EE 392B Course Introduction

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  - Image Sensor Architectures
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Motivation

- Image sensors are all around us:
    - Cell phones
    - Digital still and video cameras
    - Optical mice
    - Cars
    - Security cameras
    - PC and Web cameras
    - Scientific and industrial
- Digital cameras are replacing film and analog cameras for capture
- CMOS image sensors are making it possible to integrate capture and processing on the same chip, providing new capabilities for
    - Machine vision
    - Man-machine interface
    - Biometrics
    - Biological applications

- Image sensors are quite different from other types of sensors, e.g., pressure, temperature, . . .
    - They comprise a massive array of detectors
    - They can detect (see) over very long distances (most other sensors are *local*)
- Several important issues beyond physics and fabrication:
    - How do we read out a very large number of signals quickly?
    - What are the *spatial* and *temporal* nonidealities that limit the performance of image sensors?
    - How do we quantify their performance?
- So, to understand image sensors, we need to use tools from several areas in EE; device physics and fabrication, optics, circuits, signals, and systems

Course Goals

- Provide an introduction to the design and analysis of visible range image sensors
- Develop basic understanding of the signal path through an image sensor
- Develop an understanding of the nonidealities, performance measures, and tradeoffs involved in the design of image sensors
- Discuss recent developments and future trends in this area
- The course can be used as part of an MSEE Image Systems Eng depth sequence

Course Topics

- Silicon photodetectors: photodiode, photogate, and pinned diode; photocurrent, quantum efficiency, and dark current; direct integration
- CCD and CMOS image sensors; architectures and readout circuits, well capacity, conversion gain, readout speed
- Image sensor technologies including color filters and microlens.
- Temporal noise
- Fixed pattern noise (FPN), DSNU, PRNU
- SNR and Dynamic range
- Spatial resolution and Modulation Transfer Function (MTF)
- Pixel optics
- High dynamic range extension schemes
- Technology scaling and modification issues

Course Schedule

March 29	Overview – El Gamal.
March 31	Photodetection in silicon, photodiode operation – El Gamal.
April 5	Photocurrent and dark current – Wong. **HW1.**
April 7	Photogate and direct integration – Wong.
April 12	CCDs – Wong. **HW1 due, HW2.**
April 14	CCDs – Wong.
April 19	CCDs – Wong. **HW2 due, HW3.**
April 21	CMOS image sensors – El Gamal. **Project HO.**
April 26	CMOS image sensors – El Gamal. **HW3 due, HW4.**
April 28	Process and layout issues. – Wong. **Project Groups due.**
May 3	Noise analysis in circuits – El Gamal. **HW4 due, HW5.**
May 5	Noise analysis in image sensors – El Gamal.
May 10	Fixed pattern noise – El Gamal. **HW5 due.**
May 12	vCam – Farrell. **Take Home Midterm.**

Course Schedule Contd.

May 17	SNR and dynamic range – El Gamal. **HW6, Project information.**
May 19	Spatial resolution, MTF – El Gamal. **Project information.**
May 24	Pixel optics – Catrysse. **HW6 due.**
May 26	HDR schemes.
May 31	Course Summary. **Project Progress reports due.**
June 7	**Projects due.**

Project format:

- We plan to propose two mini-project topics for you to choose from; one in the device and technology area and the other in the sensor design and analysis area
- The projects will be done in two-student groups
- We are open to project proposals other than the recommended ones. You need to tell us early, however

Course Prerequisites

- Understanding image sensors requires basic knowledge in several areas of EE
- You need to have undergarduate (preferably MSEE) level knowledge in:
    - Device physics and fabrication
    - CMOS circuits
    - Basic signals and systems
    - Optics
- We will try to be as self-contained as possible and review some of the necessary concepts and derivations
- However, depending on your background and interest, there may be some material that you will not completely understand
    - We do not expect you to have complete understanding of everything
    - As in studying any interdisciplinary field, it is more important to develop some level of understanding of *all* aspects of the field before going deeply into any particular aspect

