CAMERA SENSORS FOR MICROSCOPY

James Francis

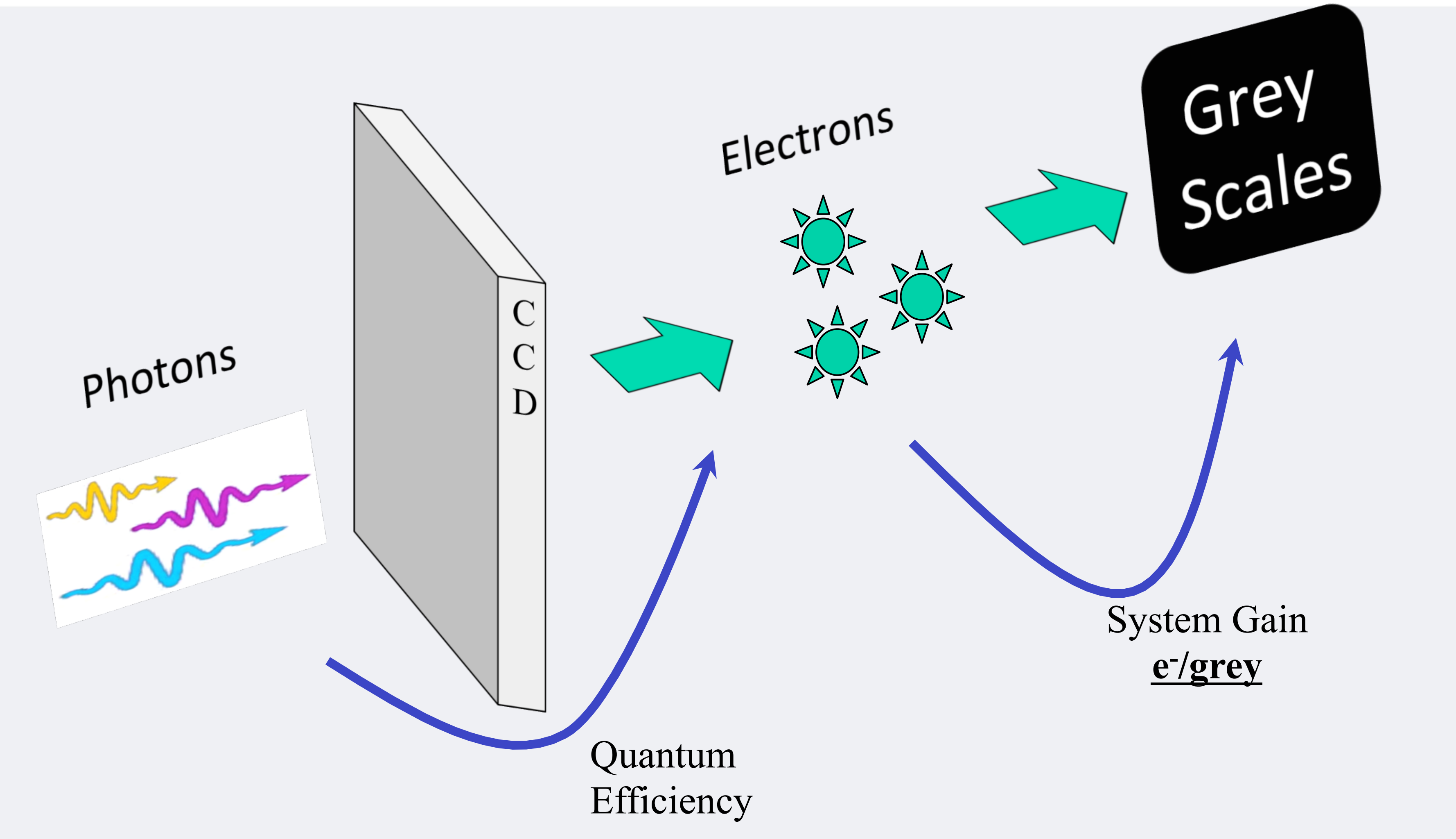
PHOTOMETRICS®
a division of Roper Scientific, Inc.

What do we want a sensor to do?

- Take a image – full marks have a medal….

- Quickly / As fast as we can
- From many different light levels
- With good dynamic range
- From signals of differing emission wavelengths
- With enough resolution to see detail
- With limited noise

What is the job of the sensor



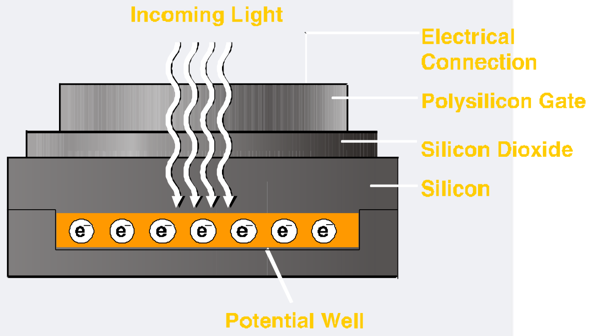
What is Quantum Efficiency?

- Quantum efficiency (QE) is the measure of the effectiveness of an imager to produce electronic charge from incident photons.

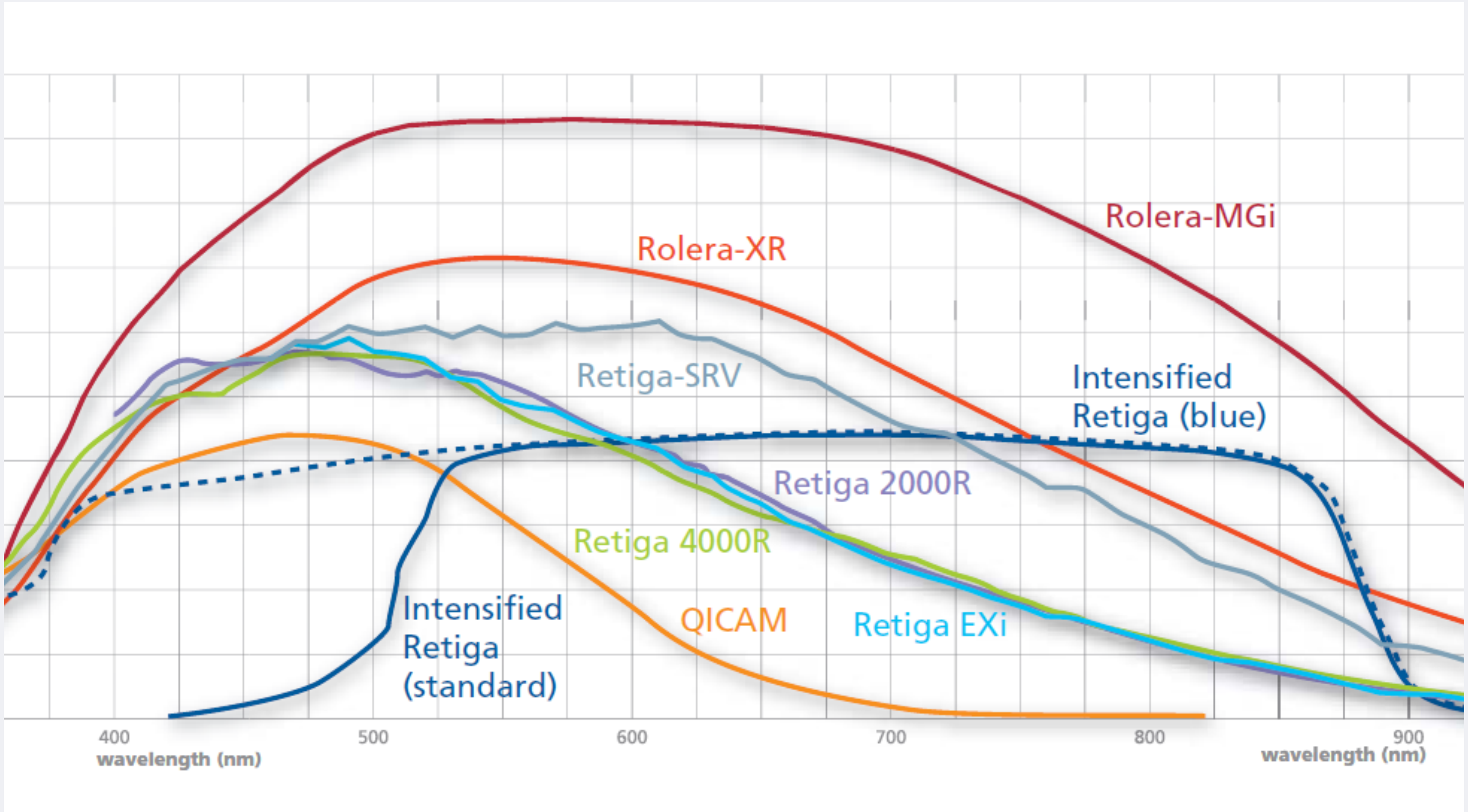
- In the high-purity crystalline form, each atom of silicon is covalently bonded to its neighbour. Energy greater than the band gap energy, about 1.1 eV, is required to break a bond and create an electron/hole pair.

- The wavelength of incoming light and photon absorption depth are directly related; the shorter the wavelength, the shorter the penetration depth into the silicon.

- Light normally enters the CCD through gates of the parallel register (front-illuminated CCD). These gates are made of very thin polysilicon, which is reasonably transparent at long wavelengths, but becomes opaque at wavelengths shorter than 400 nm. Thus, at short wavelengths, gate structure attenuates incoming light.



Sensors Response



Factors which Conspire Against us

- Signal Level – Do our samples give enough light for our required exposure or sample rate

- Noise – Do we have noise interfering with our signal

- Data Rate – Can the sensor or PC interface handle the speed we want to go

- Patterns/Glows – Cameras need a lot of engineering effort to ensure your image is not distorted by the efforts to get the signal from the sensor

Sensors – What are our main types

- CCD – Charged Coupled Device
- EMCCD – Electron Multiplied CCD
- CMOS – Complementary Metal Oxide Semiconductor

CCD Fundamentals

The Charge-Coupled Device

- Invented in 1970 at Bell Labs
- A silicon chip that converts an image to an electrical signal
- Image is focused directly onto the silicon chip
- Widely used in TV cameras and consumer camcorders
- Special high-performance CCDs made by:

    Eastman Kodak (Rochester, NY)

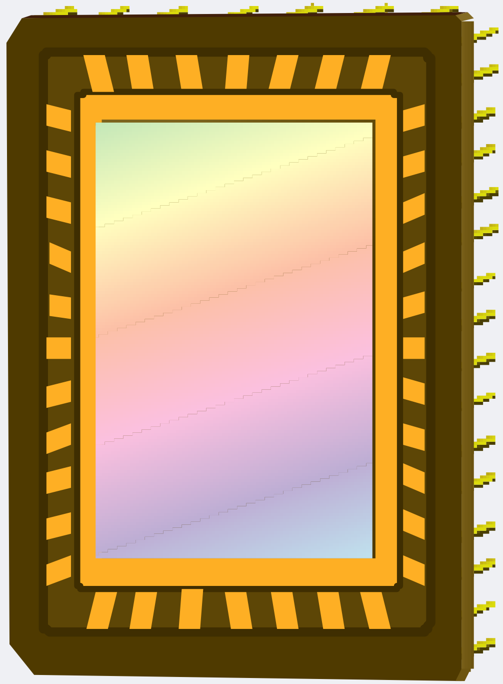
    Thomson CSF (France)

    Marconi (formerly EEV — England)

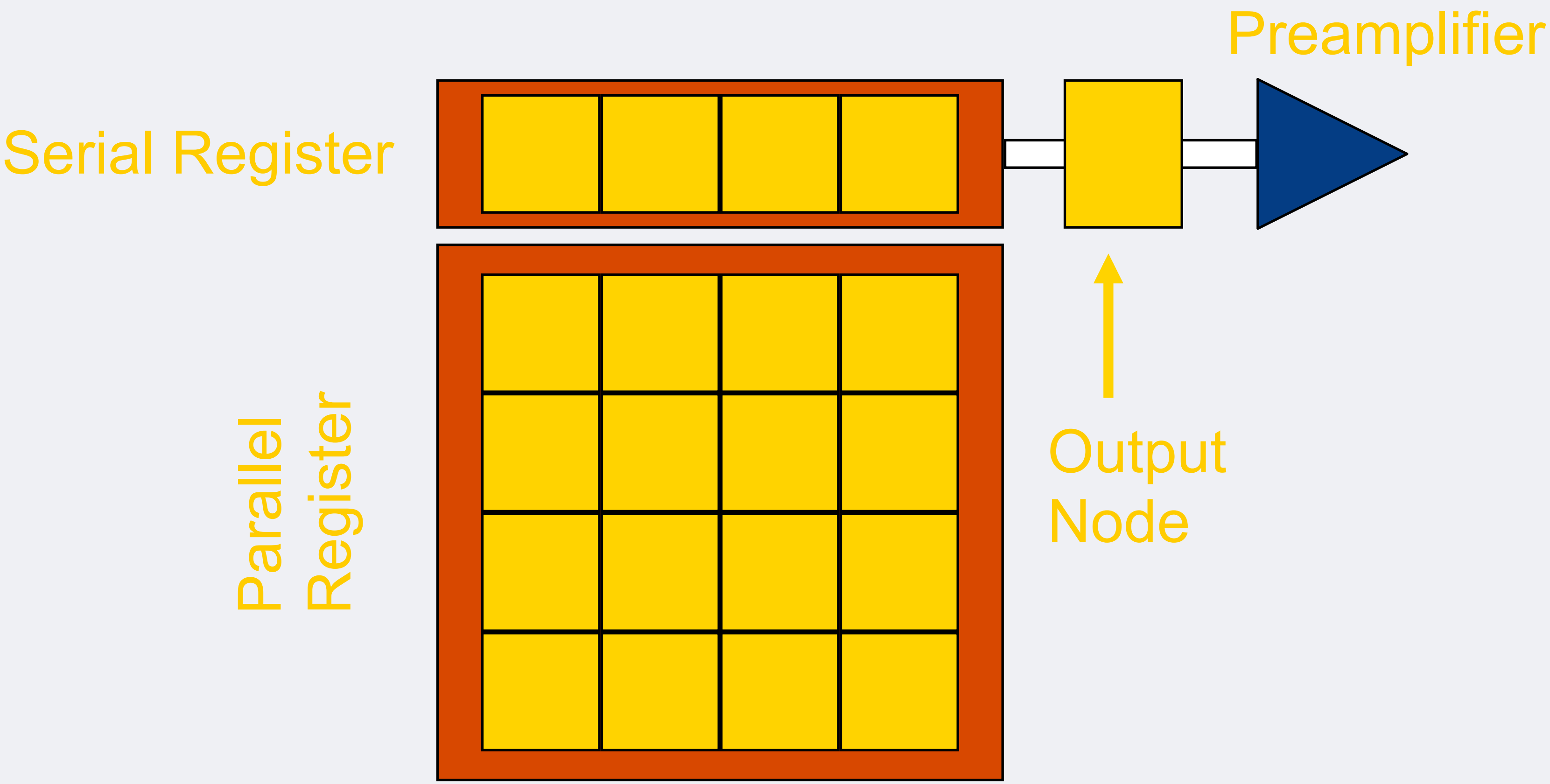
    SITe (Beaverton, OR)

