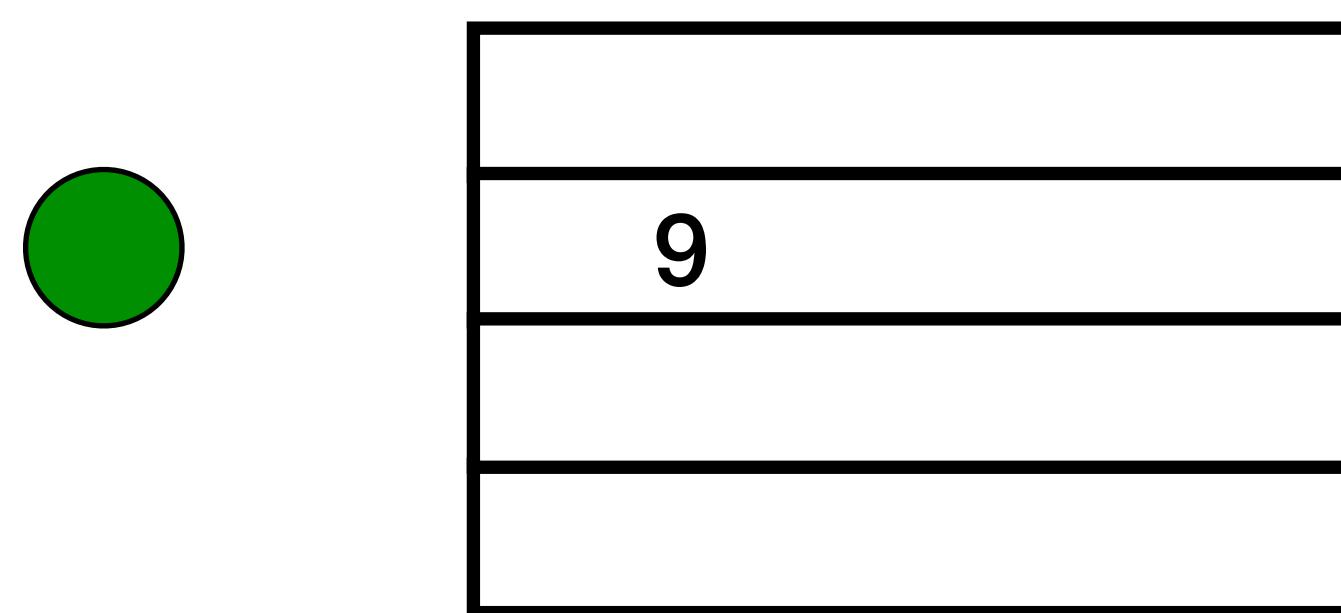
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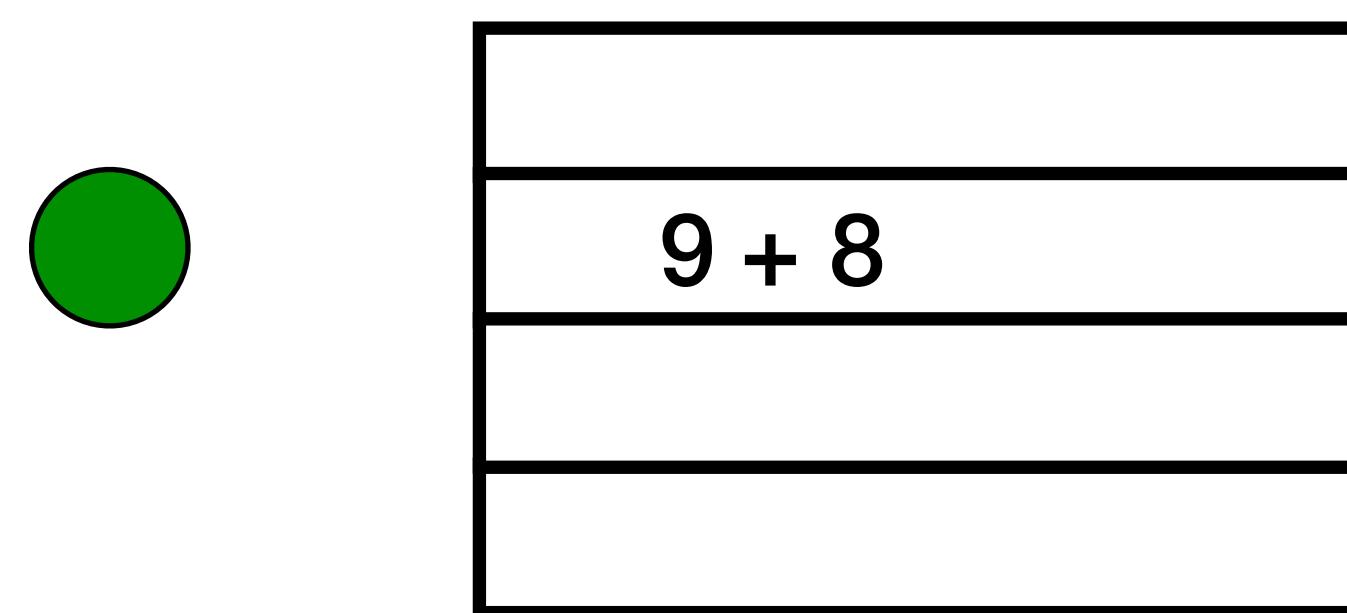
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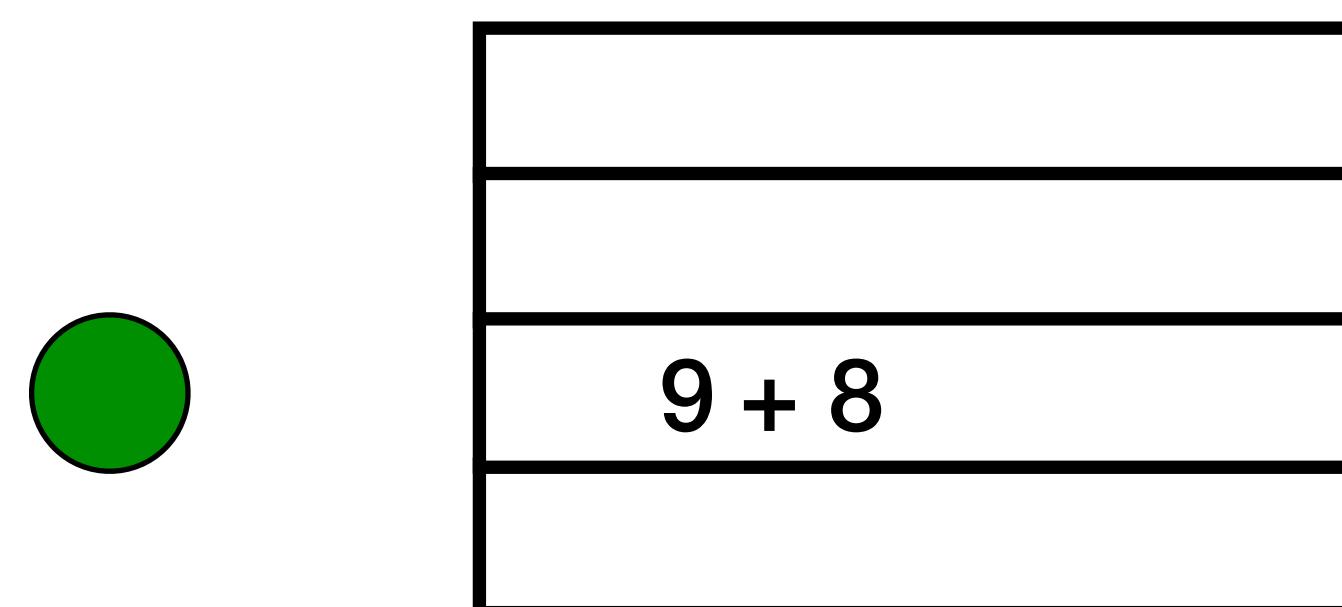
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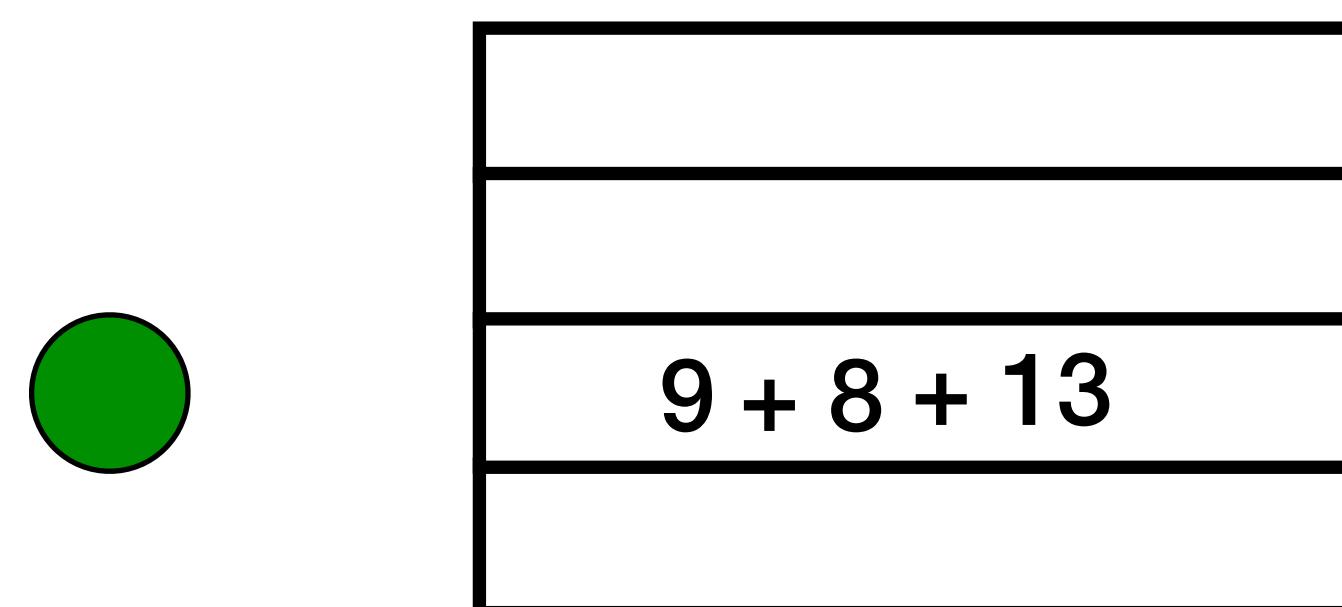