Reading and References

- The course has no required or recommended textbook. We will hand out lecture notes and some papers
- Here are some books that may be useful:
  - CCDs:
    A.J.P. Theuwissen, Solid-State Imaging with Charge-Coupled Devices
    J. D. E. Beynon, D. R. Lamb, CCD Operation, Fabrication and Limitations
  - Devise physics and fabrication:
    Muller and Kamin, Device Electronics for Integrated Circuits
    Pierret, Semiconductor Device Fundamentals
  - Circuits:
    A.S. Sedra and K.C. Smith, Microelectronic Circuits
    P. Gray and R. Meyer, Analog Integrated Circuits
  - Signals and systems:
    B.P. Lathi, Signal Processing and Linear Systems.
    A. El Gamal, EE278 Class Notes.
- We will handout a fairly comprehensive list of references

Digital Imaging System

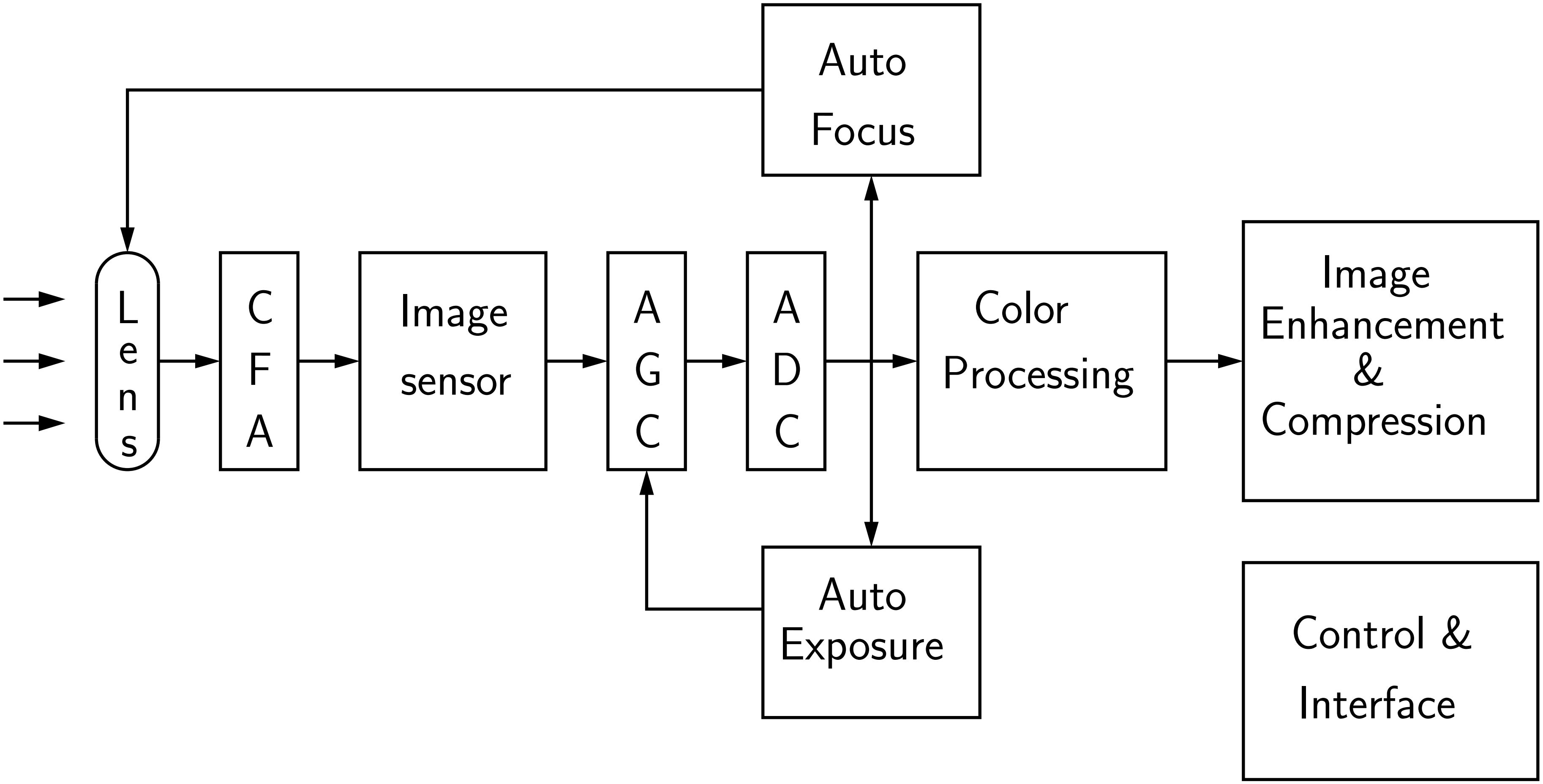


Image Sensors

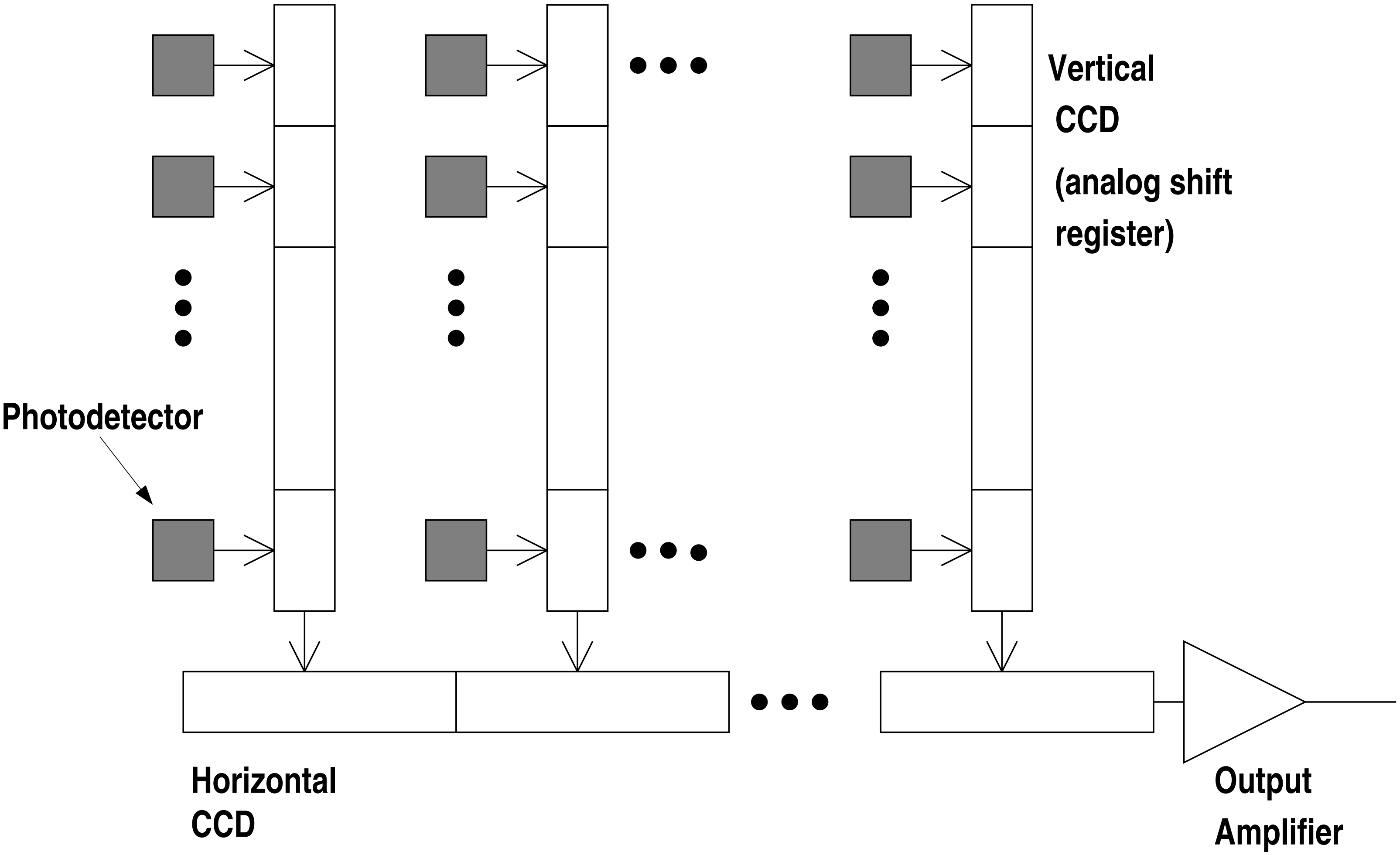
- An area image sensor consists of:
    - An $n \times m$ array of pixels, each comprising
        - a photodetector that converts incident light (photons) to photocurrent
        - one or more devices for readout
    - Peripheral circuits for readout and processing of pixel signals and sensor timing and control
- Sensor size ranges from 320×240 (QVGA) for low end PC digital camera to 7000×9000 for scientific/astronomy applications
- Pixel size ranges from 15×15 μm down to 1.5×1.5 μm