    Sony

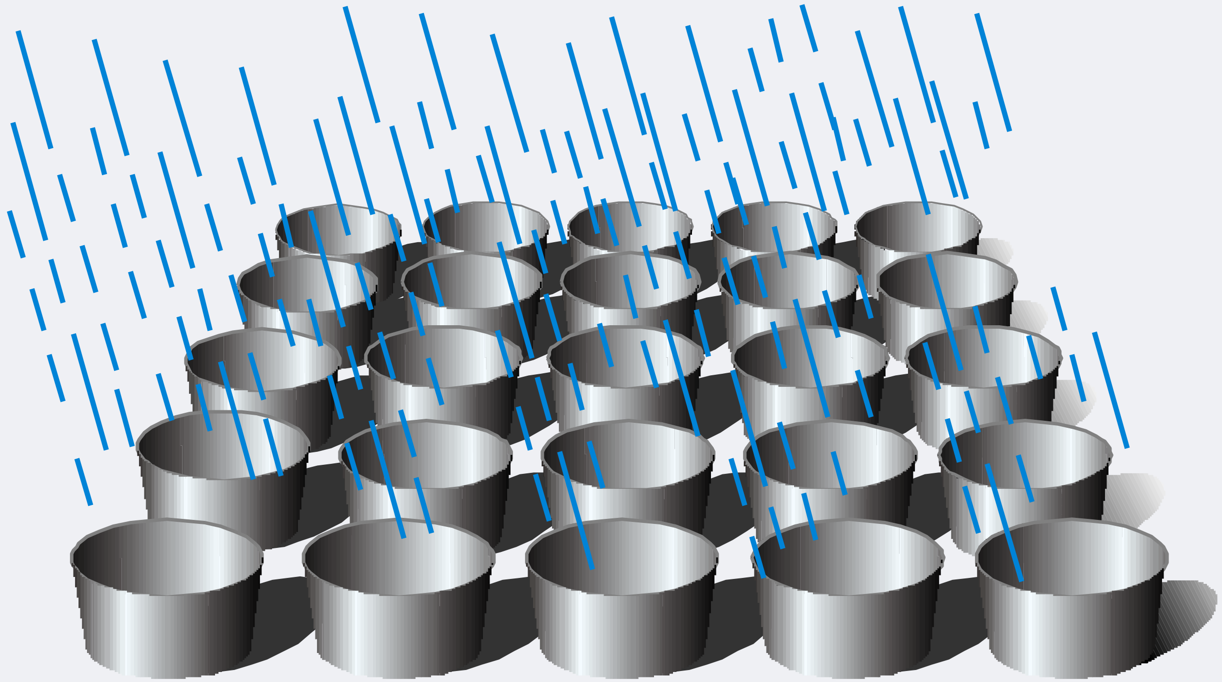
    Others



CCD Fundamentals

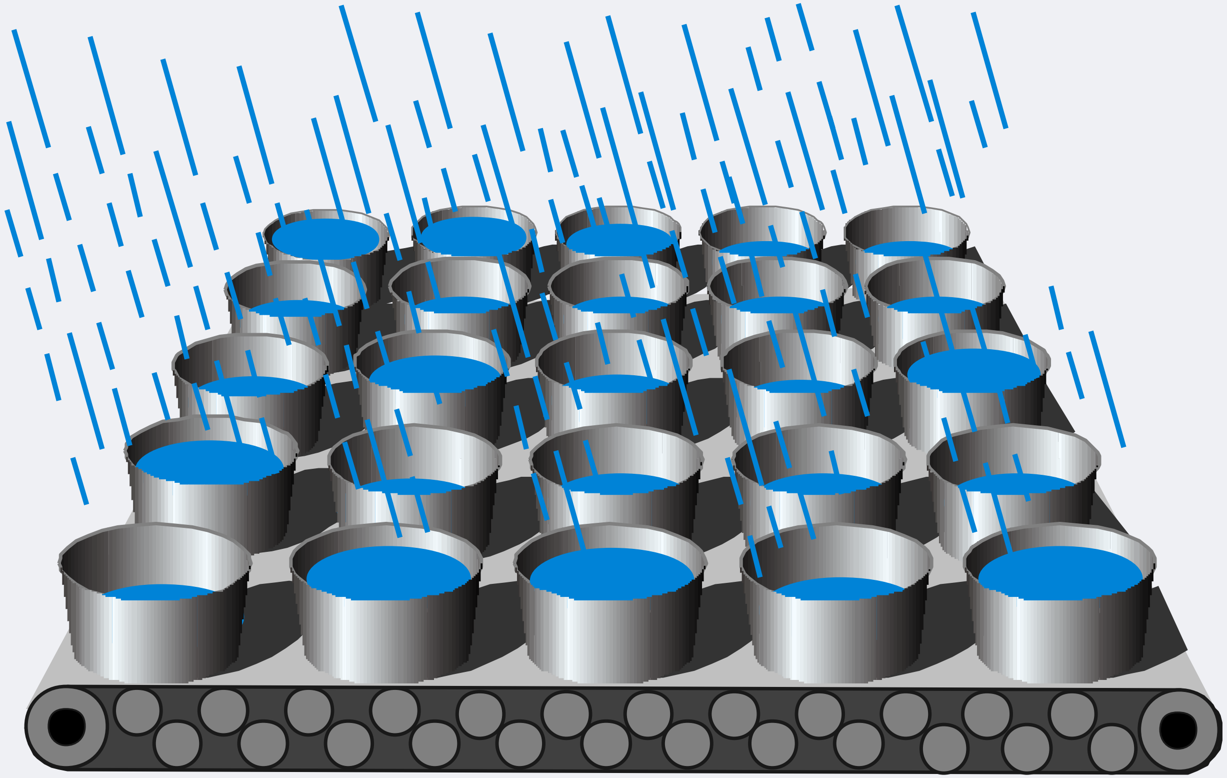


CCD Fundamentals



Array of Discrete Photodetectors

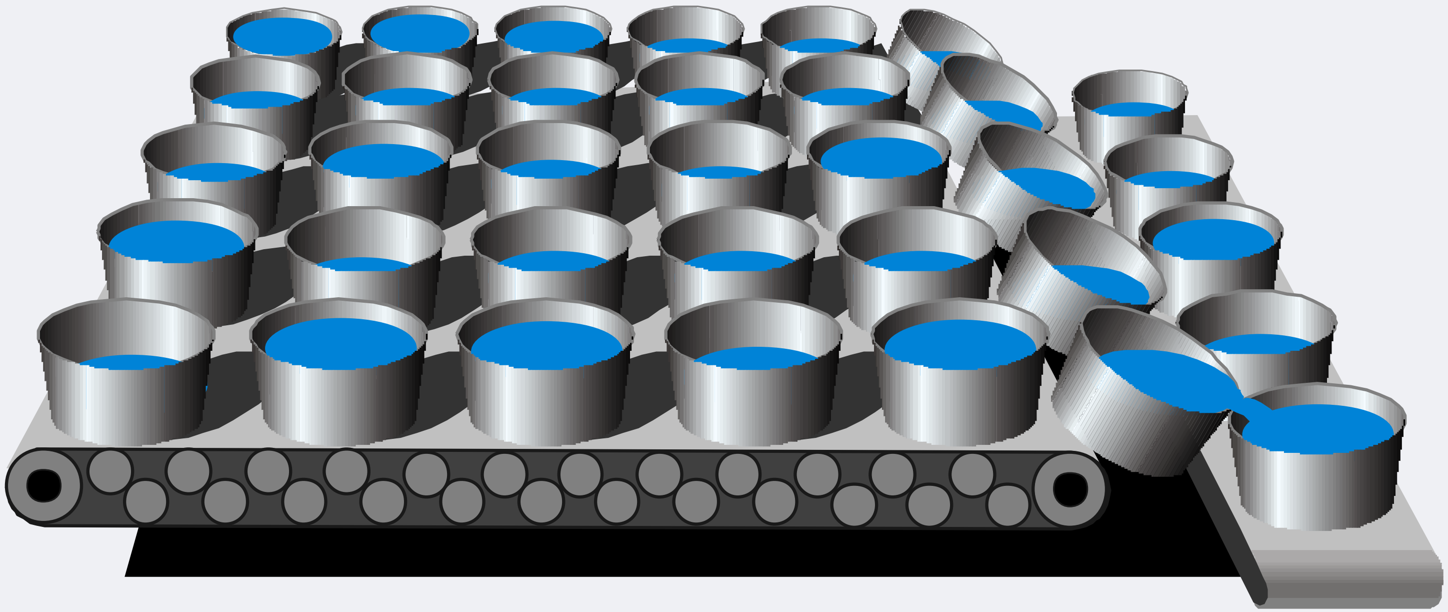
CCD Fundamentals



CCD Operation

Integration of Photo-Induced Charge

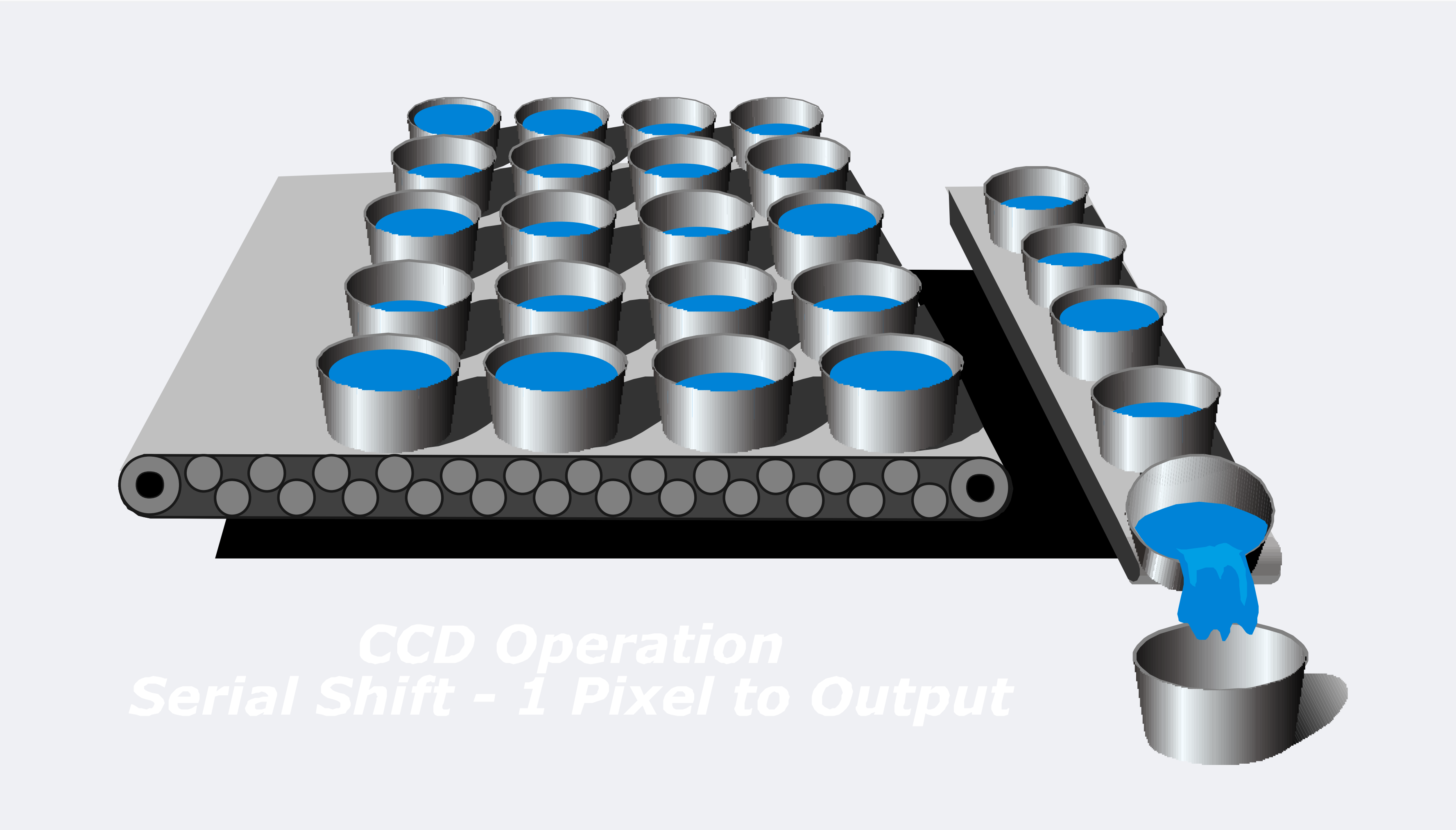
CCD Fundamentals



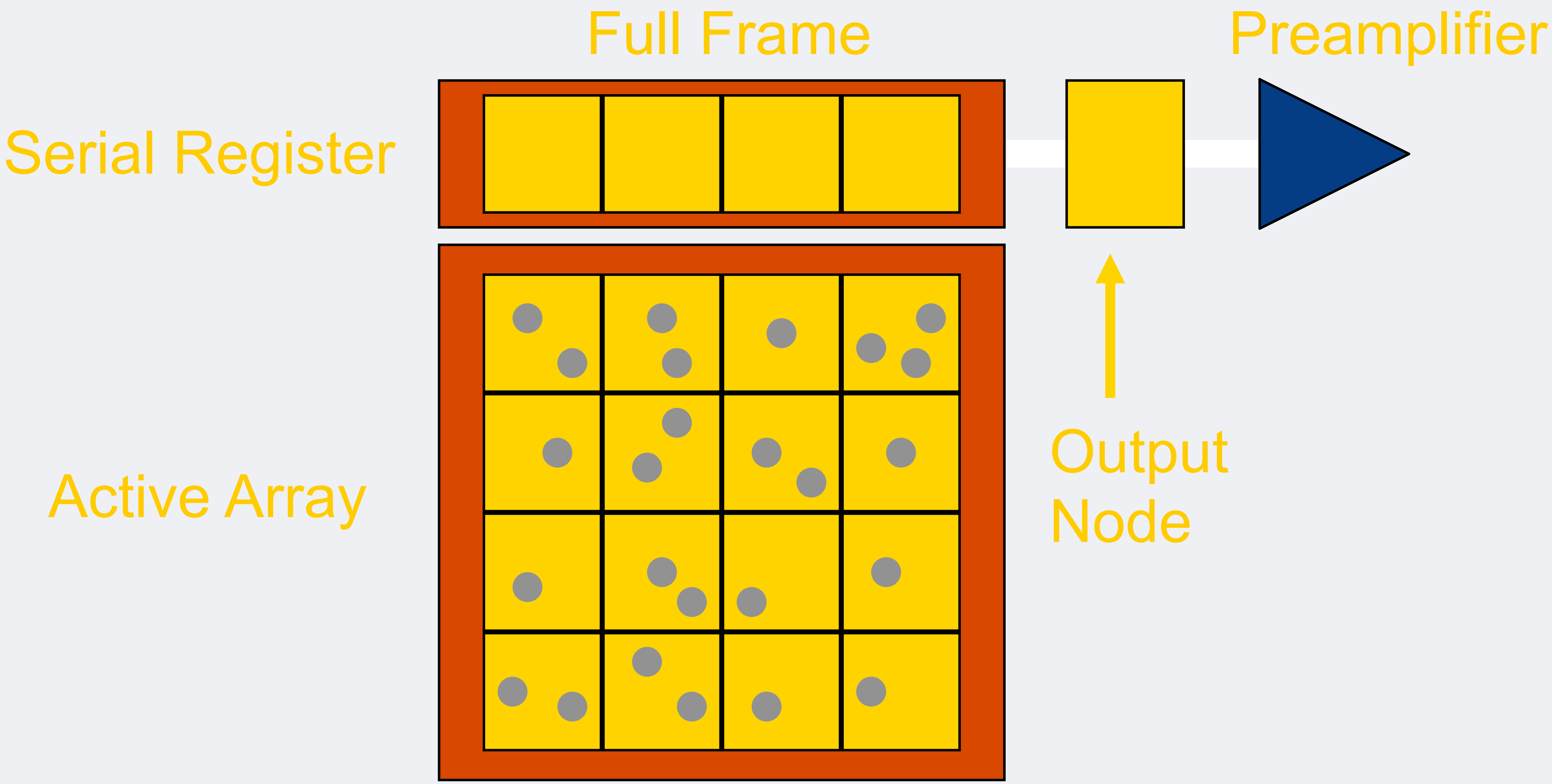
CCD Operation
Parallel Shift - 1 Row

PHOTOMETRICS
a division of Roper Scientific, Inc.