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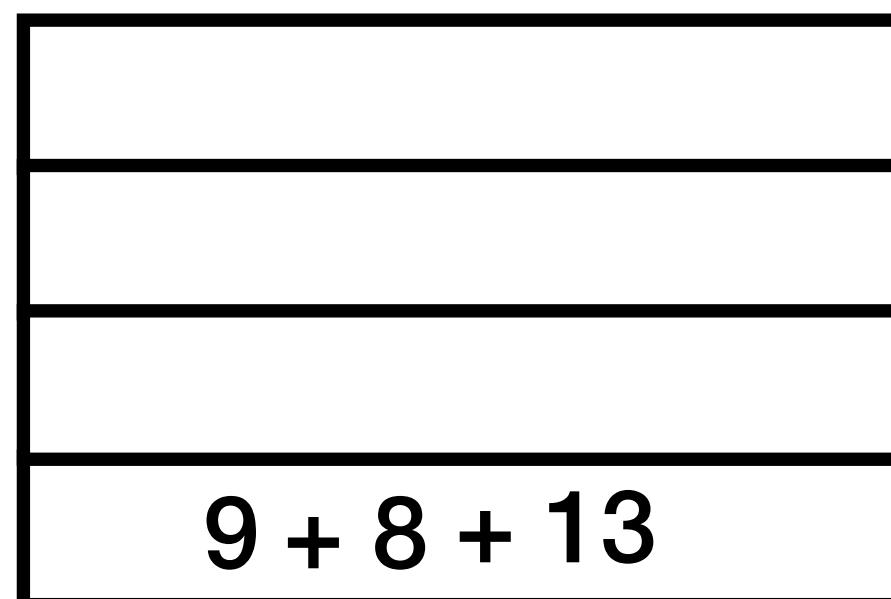
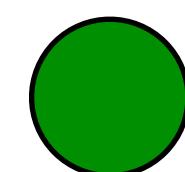
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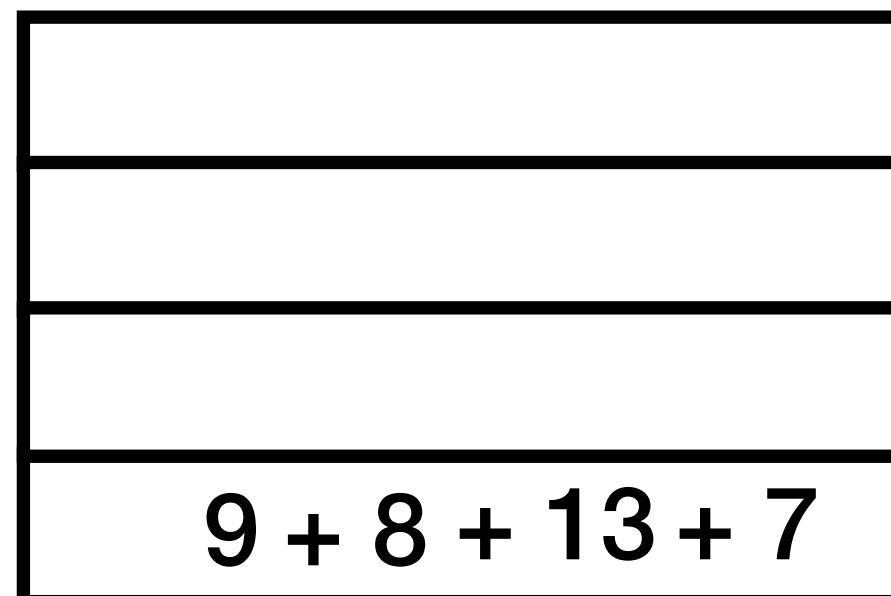
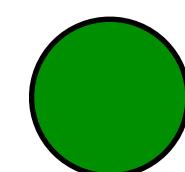