Brief History of Image Sensors

1965-1970	Bipolar, MOS photodiode arrays developed (Westinghouse, IBM, Plessy, Fairchild)
1970	CCD invented at Bell Labs
1970-present	CCDs dominate
1980-1985	Several MOS sensors reported
1985-1991	CMOS PPS developed (VVL)
1990s	CMOS APS developed (JPL, . . .)
1994-present	CMOS DPS developed (Stanford, Pixim)
2000-present	CMOS image sensors become a commercial reality

See reference [11] of the Bibliography for more details

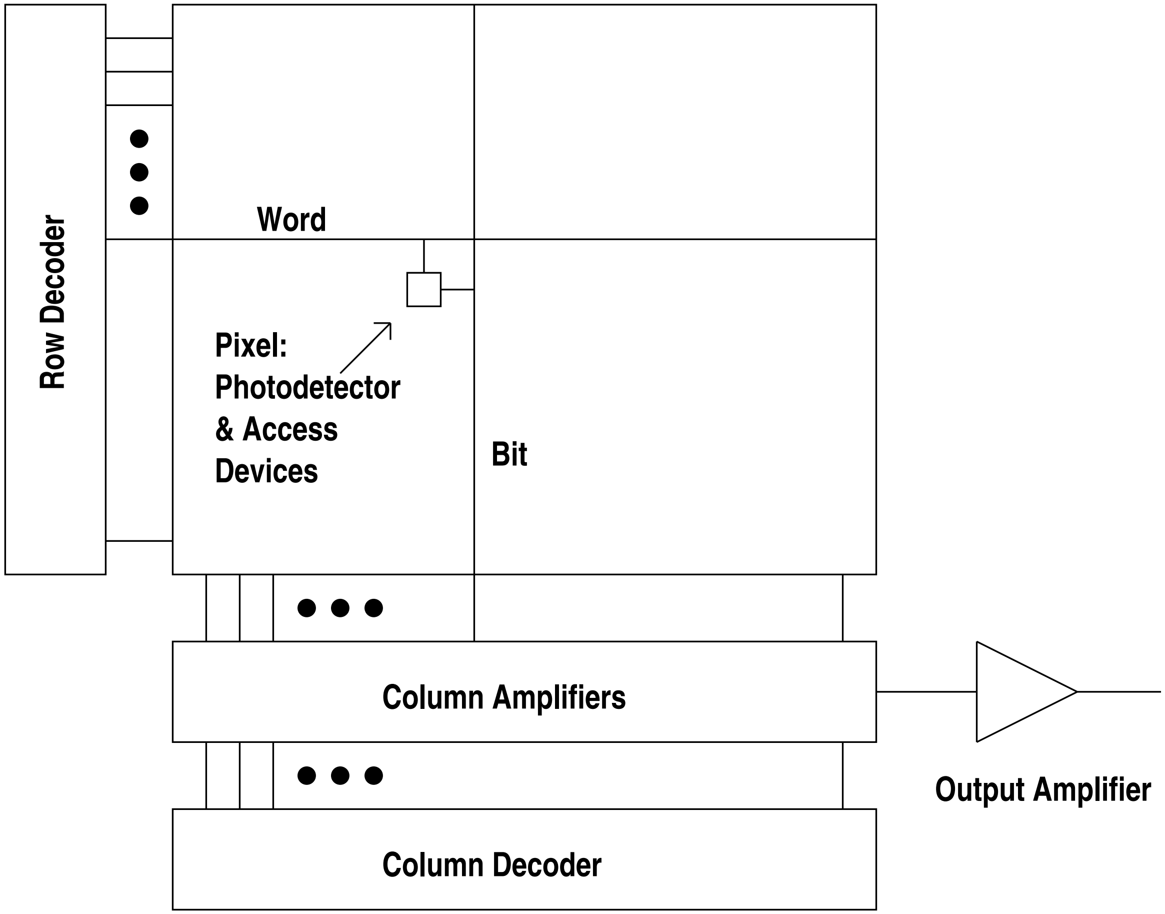
CCD Image Sensors (Interline Transfer)



CCD Image Sensors

- Advantage: High quality
  - optimized photodetectors — high QE, low dark current
  - low noise and nonuniformity — CCDs do not introduce noise or cause nonuniformity
- Disadvantages:
  - difficult to integrate other camera functions on same chip
  - high power — high speed shifting clocks
  - limited frame rate — serial readout