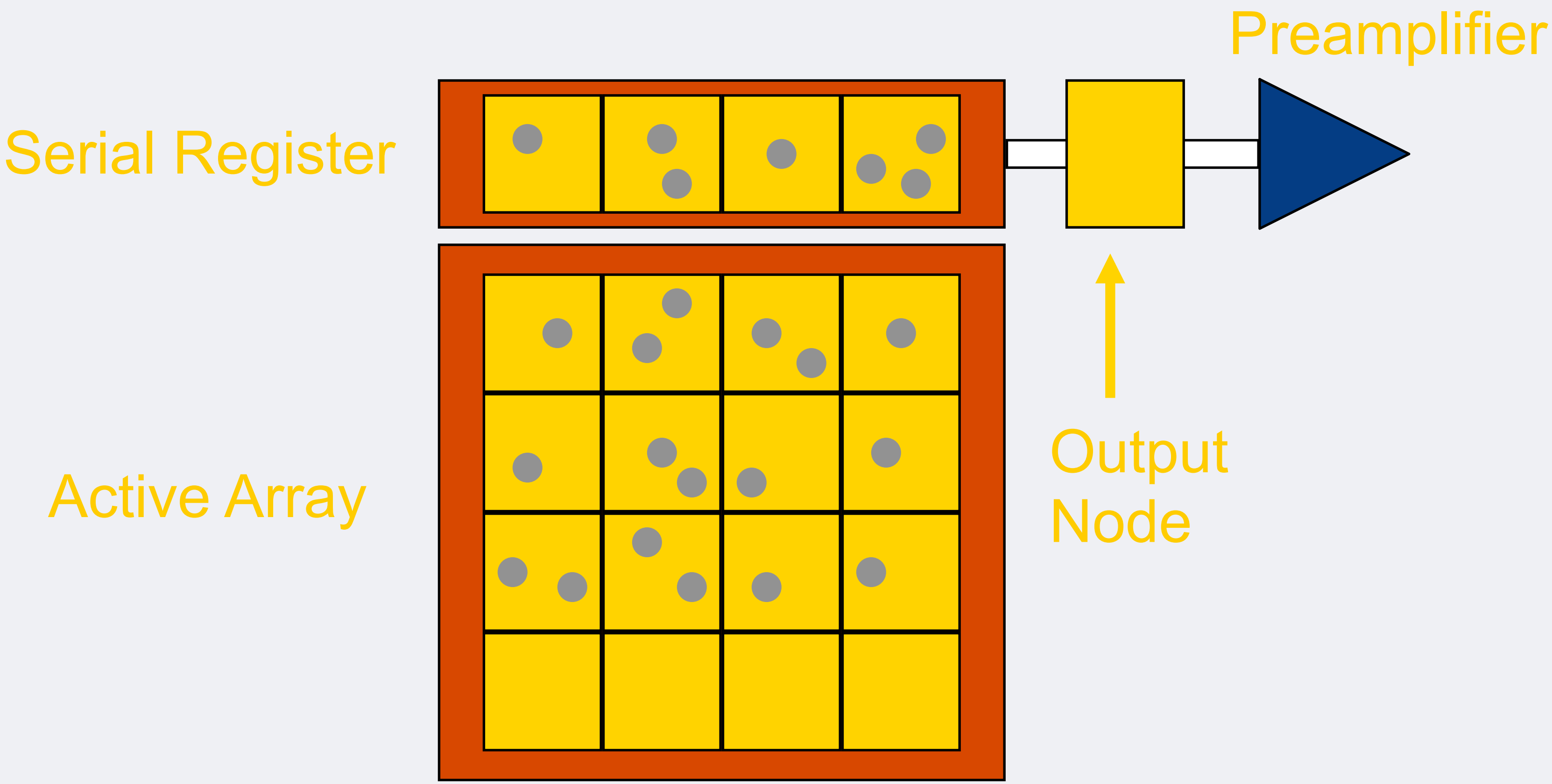
CCD Fundamentals



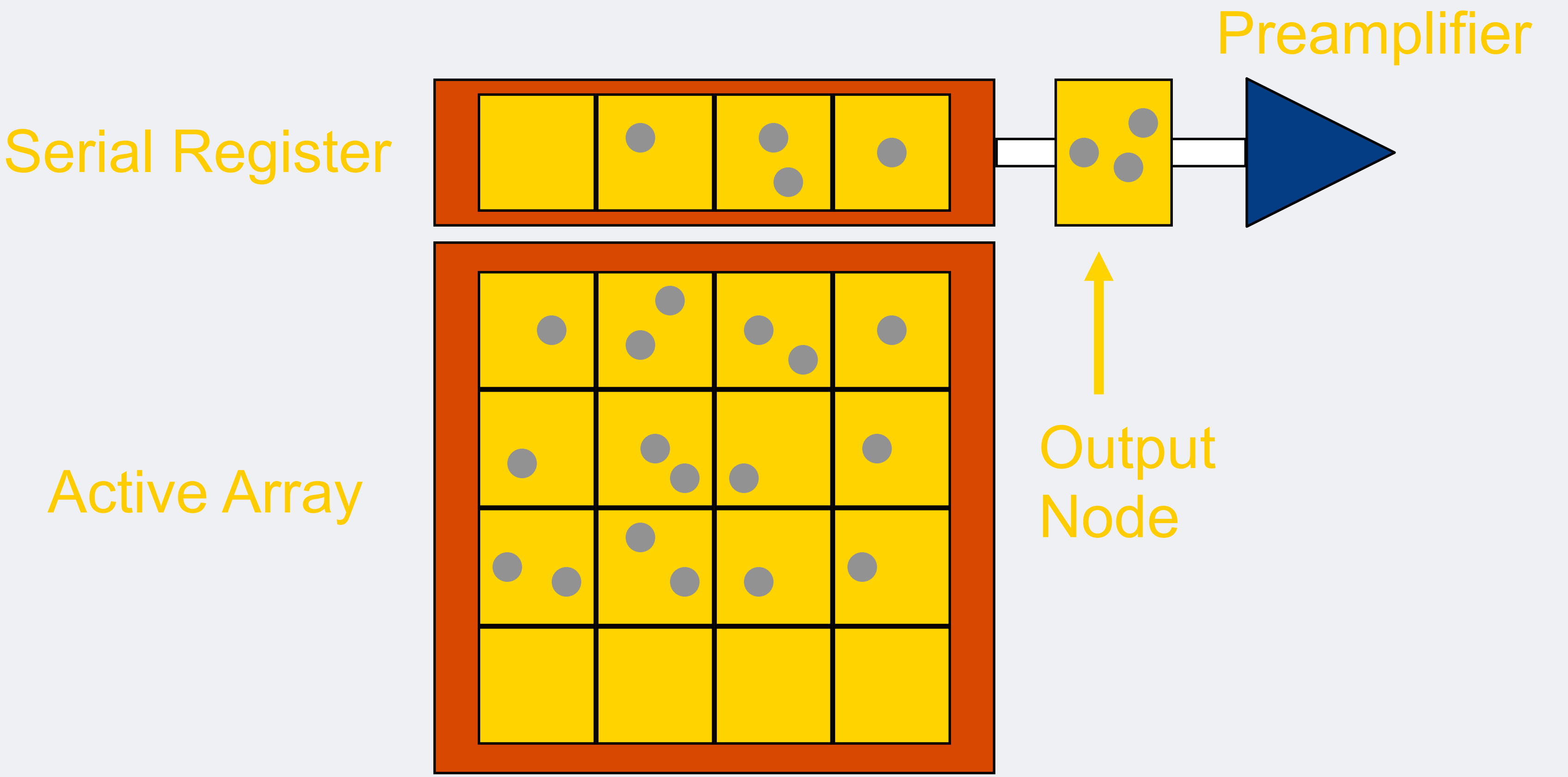
CCD Fundamentals



CCD Fundamentals

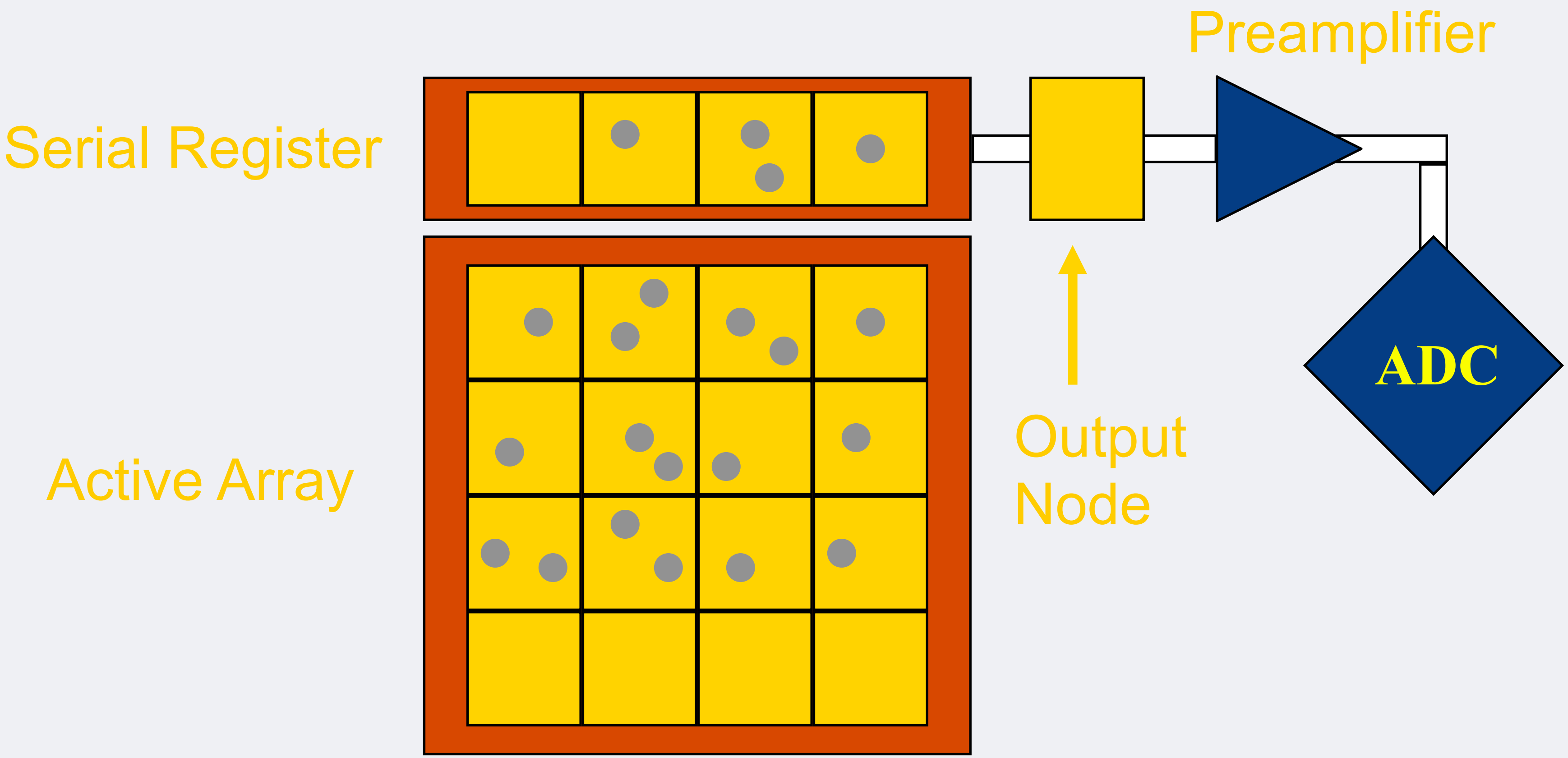


CCD Fundamentals

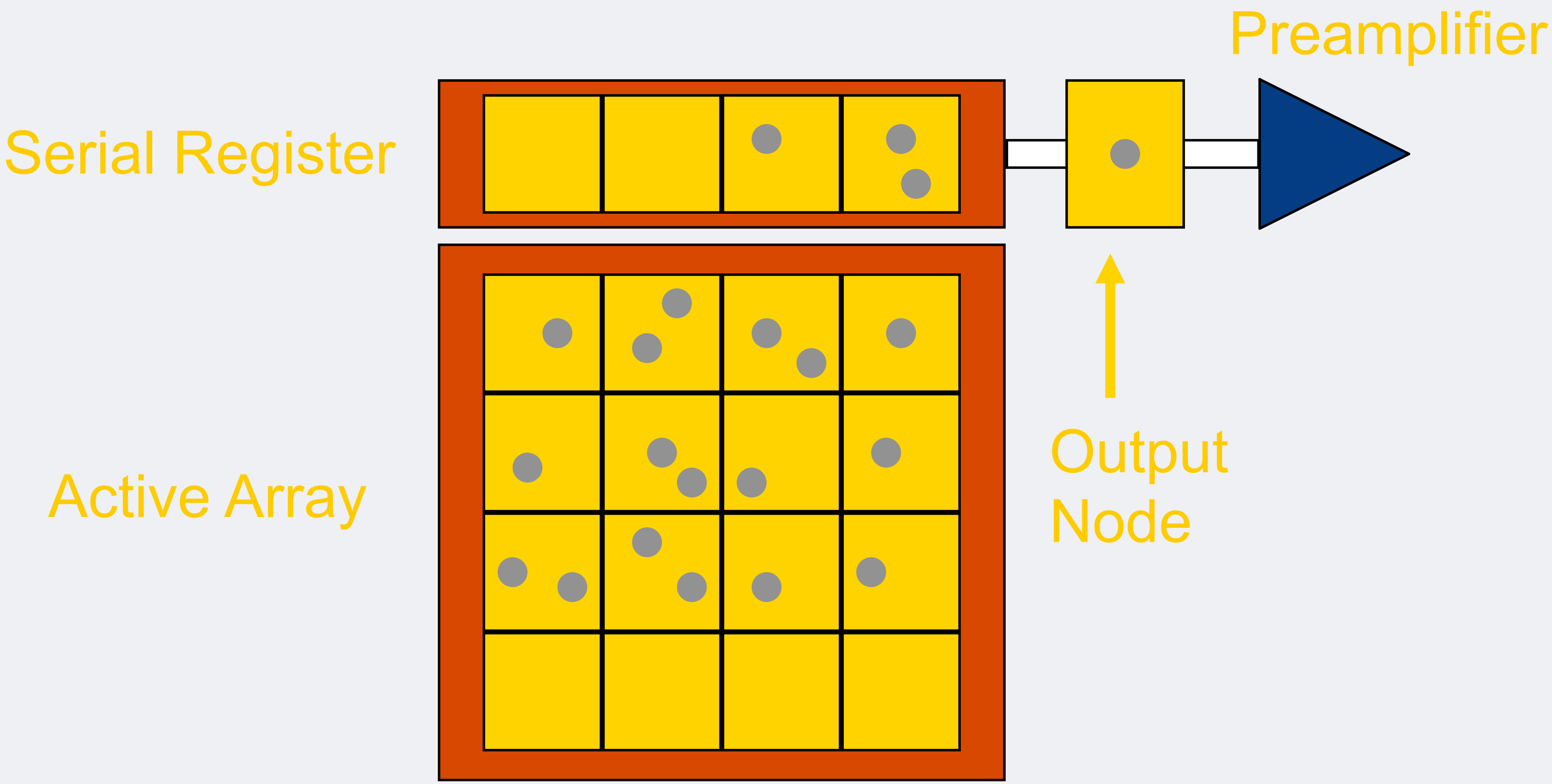


PHOTOMETRICS®
a division of Roper Scientific, Inc.