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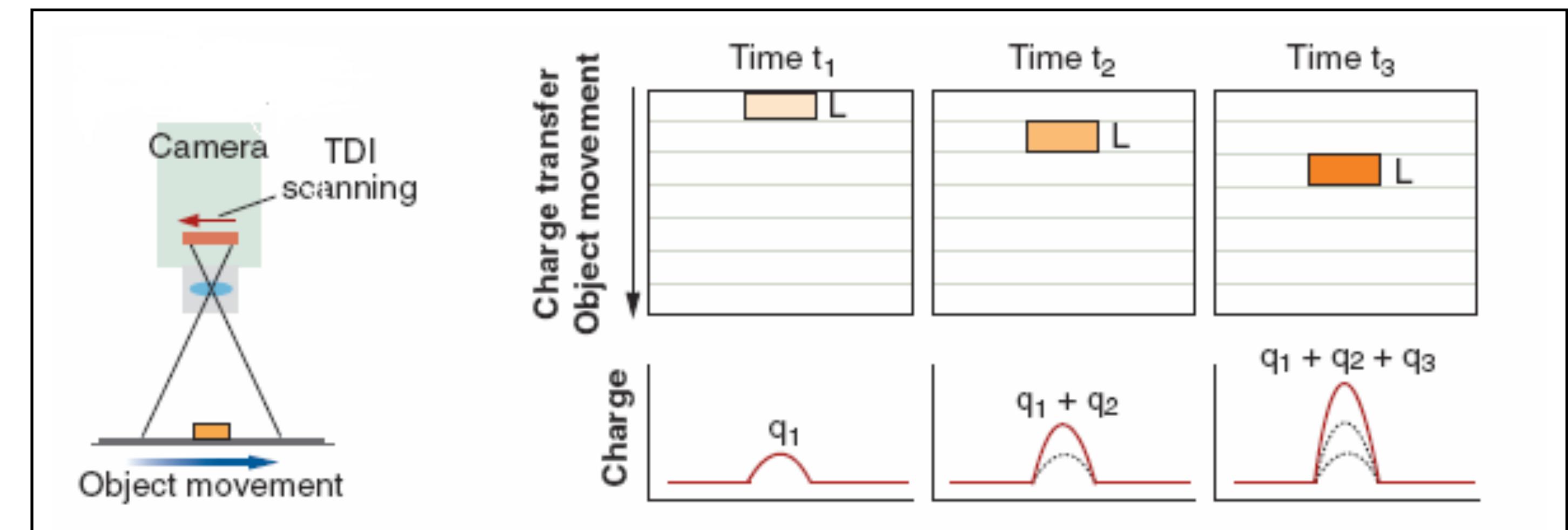
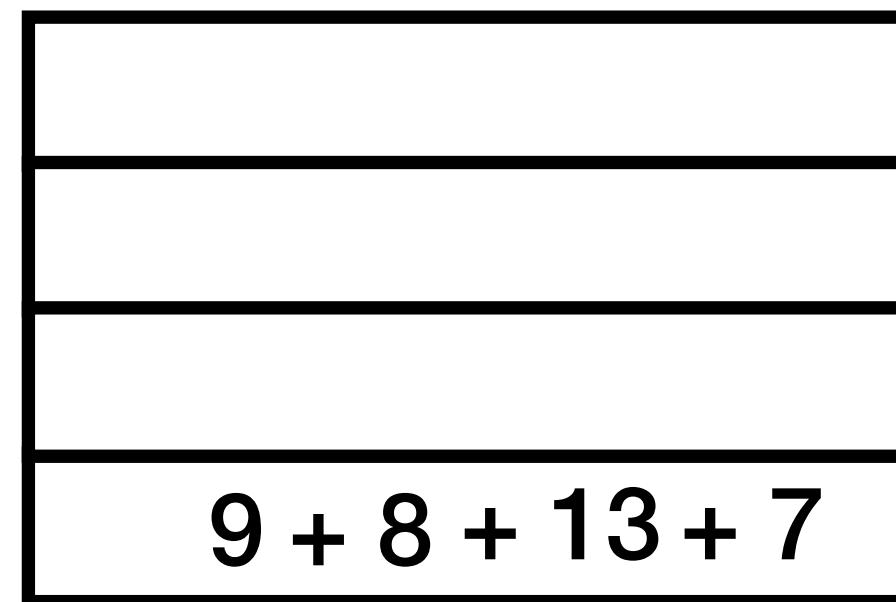
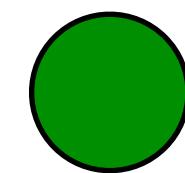
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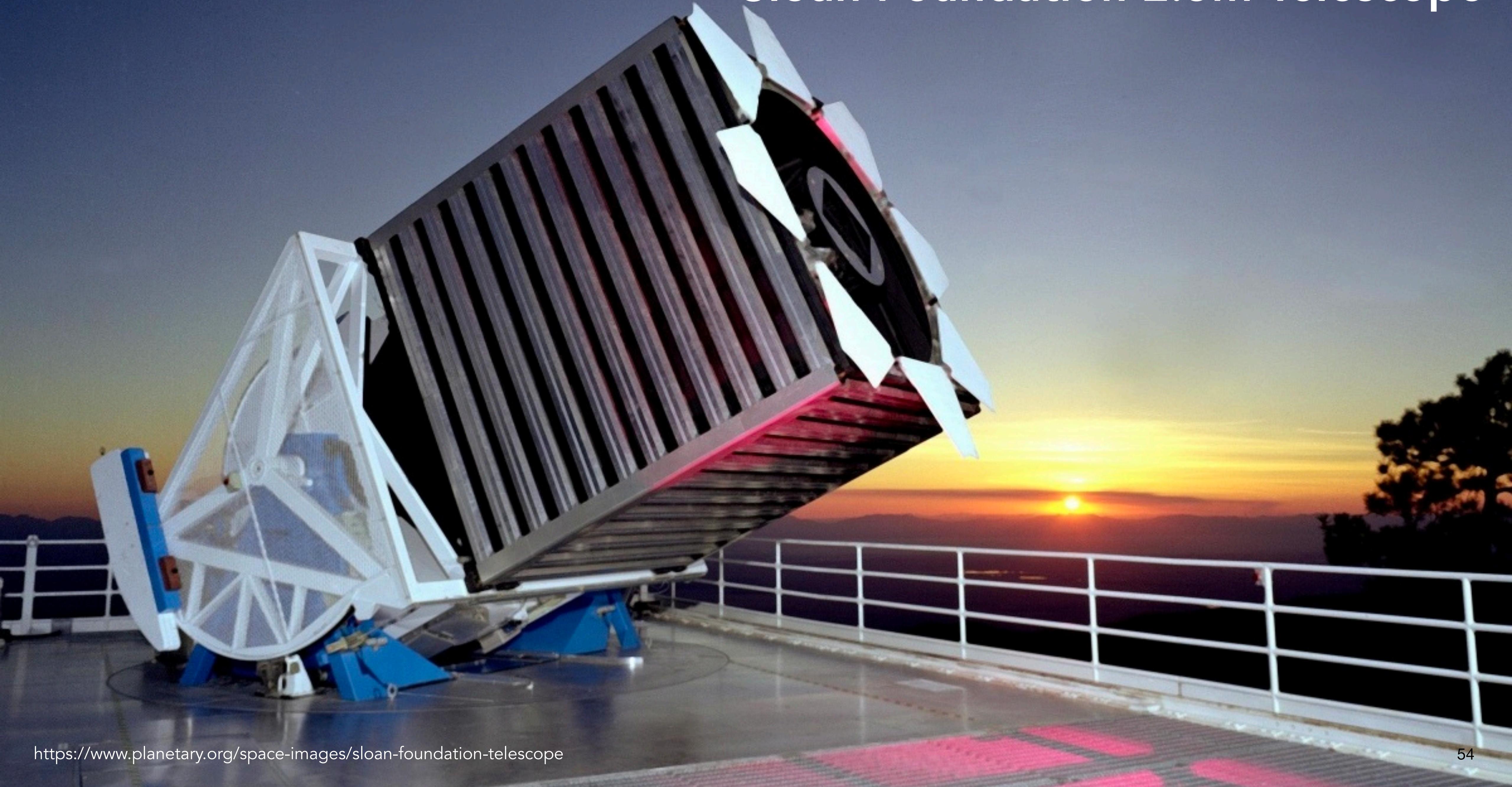
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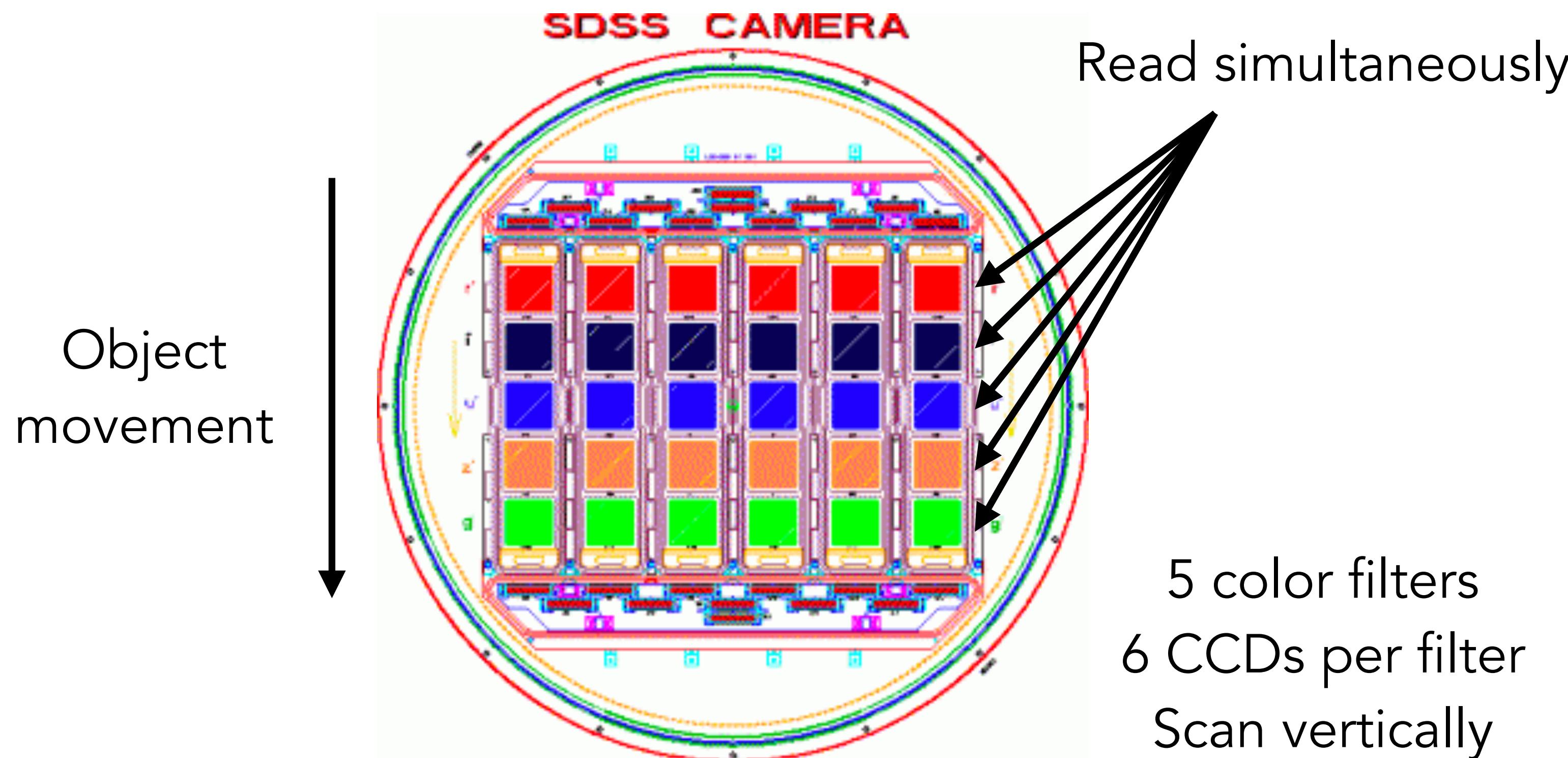