CMOS Image Sensors



Most popular type called Active Pixel Sensor (APS), pixel has photodiode and 3 transistors

CMOS Image Sensors

- Advantages:
  - can integrate other camera functions on same chip
  - lower power consumption than CCDs (10X)
  - very high frame rates can be achieved
  - very high dynamic range can be achieved
- Disadvantages: lower quality at low light CCDs
  - higher dark current (CMOS process usually modified to optimize the photodetector and reduce trasistor leakage, but it is still difficult to match the low dark current of CCDs)
  - lower QE (higher stack above photodetector reduces incident light)
  - high noise and nonuniformity due to multiple levels of amplification (pixel, column, and chip)

Signal Path Through an Image Sensor

$$\textbf{Photonflux} \xrightarrow[\textbf{Quantum Efficiency}]{} \textbf{Current density} \xrightarrow[\textbf{Integration space/time}]{} \textbf{Charge} \xrightarrow[\textbf{Conversion Gain}]{} \textbf{Voltage}$$

ph/cm^2·sec A/cm^2 Col V

- Quantum efficiency determined by pixel characteristics
- Due to the small photocurrent levels, the photocurrent is integrated over exposure time into charge
- Charge is converted into voltage for readout using linear amplifier(s)

Quantum Efficiency – Example

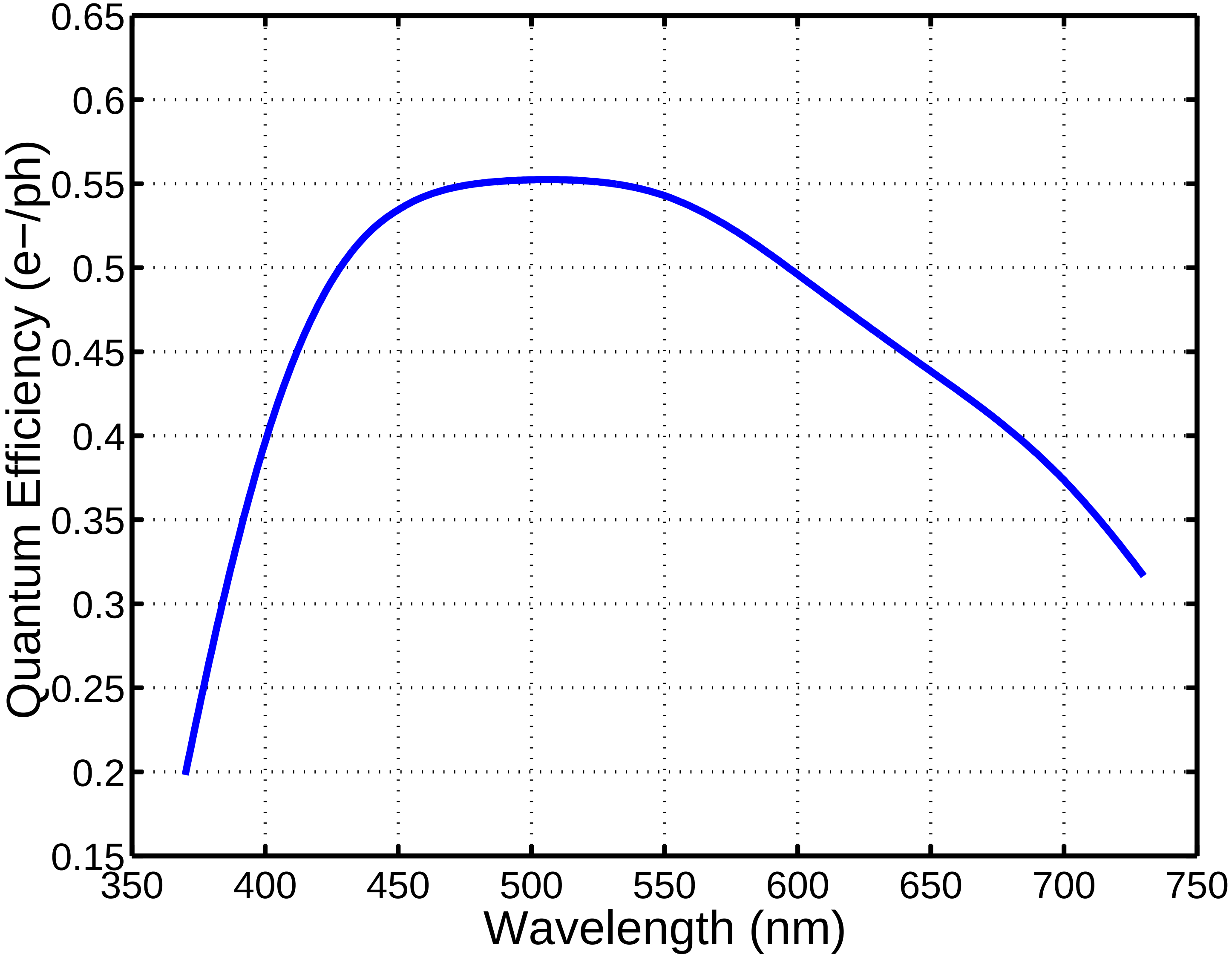


Image Sensor Non-idealities

- Temporal noise
- Fixed pattern noise (FPN)
- Dark current
- Spatial sampling and low pass filtering

Temporal Noise

- Caused by photodetector and MOS transistor thermal, shot, and 1/f noise
- Can be lumped into two additive components:
  - Read noise