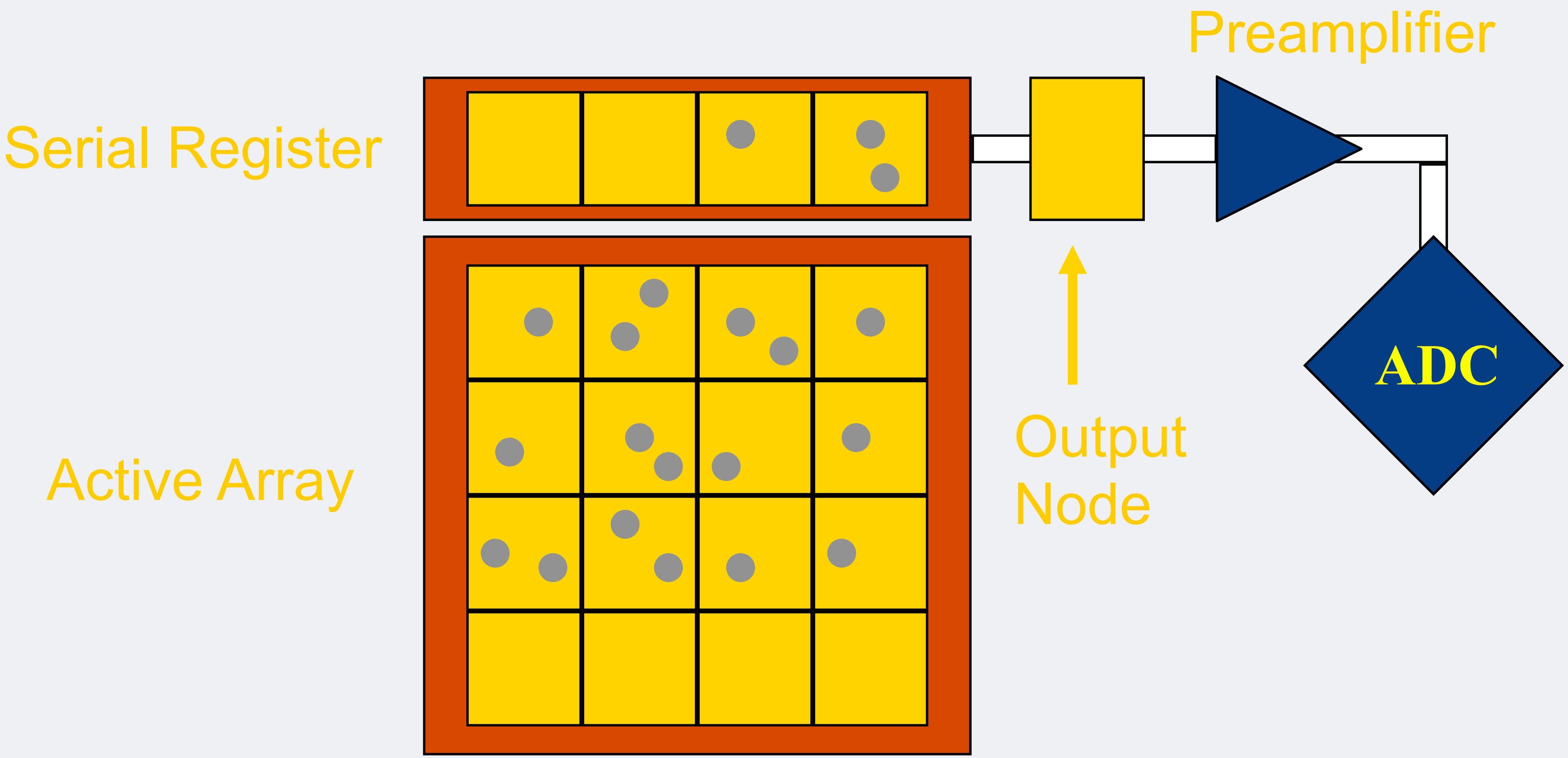
CCD Fundamentals



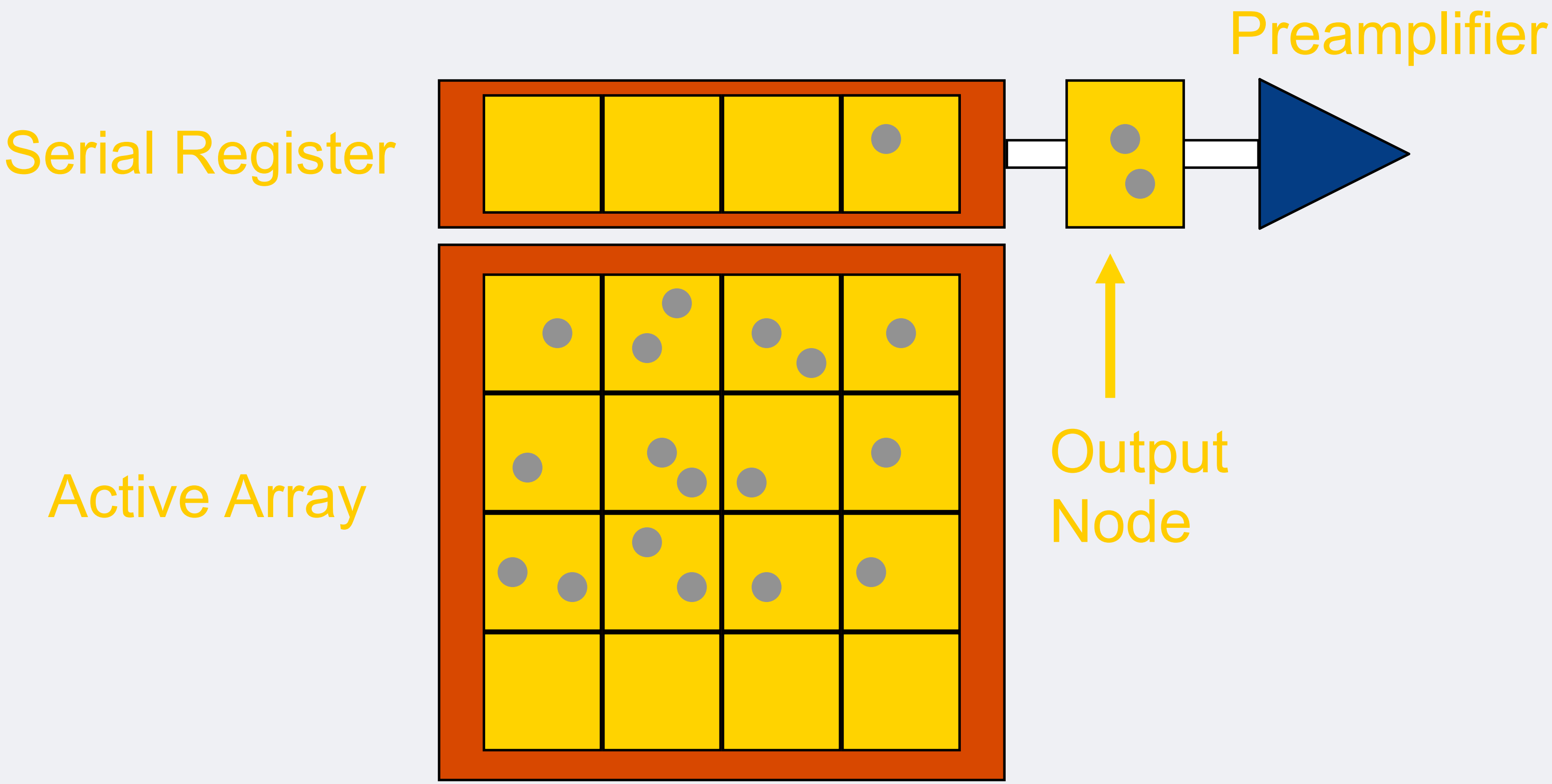
CCD Fundamentals



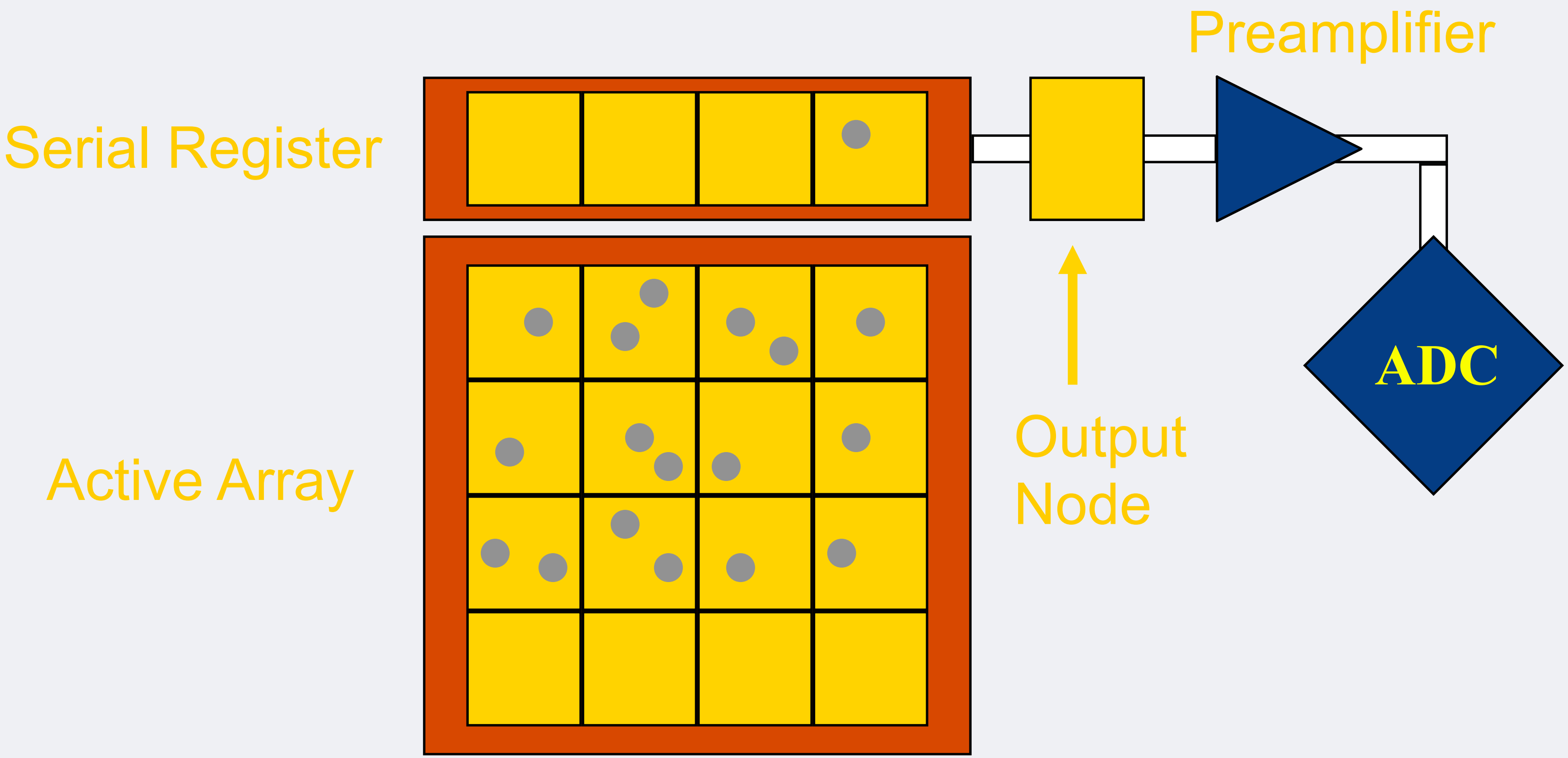
CCD Fundamentals



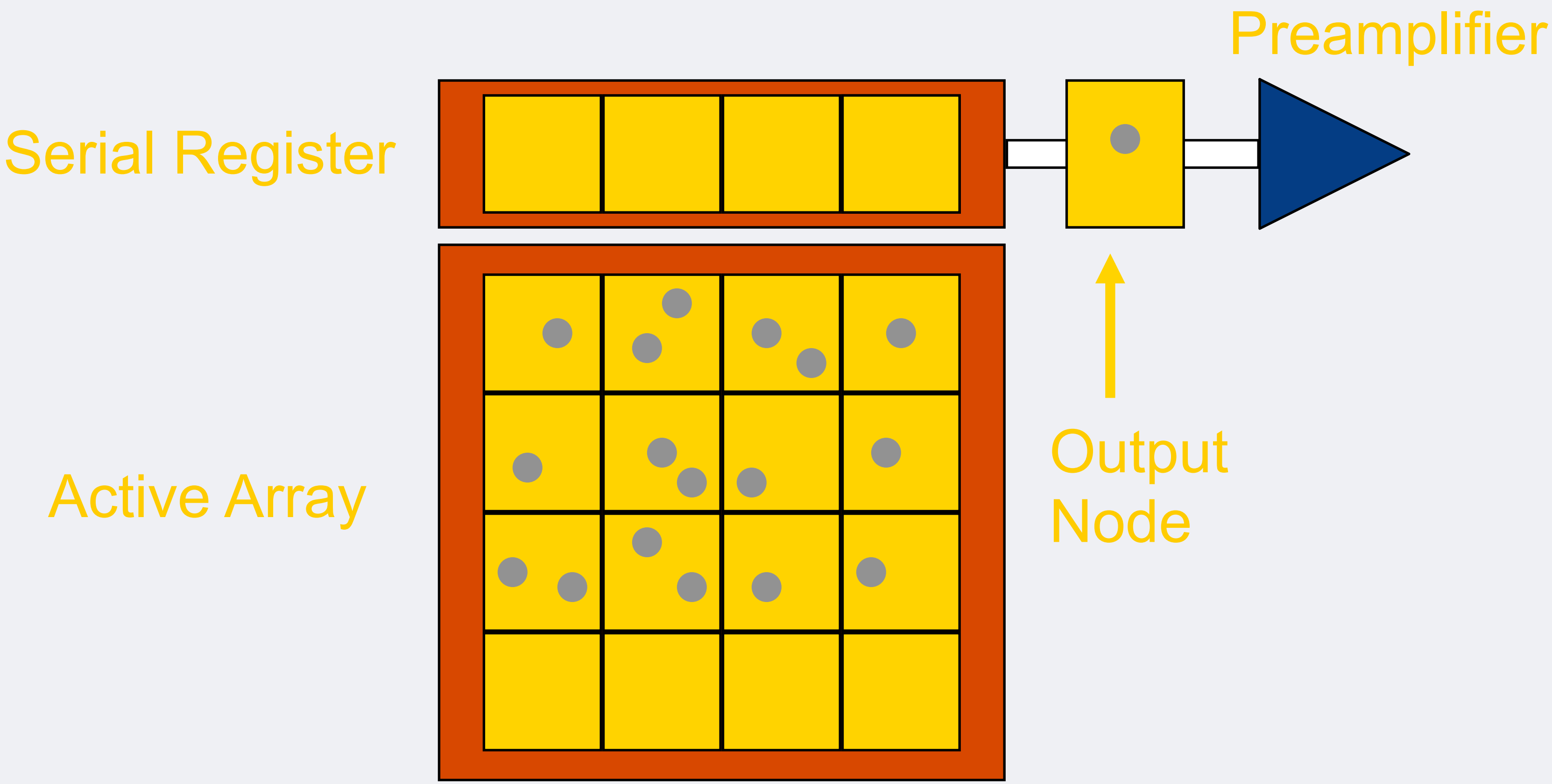
CCD Fundamentals



CCD Fundamentals

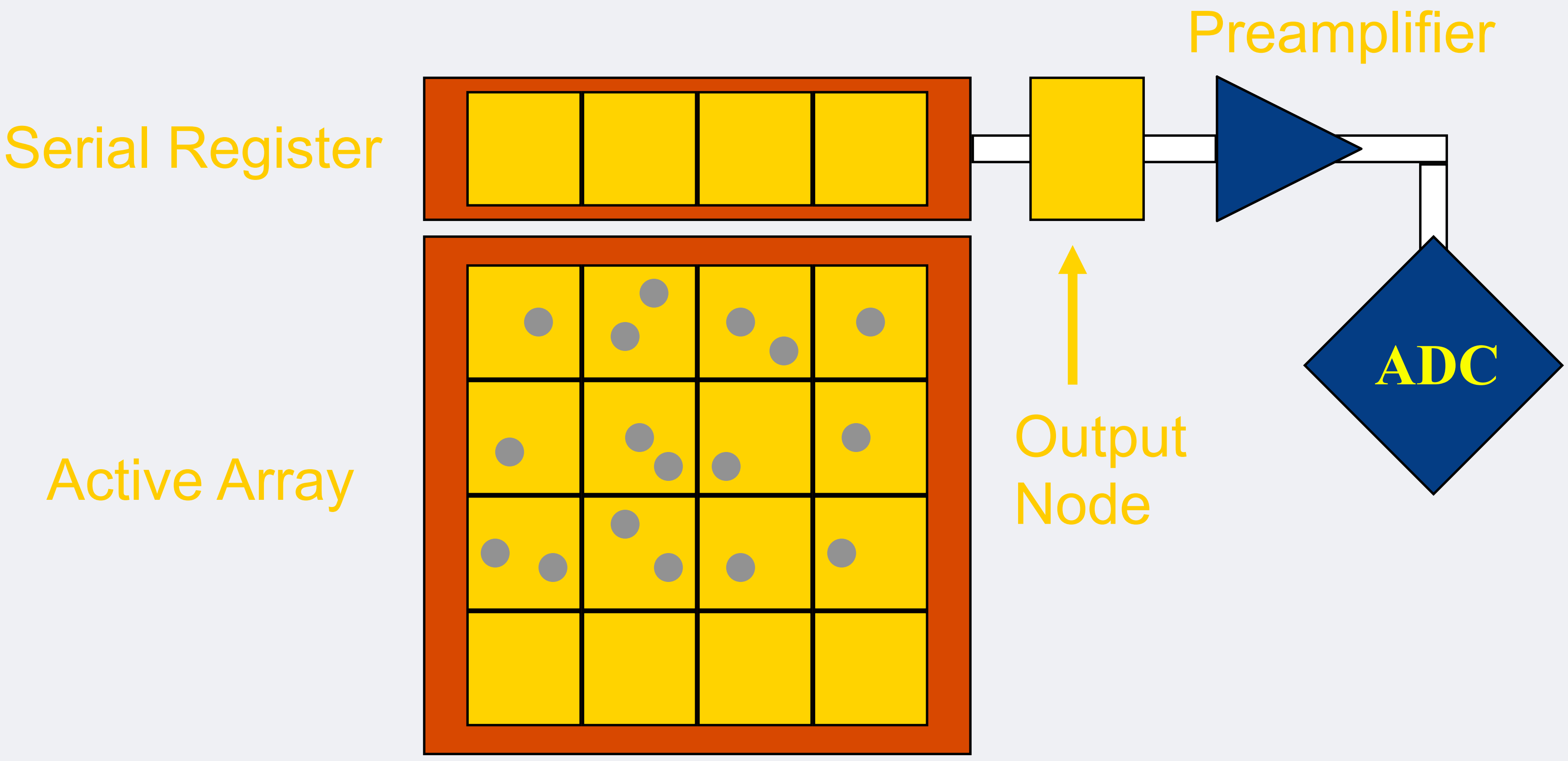


CCD Fundamentals

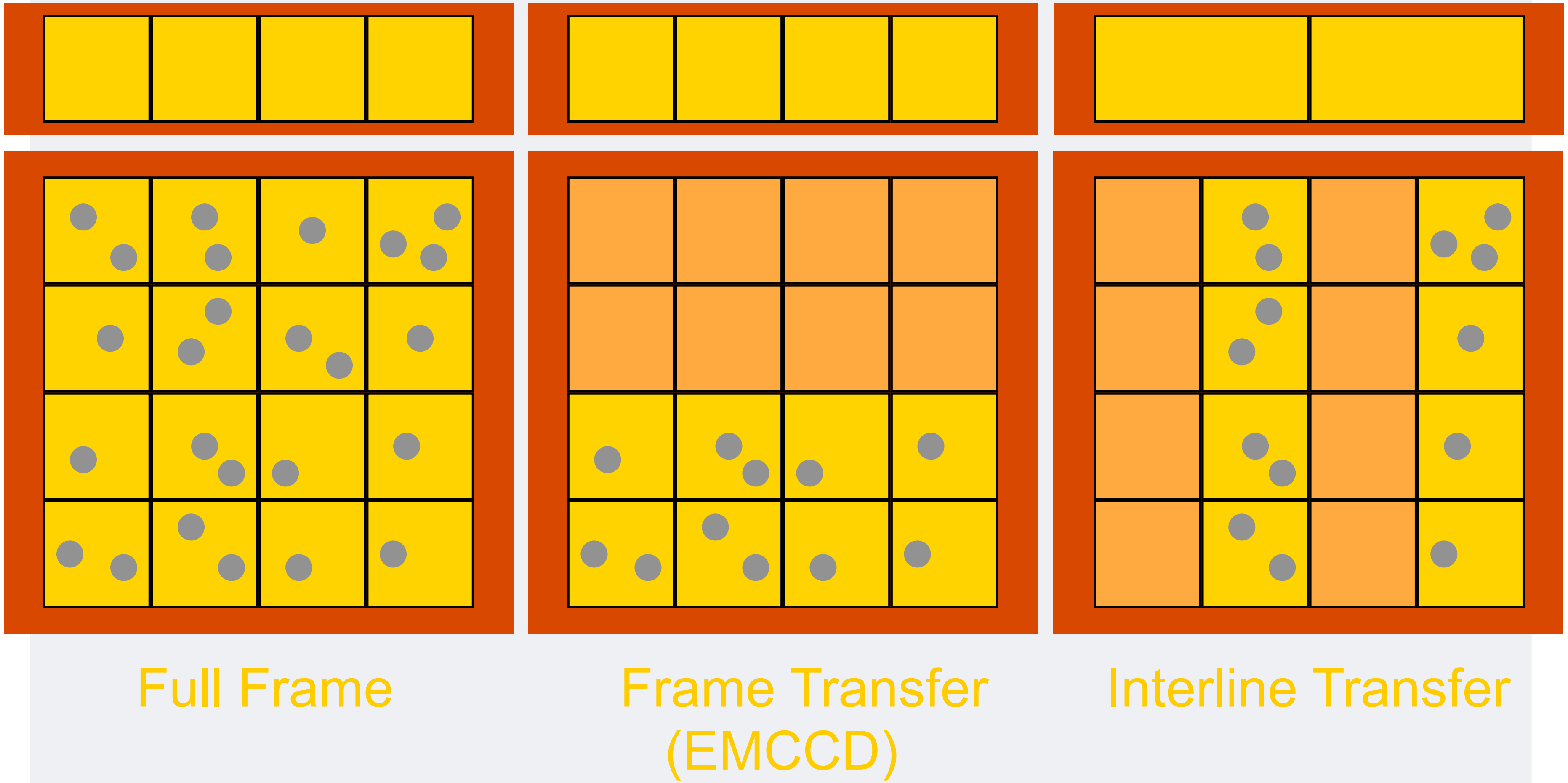


PHOTOMETRICS®
a division of Roper Scientific, Inc.

CCD Fundamentals



CCD Fundamentals



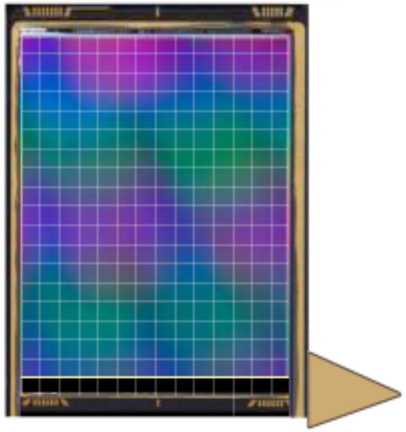
PHOTOMETRICS®
a division of Roper Scientific, Inc.

Sensor Types

CMOS Imager

The Complementary Metal Oxide Semiconductor (CMOS) includes an array of photo diodes where each diode is connected to a readout amplifier. In opposite to the CCD charge transfer technique, in a CMOS imager every photodiode/amplifier unit is connected by a multiplexer to the output. Each pixel can be addressed and readout directly on the x-y coordinates system.

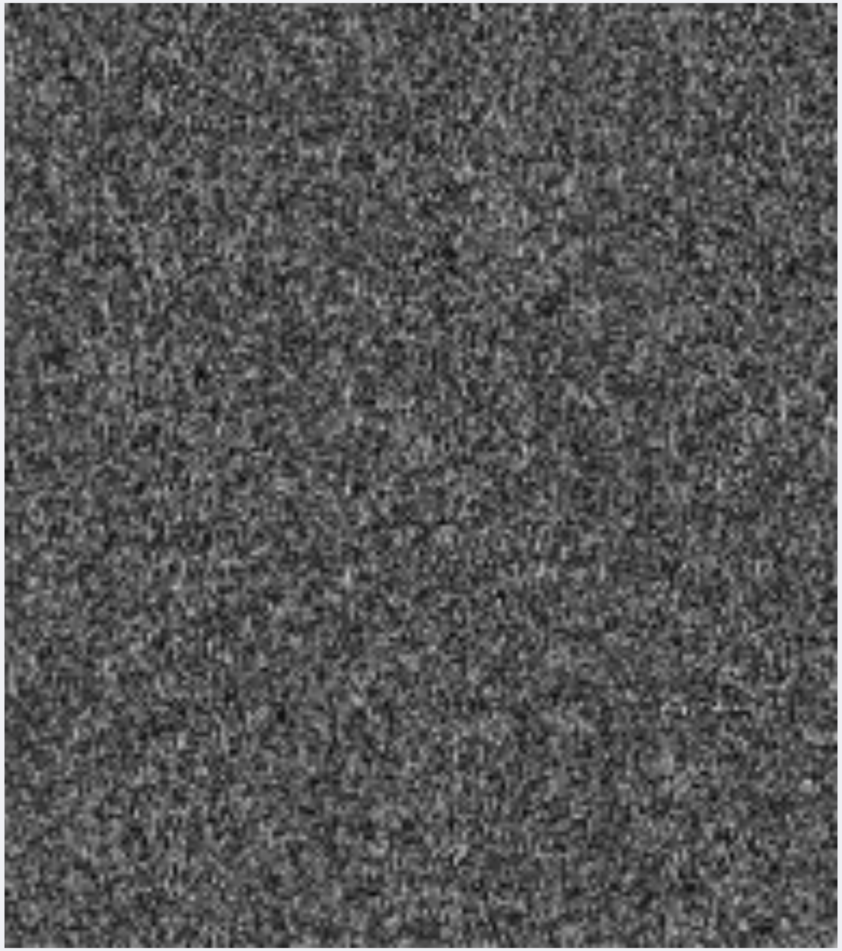
- Full Frame CCD
- Frame Transfer CCD
- Interline CCD
- EMCCD
- CMOS Readout
- CMOS Global
- CMOS Rolling



Before EMCCD and SCMOS

Lets look at camera noise

Scary, Scary Noise



=

Why is noise a pain?

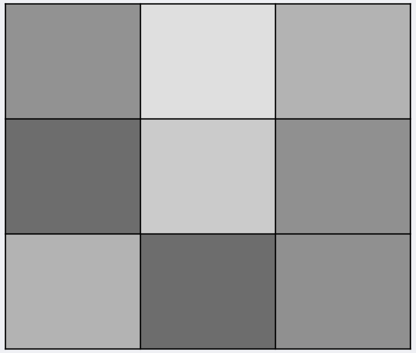
1. Lowers Image Quality
2. Reduces ability to resolve
3. Lowers Measurement confidence intervals

What is Noise ?

- Noise is uncertainty
- Noise is Plus or Minus
- Noise is driven by Statistics
- Noise can be calculated

•Noise is not background

Standard Deviation is an easy way for us to measure noise.