Sloan Foundation 2.5m Telescope



TDI in Astrophysics

Can estimate the TDI camera shift rate, since the star's movement speed is known.



Stacked Sensor

Why Stacking?

Enable in-sensor computing to reduce data transmission overhead

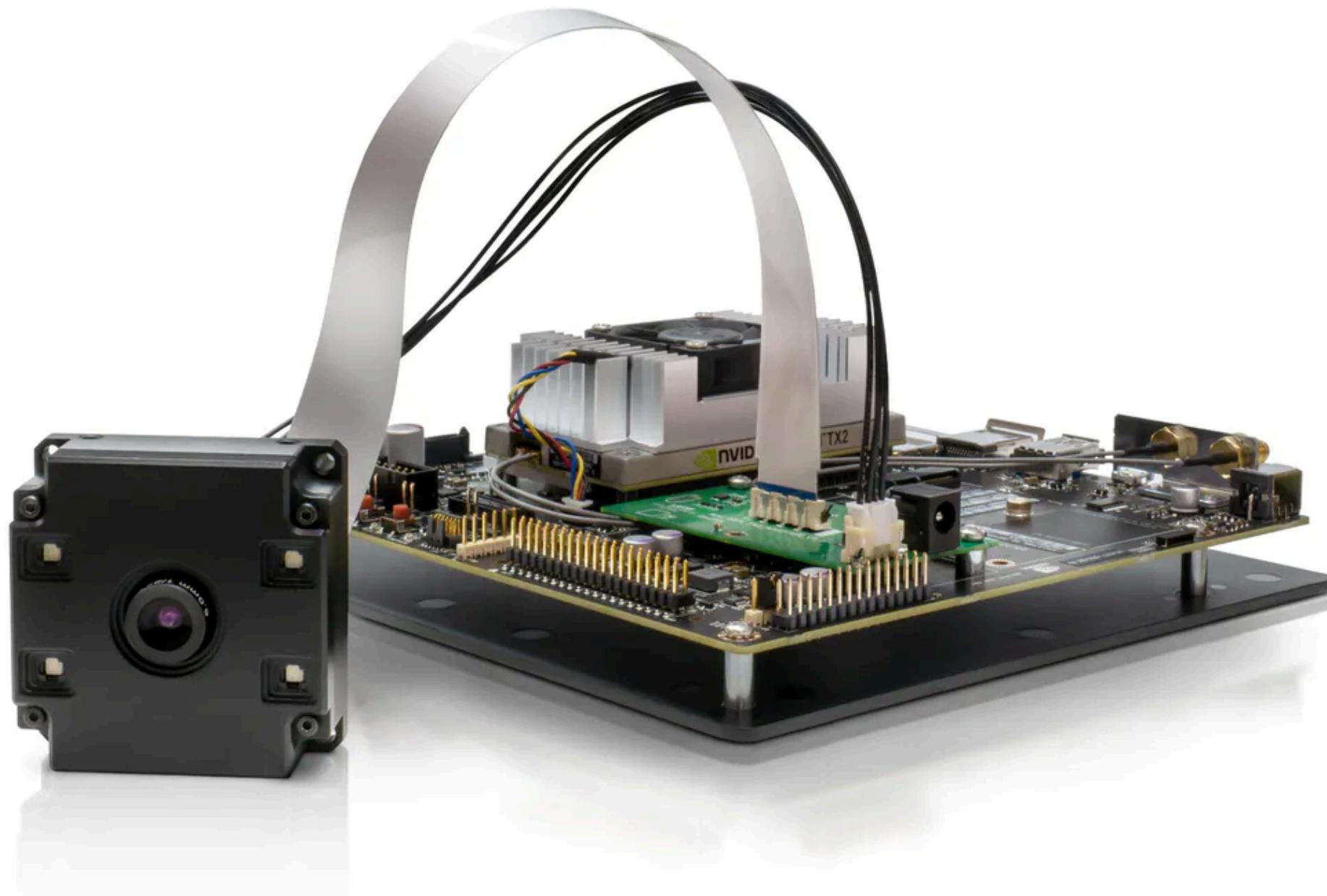
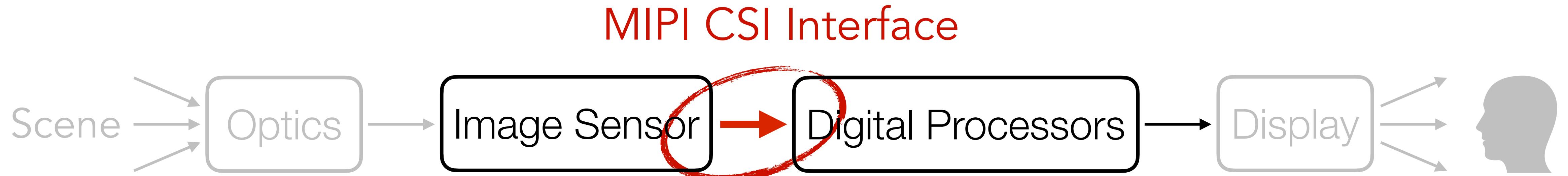
Save area:

- Pixels have become more complicated, taking more area.
- Grow vertically rather than horizontally to reduce sensor footprint.