  - Integration noise (due to photodetector shot noise)
- Noise increases with signal, but so does the signal-to-noise ratio (SNR)
- Noise under dark conditions (read noise) presents a fundamental limit on sensor dynamic range (DR)

Fixed Pattern Noise (FPN)

- FPN (also called nonuniformity) is the spatial variation in pixel outputs under uniform illumination due to device and interconnect mismatches over the sensor
- Two FPN components: offset and gain (called Pixel Response Nonuniformity or PRNU)
- Most visible at low illumination (offset FPN more important than gain FPN)
- Worse for CMOS image sensors than for CCDs
- Offset FPN can be reduced using correlated double sampling (CDS)

Dark current

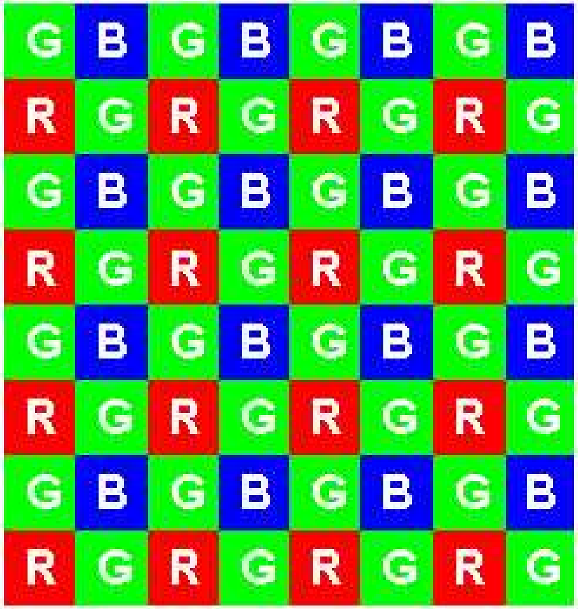
- Dark current is the photodetector leakage current, i.e., current not induced by photogeneration
- It limits the photodetector (and the image sensor) dynamic range
    - introduces unavoidable shot noise
    - varies substantially across the image sensor array causing *nonuniformity* (called Dark Signal Nonuniformity or DSNU) that cannot be easily removed
    - reduces signal swing

Sampling and Low Pass Filtering

- The image sensor is a spatial (as well as temporal) sampling device — frequency components above the Nyquist frequency cause aliasing
- It is not a point sampling device — signal low pass filtered before sampling by
  - spatial integration (of current density over photodetector area)
  - crosstalk between pixels
- Resolution below the Nyquist frequency measured by Modulation Transfer Function (MTF)
- Imaging optics also limit spatial resolution (due to diffraction)