8	12	6
6	10	8
10	6	8

Noise Sources

CCD systems suffer from 3 types of noise:

1. ***Dark Current*** – noise from heat and cosmic noise - exposure dependent

2. ***Read Noise*** – noise of reading the signal - fixed

3. ***Photon Shot*** – square route of signal - signal dependent

Other Noises

1. Excess Noise Factor – EMCCD
2. Clock Induced Charge – All but mainly observed in EMCCD
3. Random Telegraph Noise - CMOS

EMCCD

EM CCD – Electron Multiplied CCD sensors have been in place for over 10 years ago and are used for scientific, military and surveillance applications

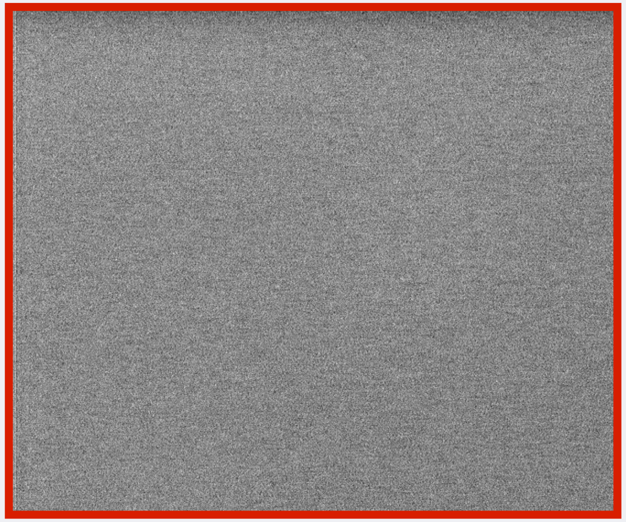
Photometrics introduced the first scientific grade camera (Cascade 650) in 2000 to enable customers with low light to achieve higher speed dynamic imaging

Based on CCD technology, the advancement comes from the addition of an Electron Multiplication register enabling higher signals to be achieved relative to the fixed camera noise - Read Noise