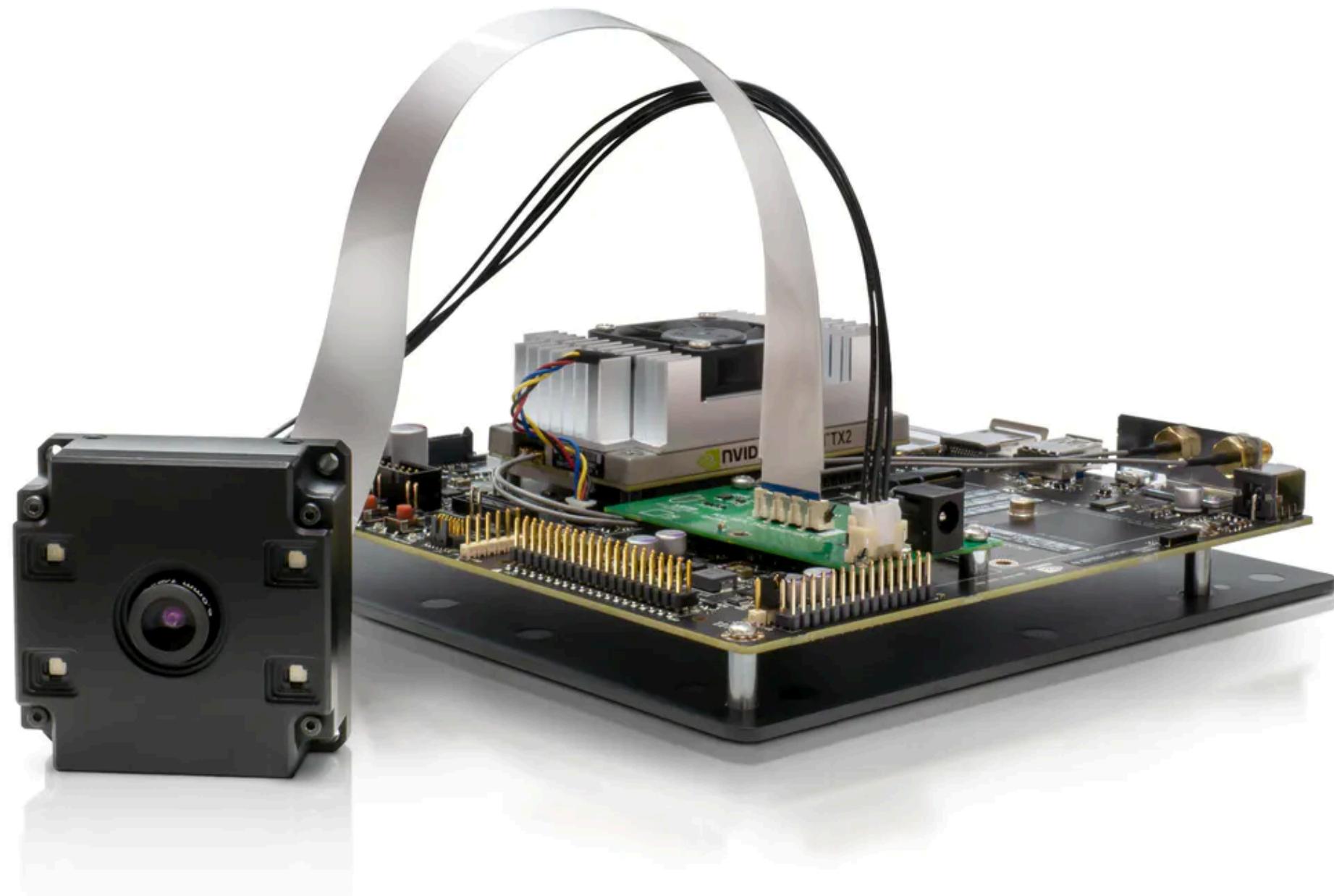
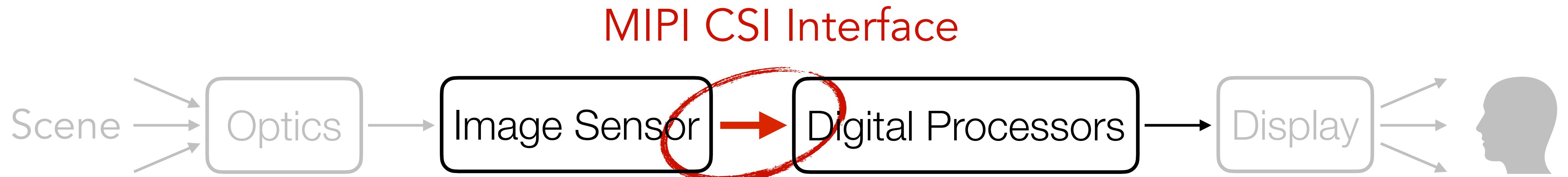
Can even stack memory (e.g., DRAM/SRAM) and processors with the pixel array in one sensor.

- Enable ultra-high frame rate
- Better support in-sensor processing (imaging you have a cache in sensor!)