Color Imaging

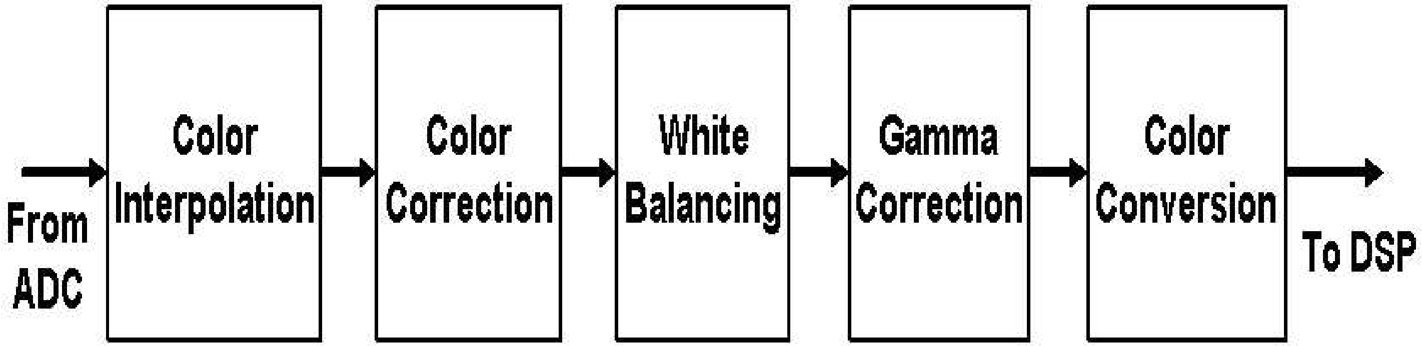
- To capture color images, each pixel needs to output three values (corresponding, for example, to R, G, and B)
- The most common approach is to deposit color filters on the sensor in some regular pattern, e.g., the RGB Bayer pattern



G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G

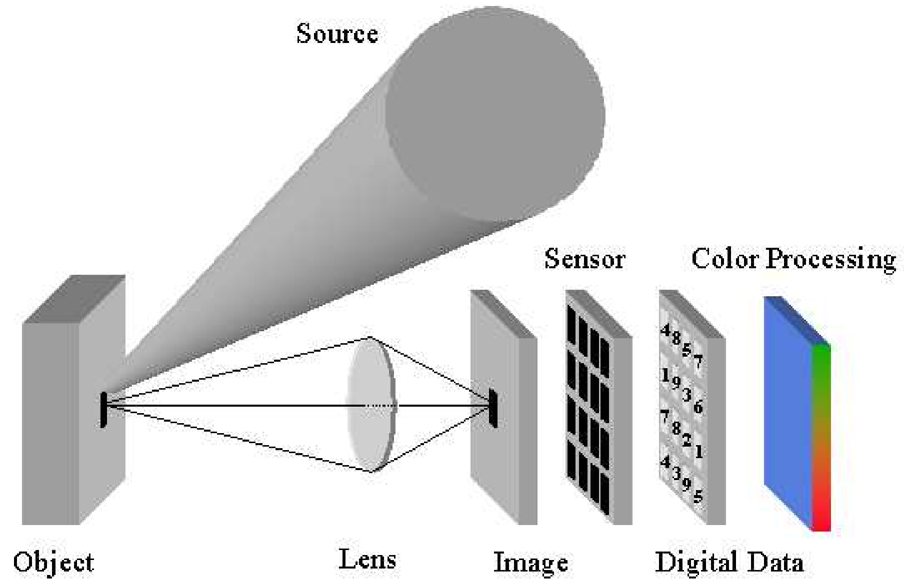
- A lot of processing is needed to obtain three colors for each pixel with the right appearance

Color Processing



- Interpolation used to reconstruct missing color components
- Correction and balancing used to improve appearance of color
- Gamma correction and color space conversion needed before image enhancement and compression
- Color processing very computationally demanding — over 300 MOPS needed for a 640×480 sensor operating at 30 frames/s
- We do not discuss color processing and other digital image processing that take place in a digital camera in this course

The vCam Camera Simulator



- Set of MATLAB routines modeling the light source, the object, the optics, the sensor, and the ADC
- Parameters of the scene, the sensor, and the camera can be set and the corresponding output image obtained
- Allows us to visualize the effects of different sensor parameters and nonidealities
- Allows us to explore the sensor design space
- Will be used in the last homework set and in the course project

Recent Developments and Future Trends

- CMOS image sensor technology scaling and process modifications:
    - approach CCD quality
    - reduce pixel size
    - increase pixel counts
- Integration of image capture and processing:
    - most commercial CMOS image sensors today integrate A/D conversion, AGC, and sensor control logic on the same chip
    - some, e.g., also integrate exposure control and color processing
- Per-pixel integration is being exploited to provide new capabilities:
    - High dynamic range sensors
    - Computational sensors
    - 3D sensors
    - Lab-on-chip
- Vertical integration promises higher levels of per-pixel integration