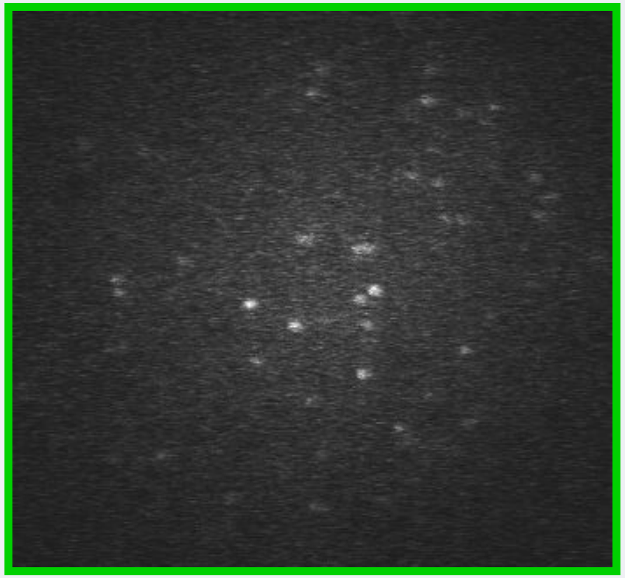
The Read Noise Limitation

The low-light level applications are read noise limited

i.e. the signals below the read noise cannot be seen

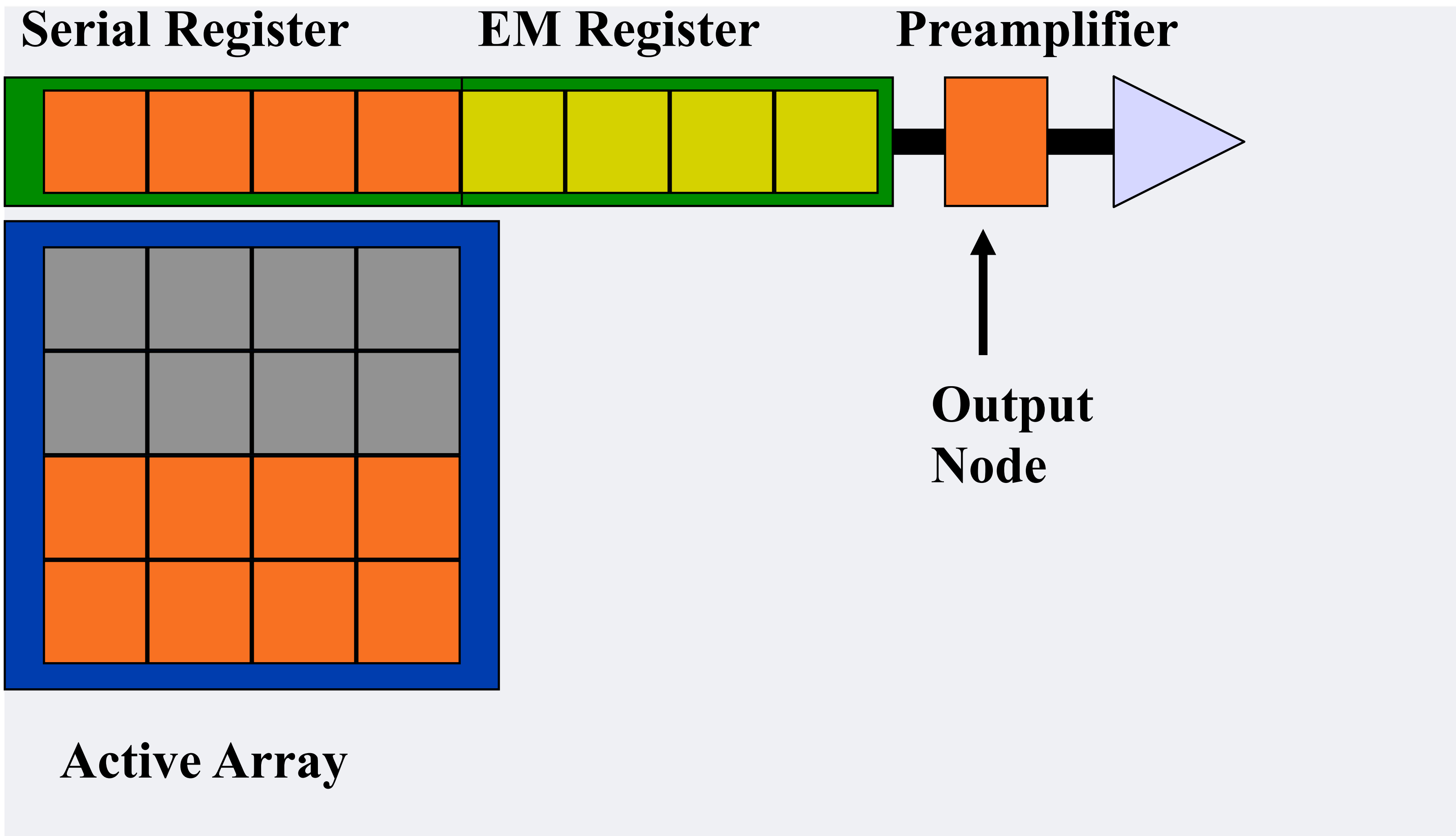


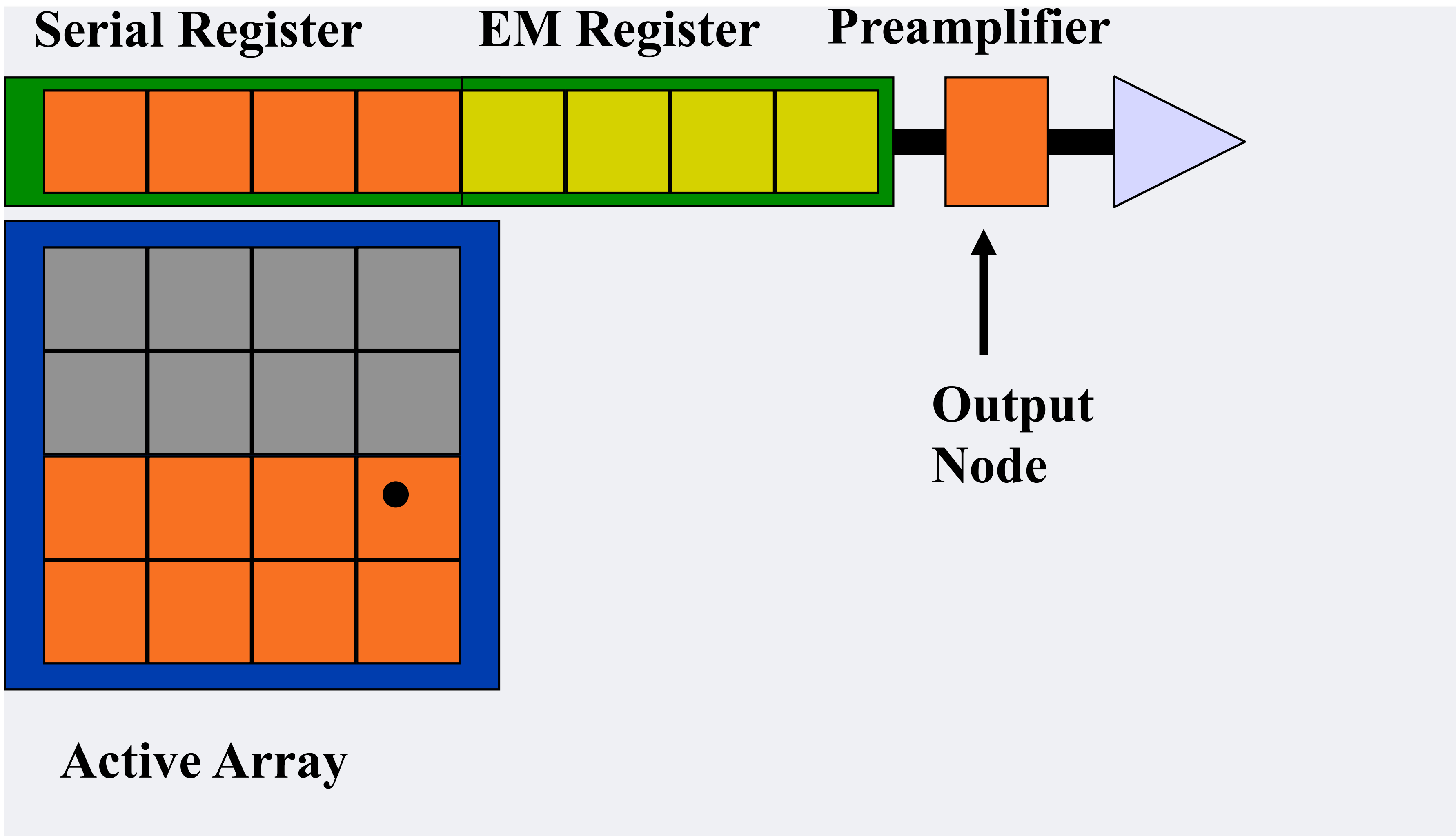
Read noise limited



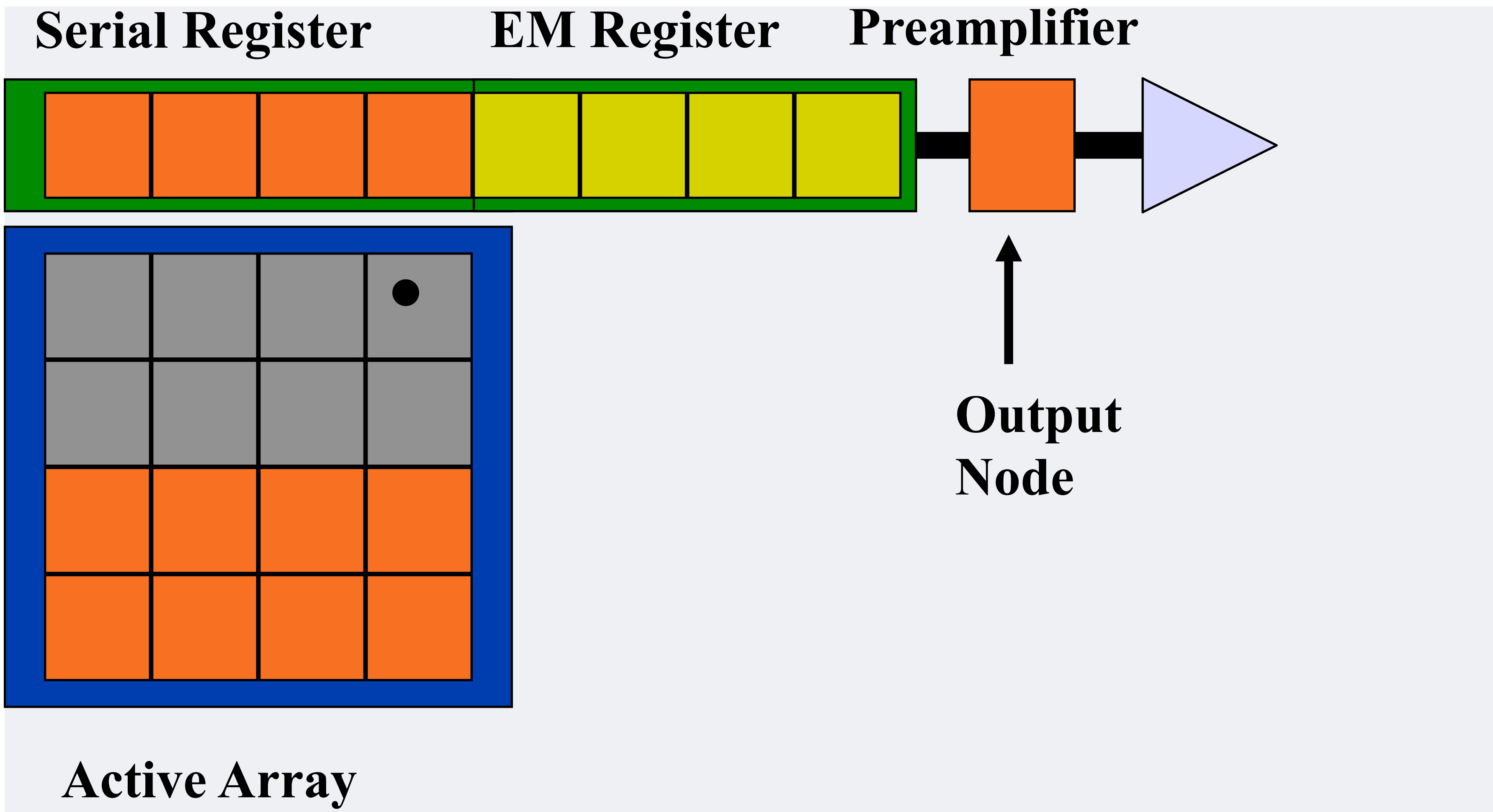