Data Transmission Bottleneck



Data Transmission Bottleneck



Energy

1 B MAC
Compute

1

1 B MIPI
CSI-2 Tx



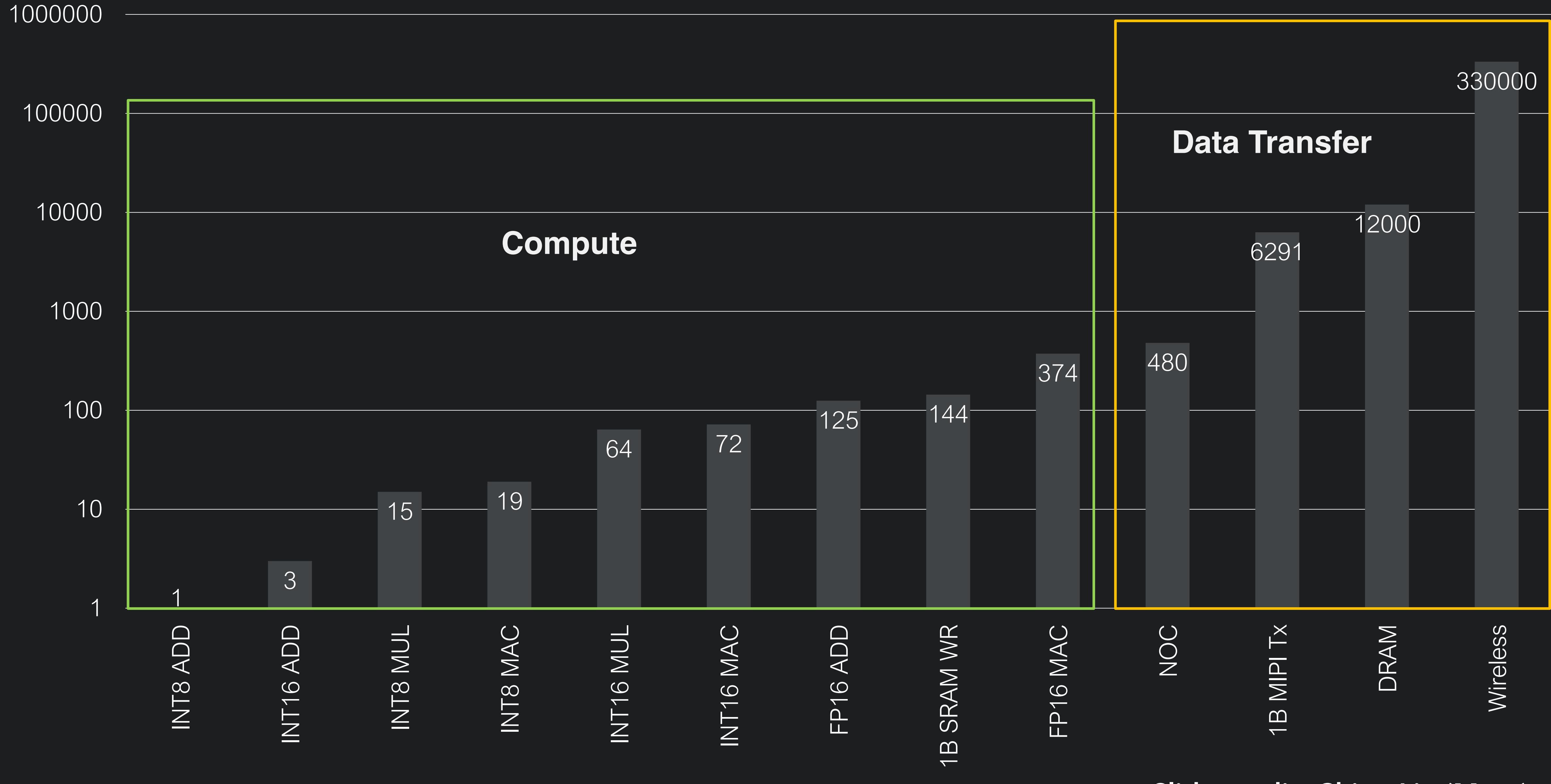
~331 X

1 B WiFi

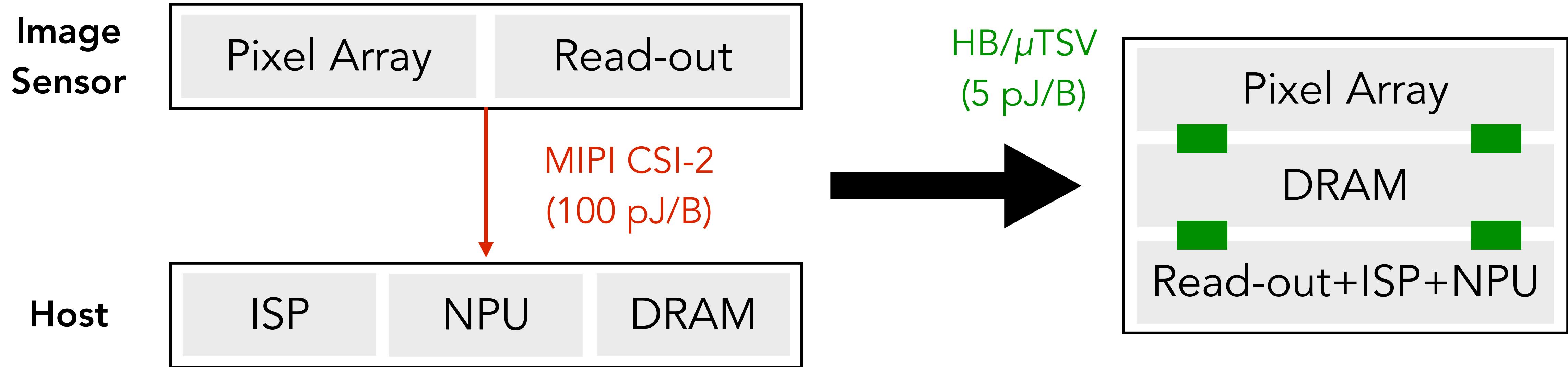


~10⁵ X

Normalized Energy

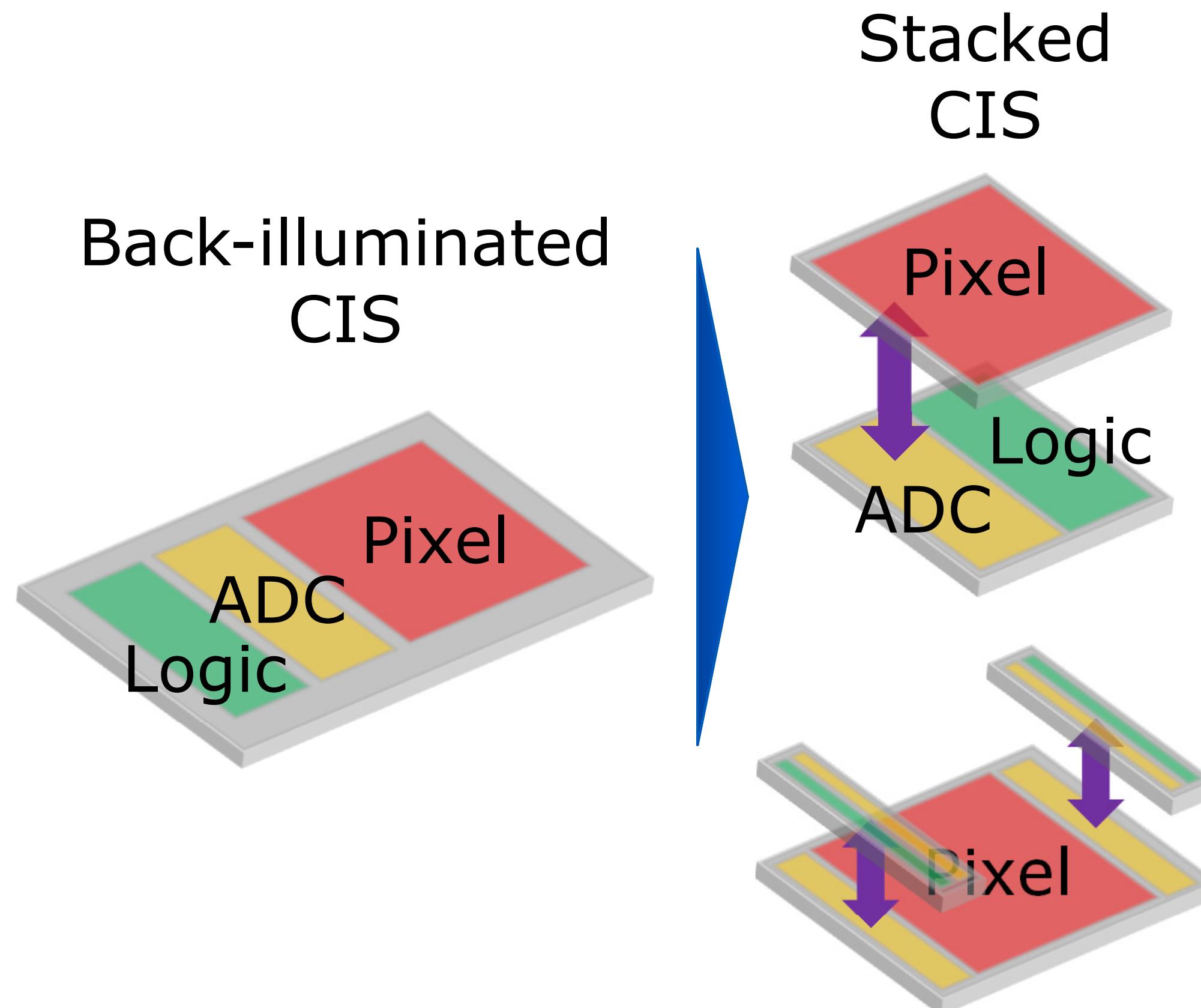


Moving Computation Into Sensor



Stacked CMOS Image Sensor

- Performance improvement accelerated using 3D configuration

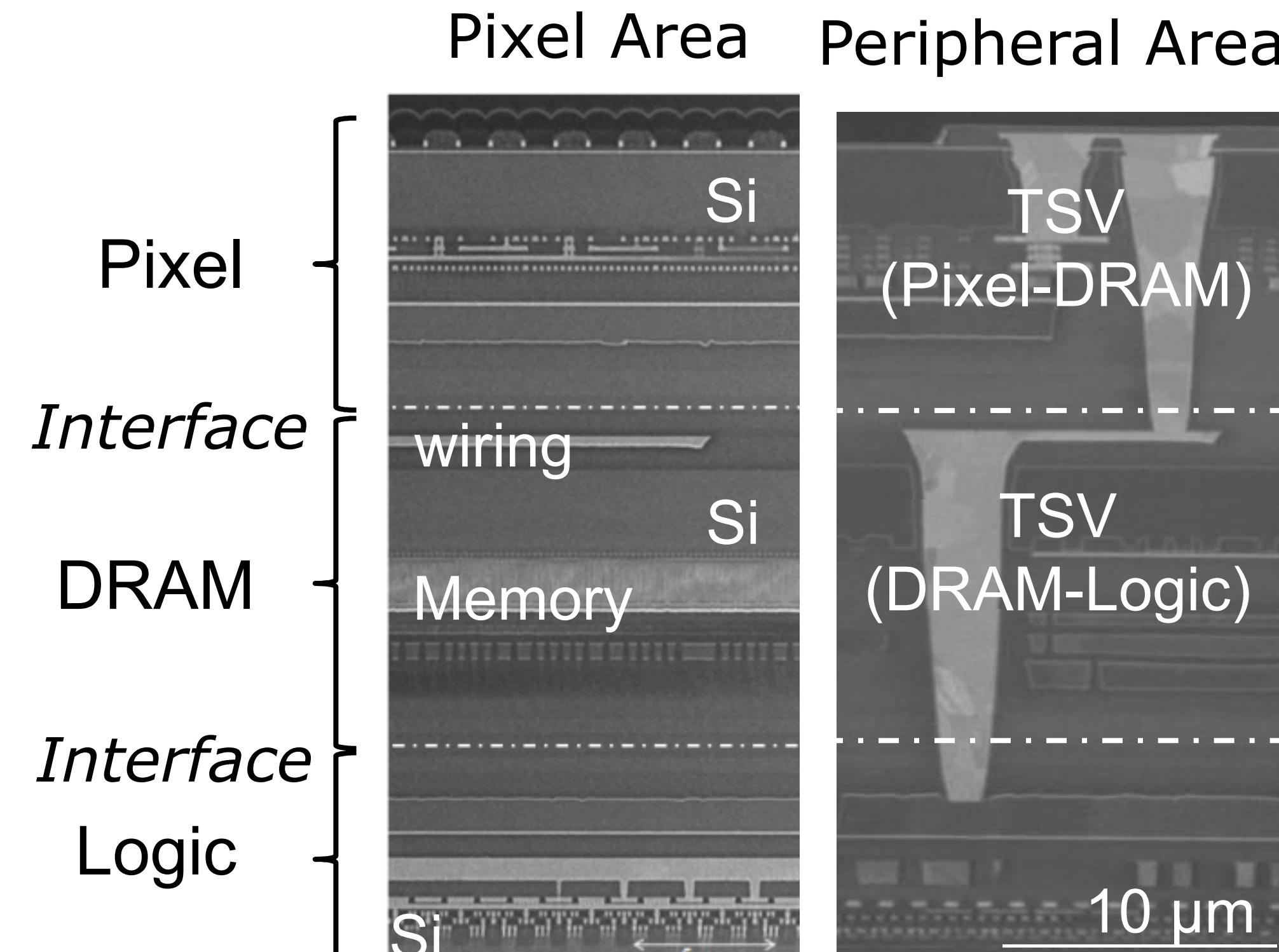
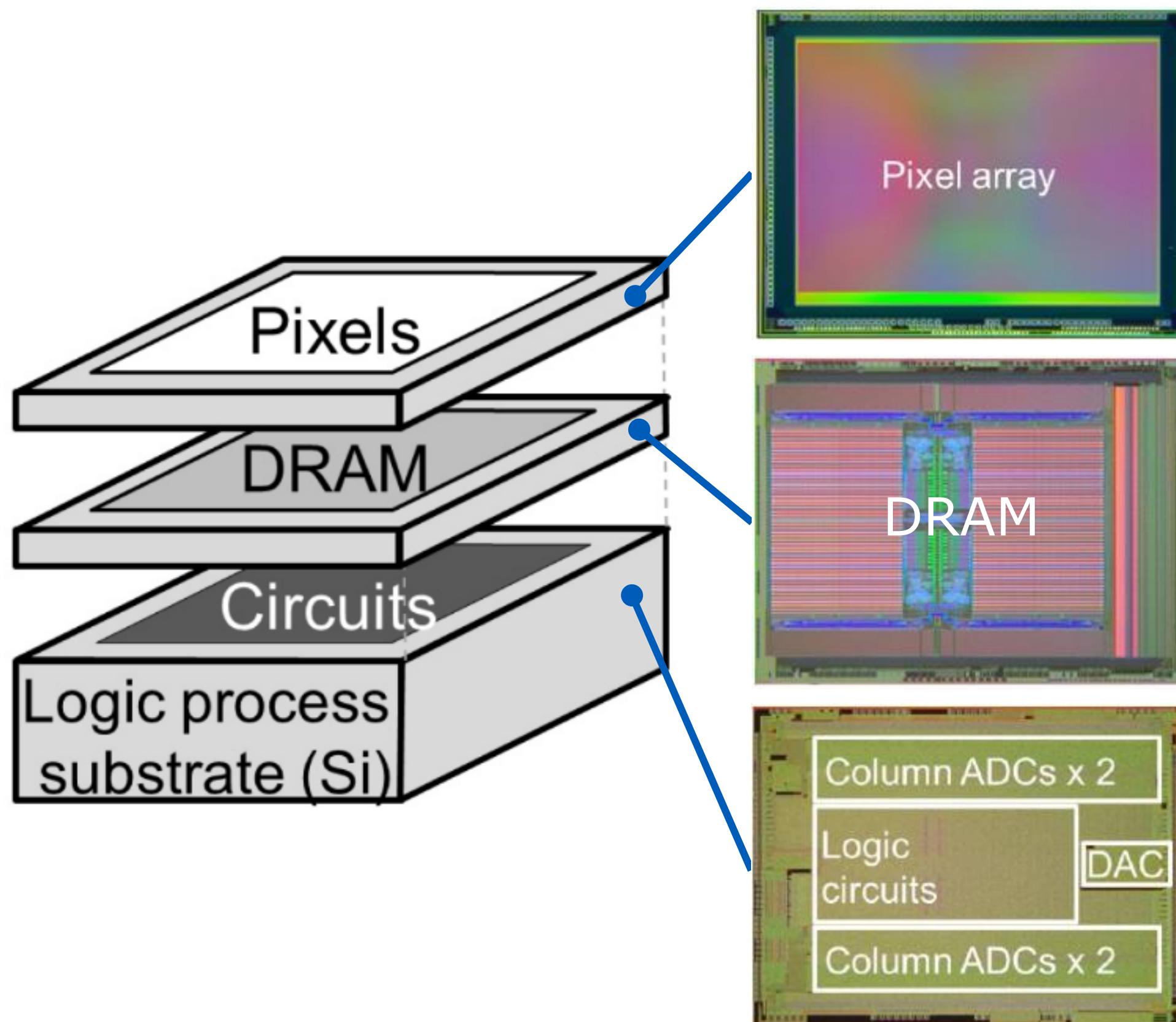


Highly parallel ADCs & Optimized process technologies

- Double parallel ADCs
- Chip-on-chip stacked CIS
- Three-layer stacked CIS

Three-layer Stacked CIS with DRAM

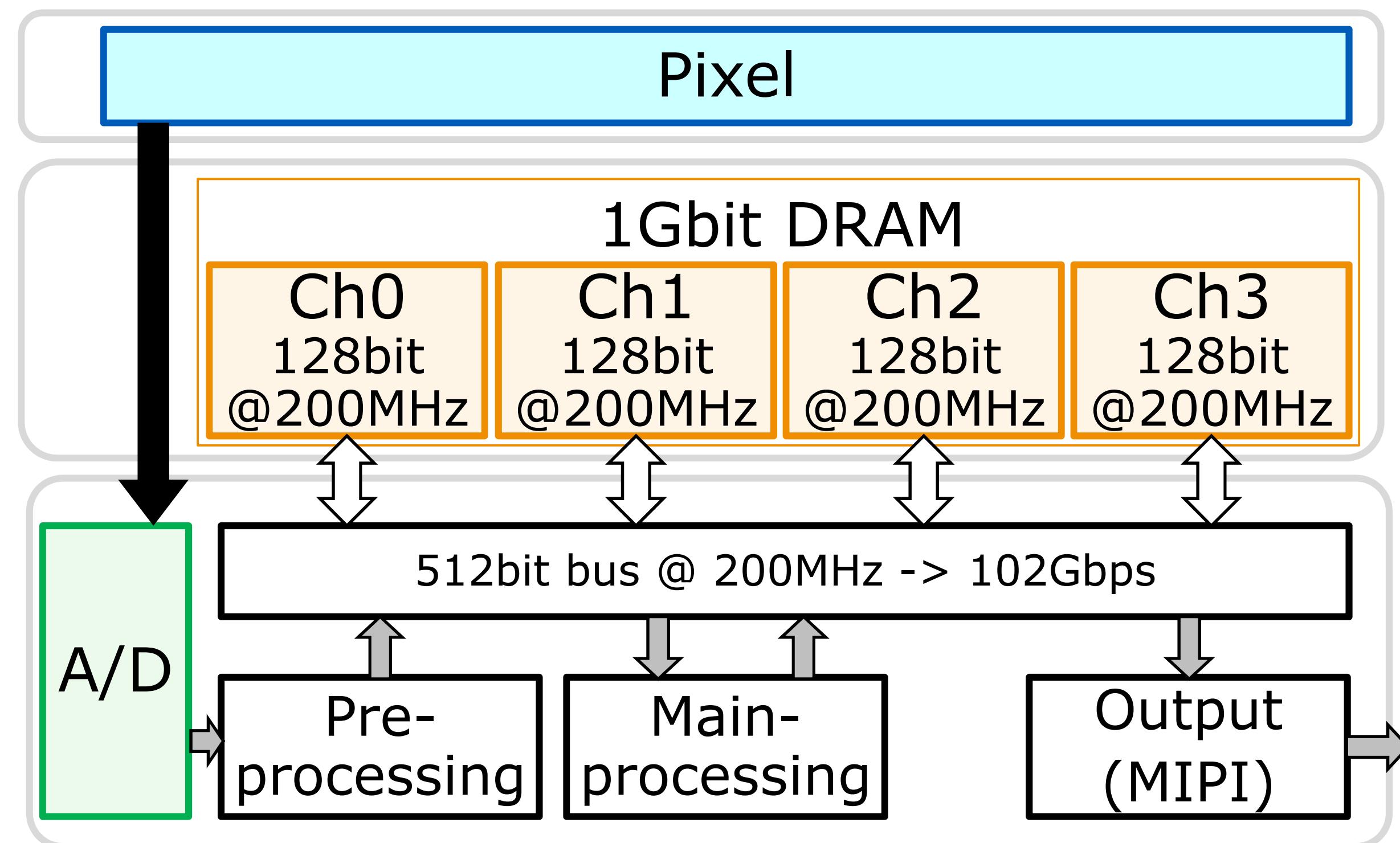
- DRAM buffer having wide data bandwidth for slow-motion capture



T. Haruta, ISSCC 2017
H. Tsugawa, IEDM 2017

Sony Develops the Industry's First^{*1} 3-Layer Stacked CMOS Image Sensor with DRAM for Smartphones

High-Speed Data Readout Minimizes Distortion^{*2} in Still Images, and Enables Super Slow Motion Movie Shooting



Data read-out is slow, limiting the frame rate to be ~ 100 FPS max.