By minimizing the read noise

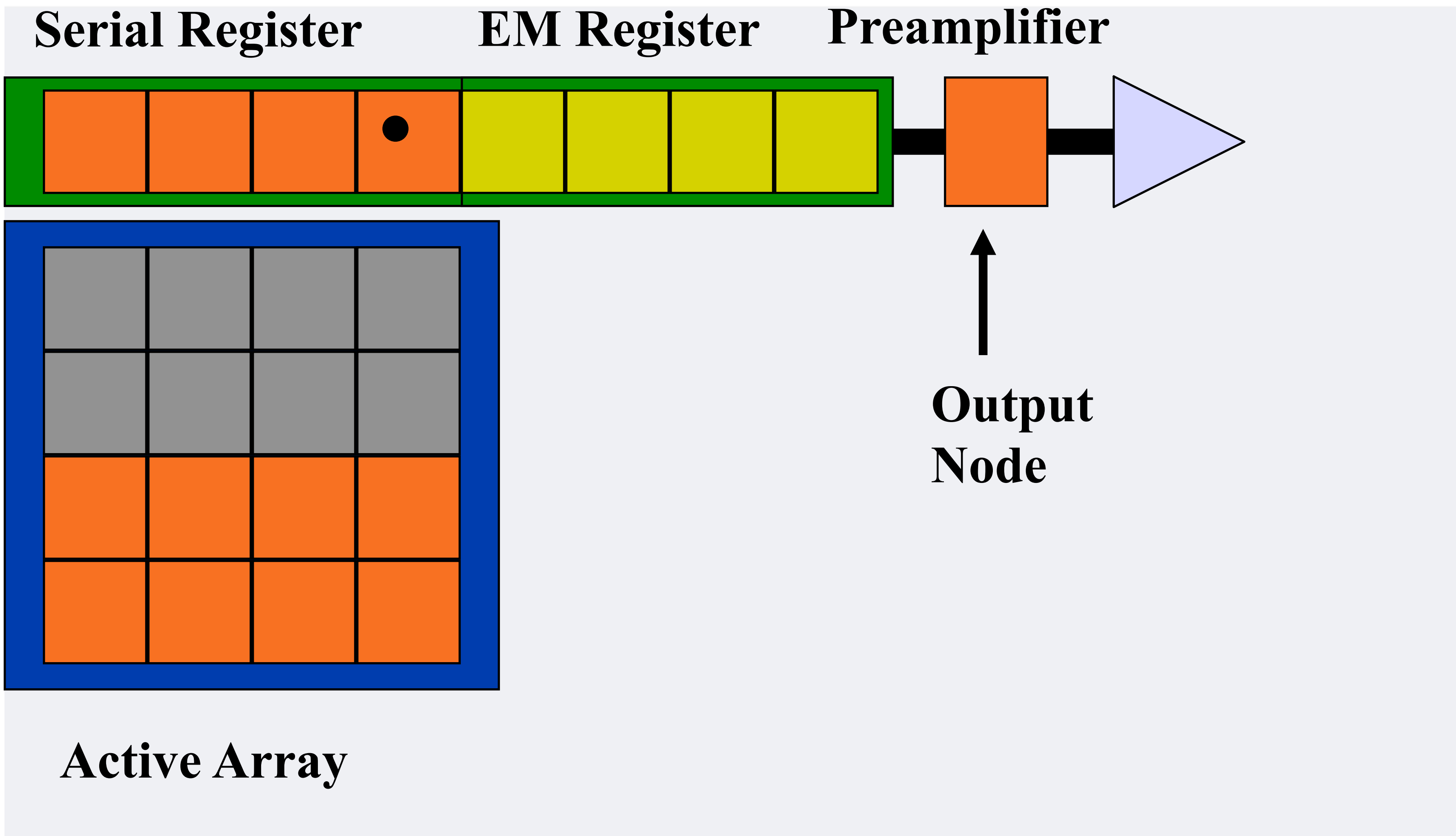
Example: single molecule fluorescence

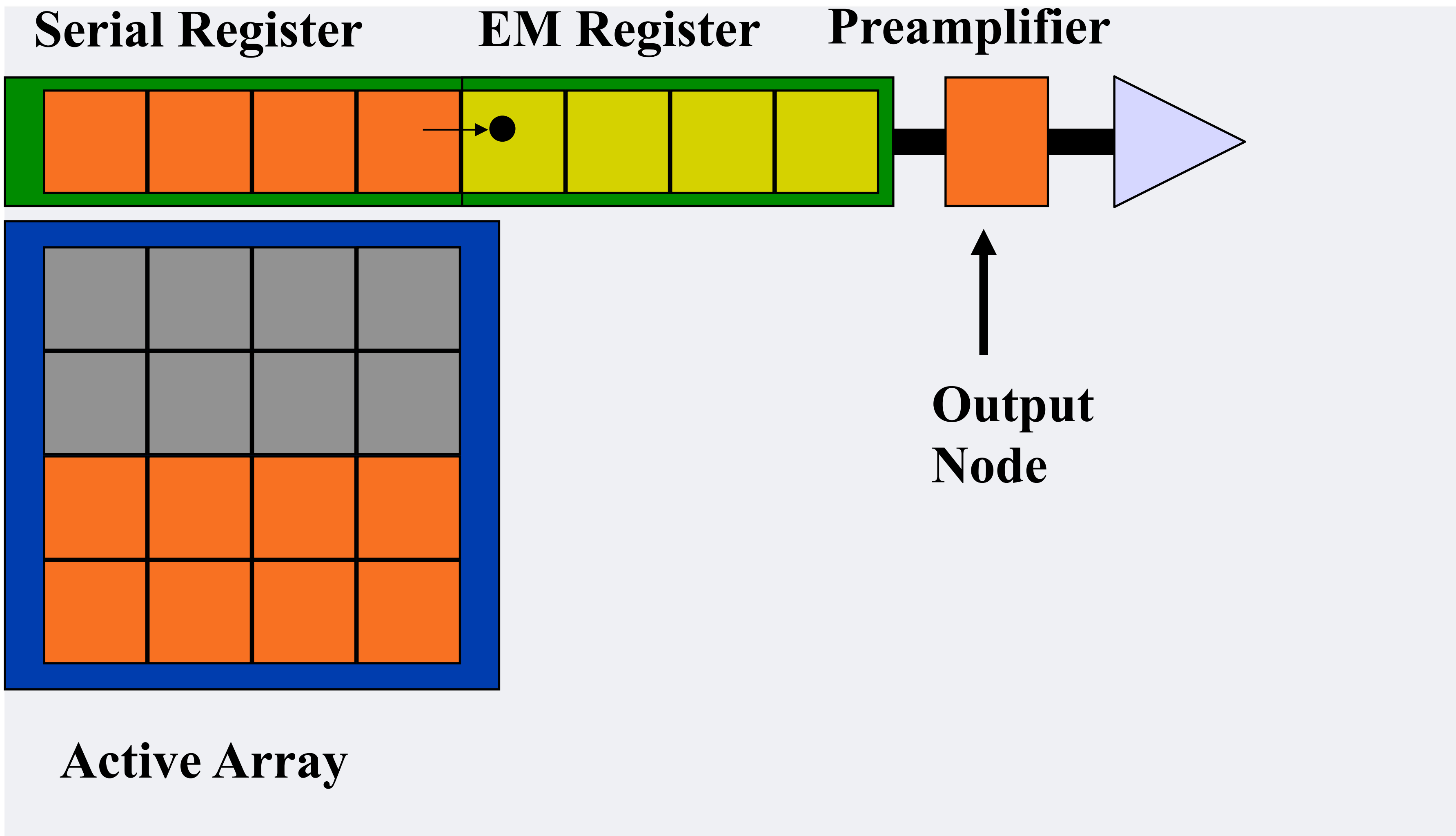

Serial Register
EM Register
Preamplifier
Output
Node
Active Array

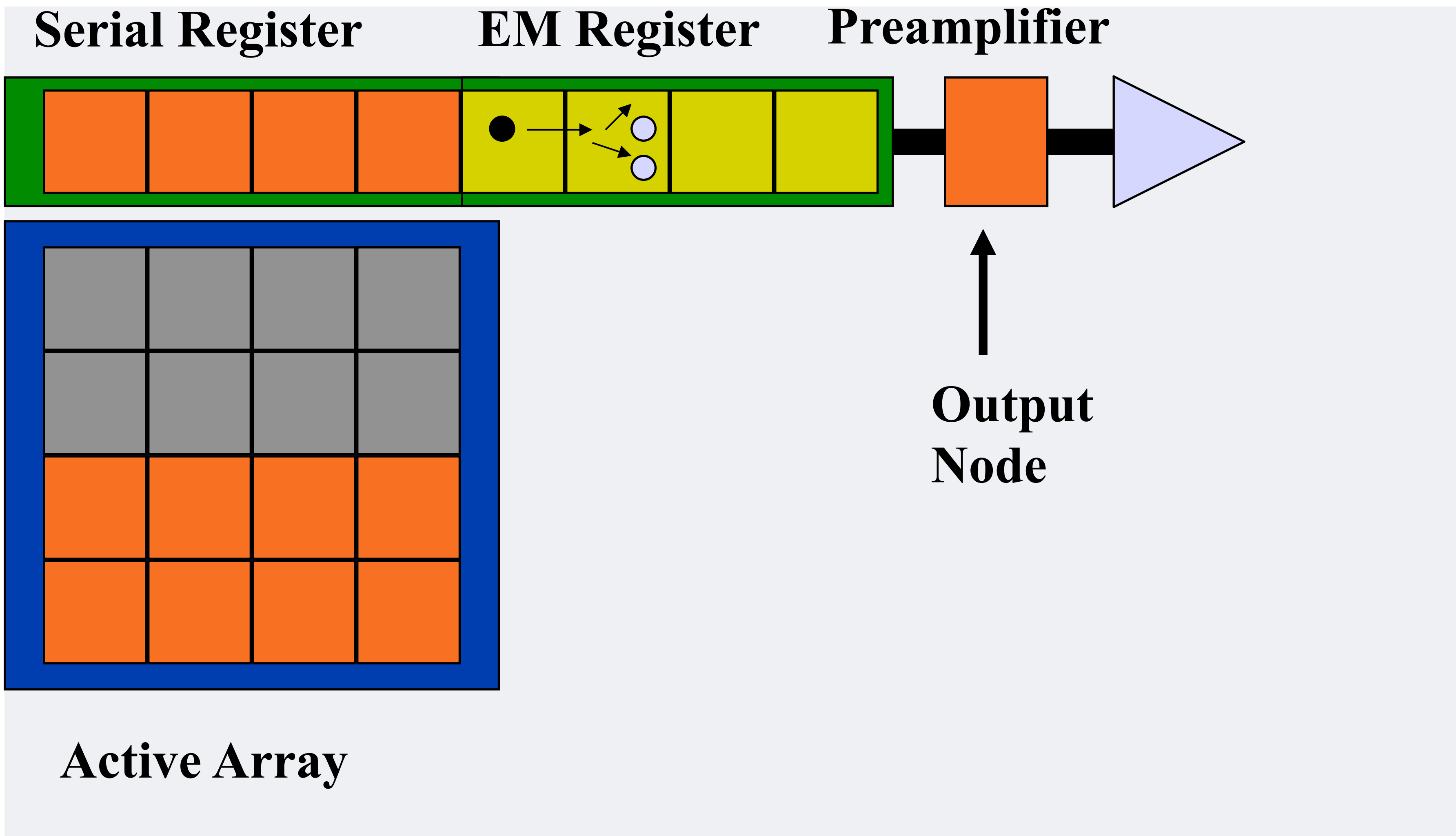


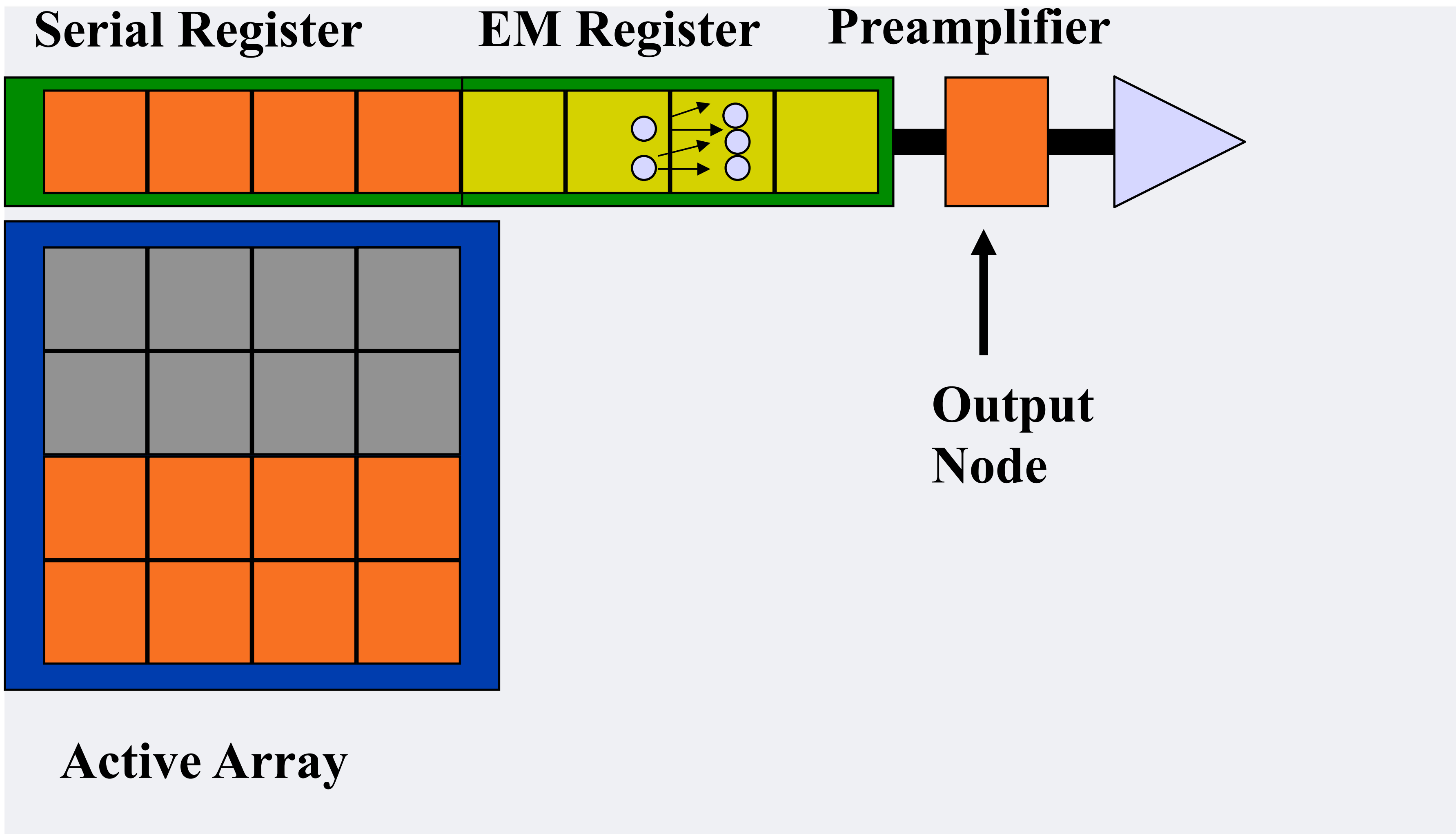
PHOTOMETRICS®
a division of Roper Scientific, Inc.