In-sensor DRAM stores high-speed captures to enable high speed capture (~1,000 FPS)

25 Mbps to CPU

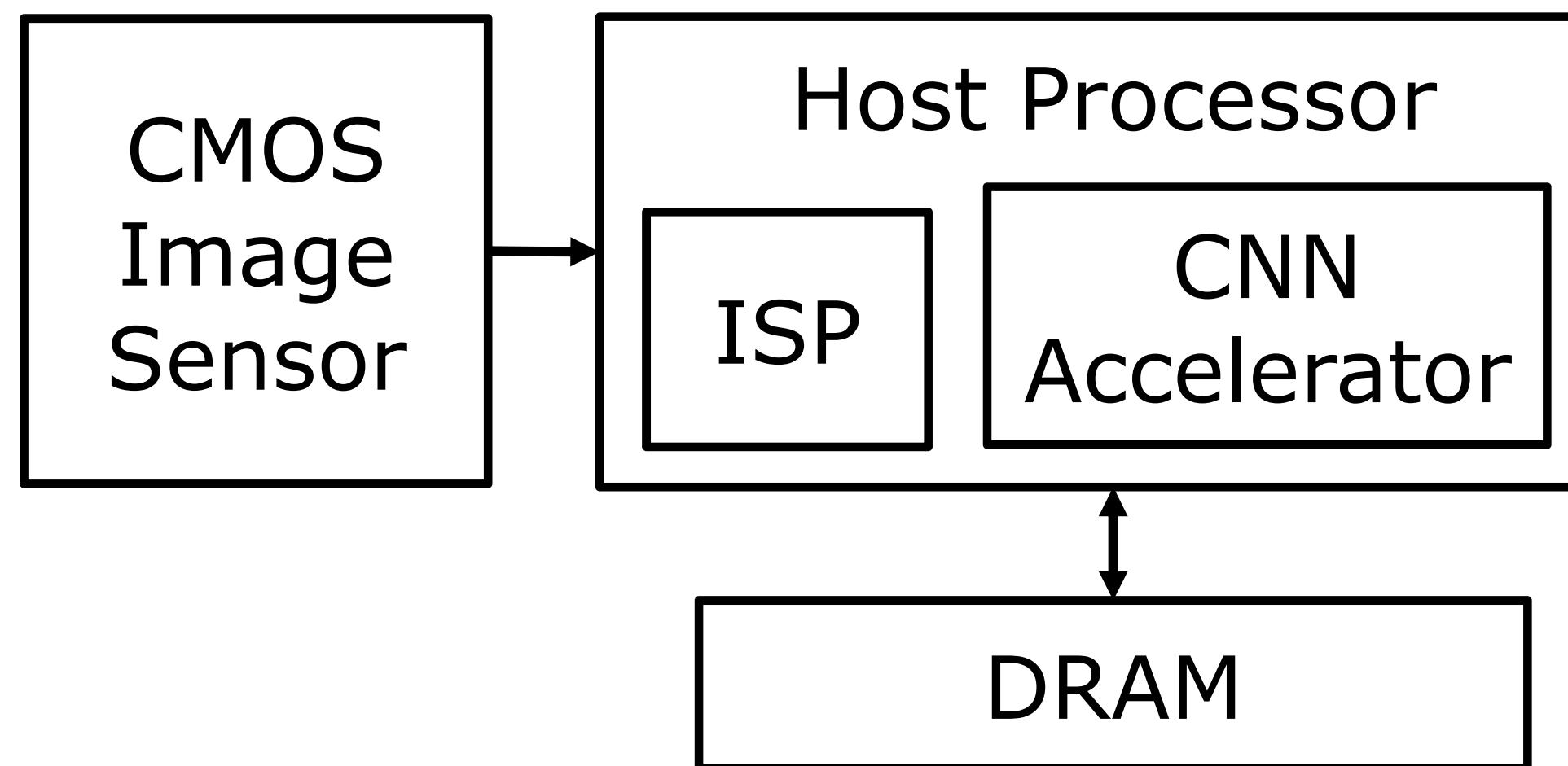
speed

T. Haruta, ISSCC 2017

Sony to Release World's First Intelligent Vision Sensors with AI Processing Functionality^{*1}

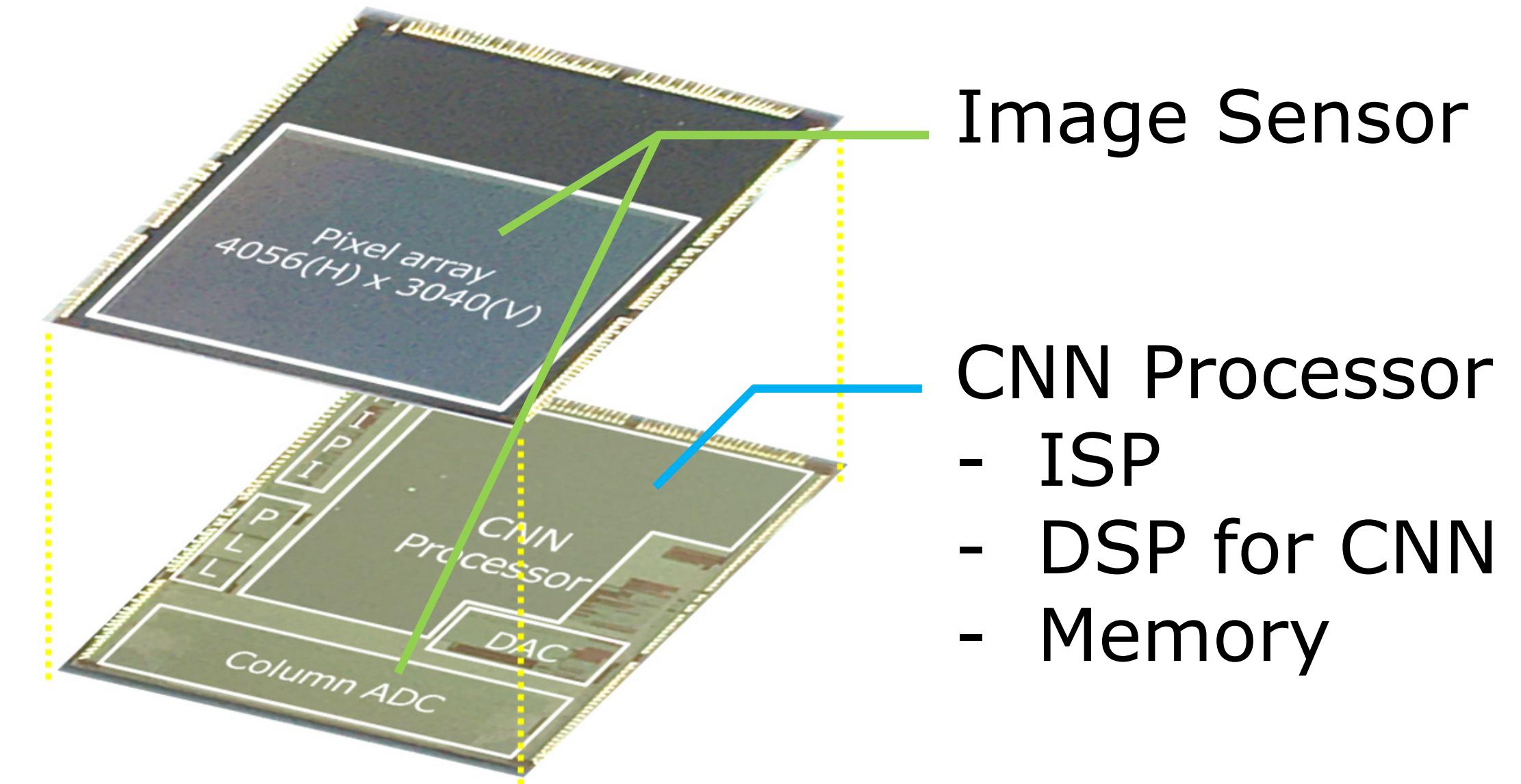
Enabling High-Speed Edge AI Processing and Contributing to Building of Optimal Systems Linked with the Cloud

Conventional Configuration



Larger, higher power and more costly

Intelligent Vision Sensor



All functions are implemented on chip

To be presented by R. Eki, ISSCC 2021