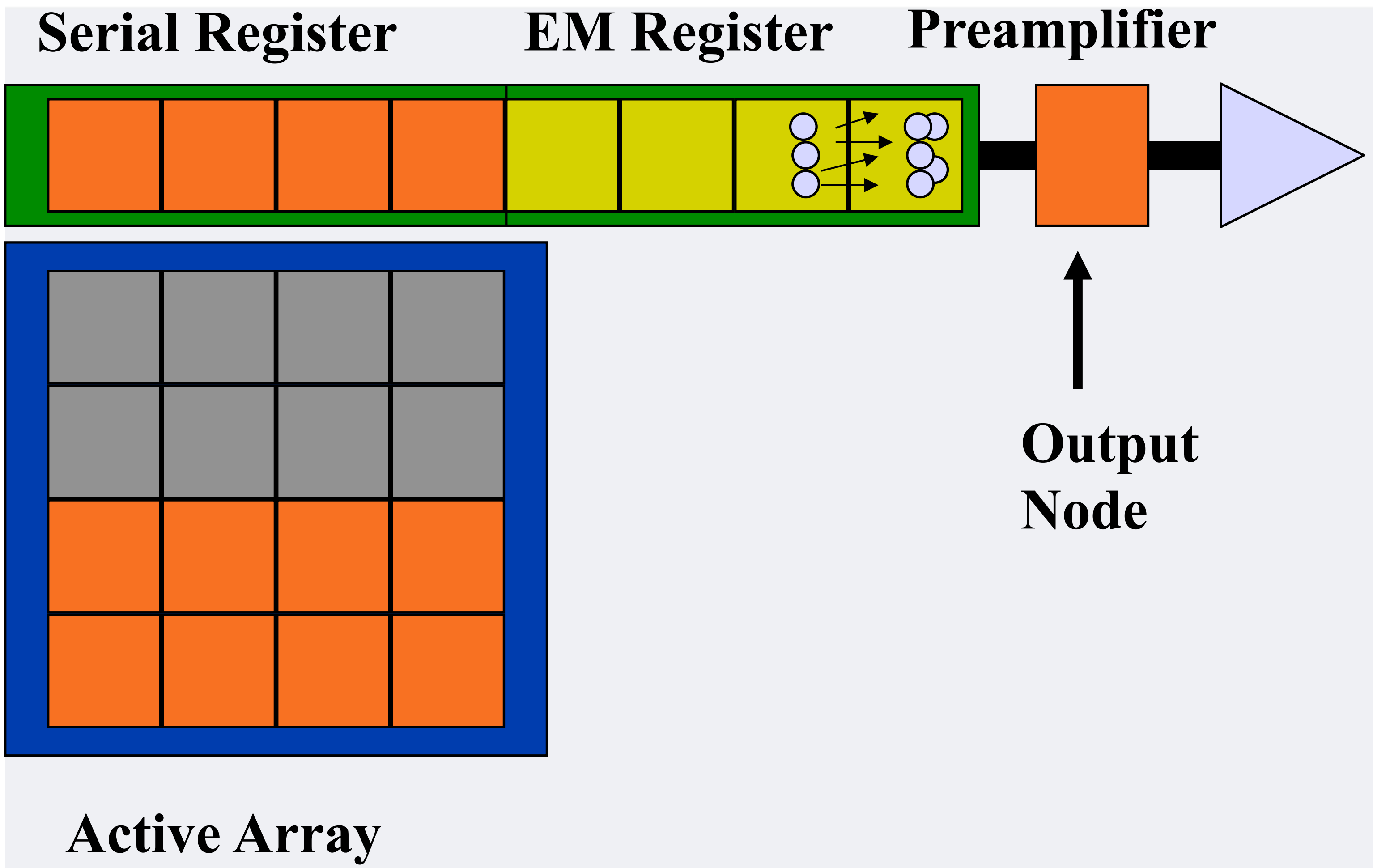

Serial Register
EM Register
Preamplifier
Output
Node
Active Array


Serial Register
EM Register
Preamplifier
Output
Node
Active Array

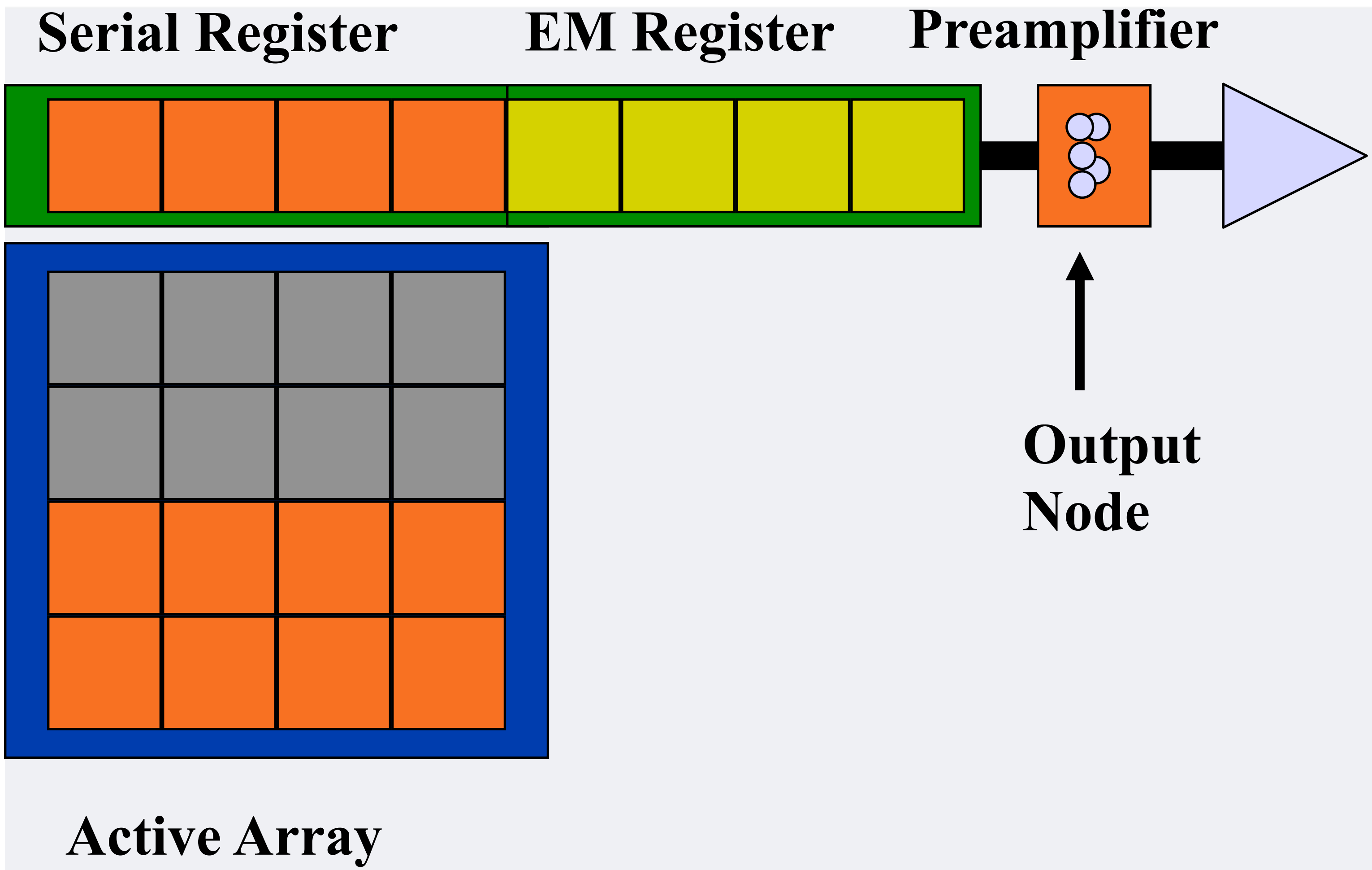

Serial Register
EM Register
Preamplifier
Output
Node
Active Array


Serial Register
EM Register
Preamplifier
Output
Node
Active Array


Serial Register
EM Register
Preamplifier
Output
Node
Active Array



PHOTOMETRICS
a division of Roper Scientific, Inc.


Serial Register
EM Register
Preamplifier
Output
Node
Active Array

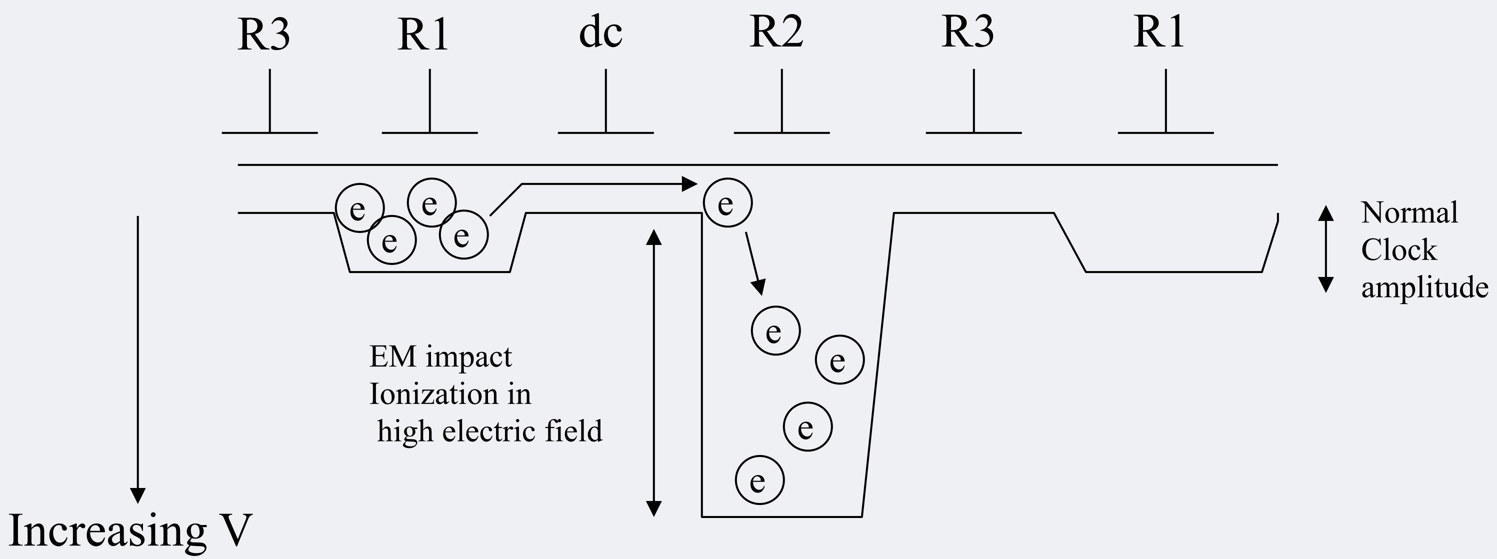
More detailed look at EMCCD's

- They contain a 'gain register' between the usual serial shift register and the output amplifier.

- Similar to serial register except for R2 phase of the clock cycle which has 2 electrodes
  - 1^{st} held at fixed potential
  - 2^{nd} which is clocked at a much higher voltage amplitude (40-50V) than is required for charge transfer alone.
  - Intense electric field between them causes transferring electrons to cause ***impact ionization***

- Note that EMCCDs are subject to aging and that over time the voltage applied will give reducing amounts of ionization.

Electron multiplication / Impact ionization

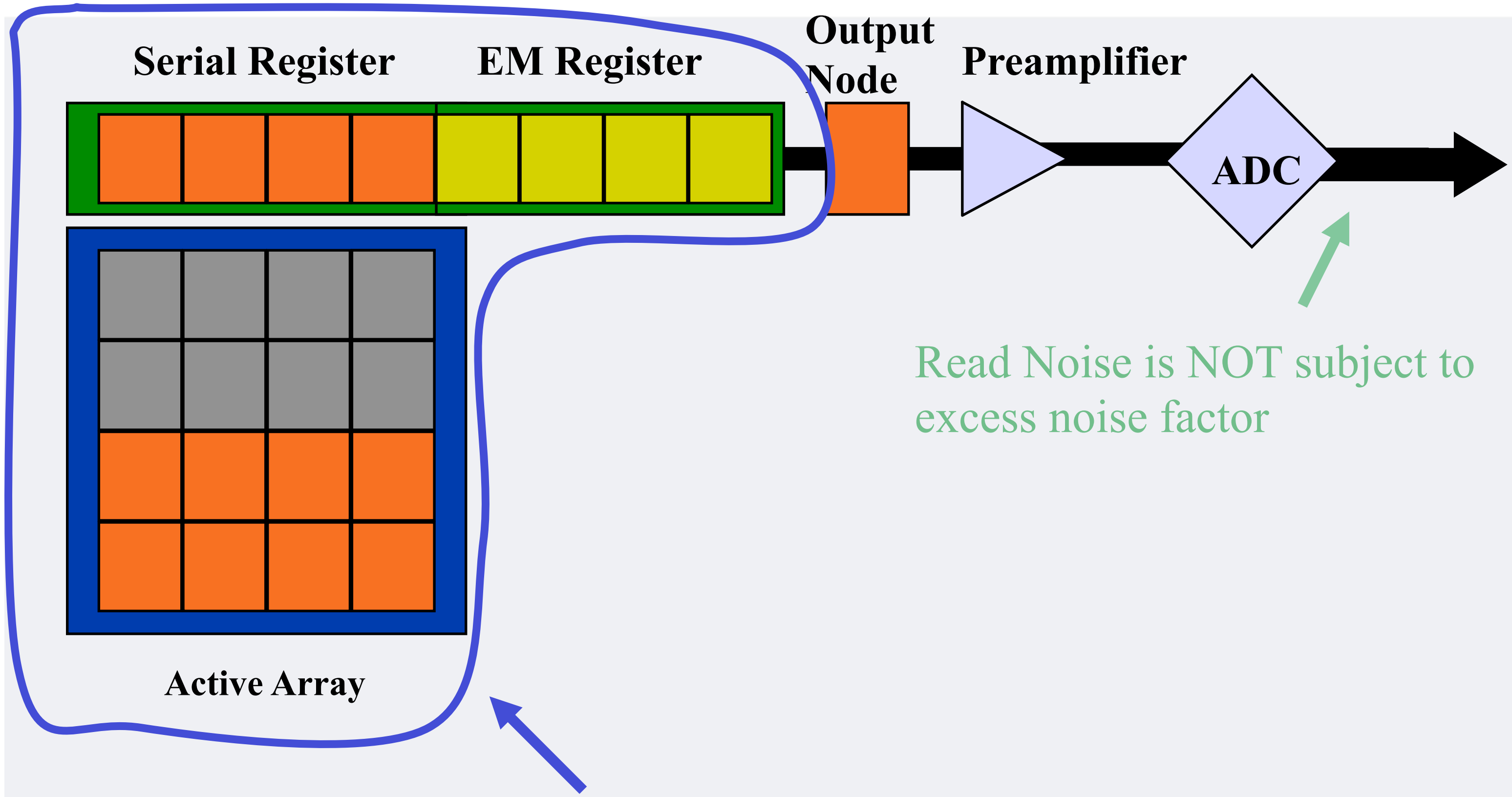


Multiplication per transfer quite small (x1.01 to x1.016). Executed over a large number of transfers leads to significant EM Gain!

Mathematically: $G = (1+g)^N$
G= EM gain, g=probability of secondary electron generation

$1.015^{536} = 2923$X EM Gain

Basic concepts



Anything that occurs here is subject to excess noise factor!

e.g. Shot noise, Dark Noise, CIC

CMOS

- CMOS as a technology is as old as CCD but was not considered as a sensor capable of light detection until 1992 by Dr. Eric Fossum, a scientist at NASA's Jet Propulsion Laboratory

- CMOS technology, as CCD, uses an array of light sensitive pixels to collect full area image

- CMOS technology differs by completing all digitisation at the pixel point rather than needing to read the signal and then digitise

- CMOS sensors also, by nature, require around 100x less power than CCD making them the perfect choice for camera phone sensors

- As sensors are mass produced for mobile phone imaging and also for non-imaging applications, the pricing has been driven low by the market

CMOS Architecture

Introduction

Charge Coupled Device (CCD) detectors come in three major architectures, Full Frame (FF), Frame Transfer (FT) and Interline (IL). The animation shows the different CCD types and readout modes.

Full Frame CCD

Frame Transfer CCD

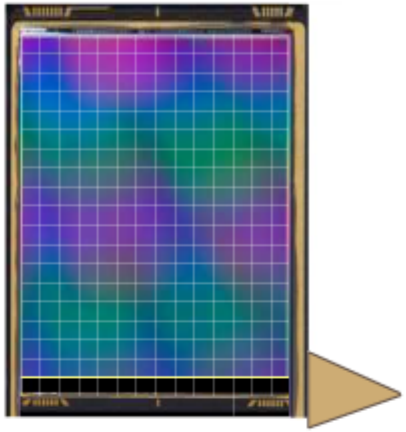
Interline CCD

EMCCD

CMOS Readout

CMOS Global

CMOS Rolling



CMOS – Any downsides?

- Each photo site in the CMOS sensor has three or more transistors ,which has its benefits and its draw backs
- The transistors allow for processing to be done right at the photo site, and each pixel/photo site can be accessed independently
- Because the transistors occupy space on the array, some of the incoming light hits the transistors and not the photo sites, which leads to picture noise
- CMOS sensors also function at a very low gain which may contribute to noise.
- Small pixel sizes often lead to small full well capacities and low dynamic range
- Rolling Shutter mode not accepted and can lead to

Where is CMOS currently used?

- Brightfield Microscopy
- Industrial Inspection
- High Speed applications

Where is CMOS Heading ?

- High Speed Fluorescence Microscopy for dynamic studies and observation

SCMOS

- Scientific CMOS is a new way of rebranding CMOS where new sensors produced by Sony and Fairchild Imaging utilize low read noise for high speed medium light level imaging

- These offer high resolutions and high speed which will enable much faster imaging

- Currently sensor suffer from a few issues but over the next few years this market will establish for many new high speed experiments such as SPIM and high speed tracking

FIN