A Graduate Course on Image Sensors and Digital Cameras

Abbas El Gamal and Ting Chen

Information Systems Laboratory
Department of Electrical Engineering
Stanford University

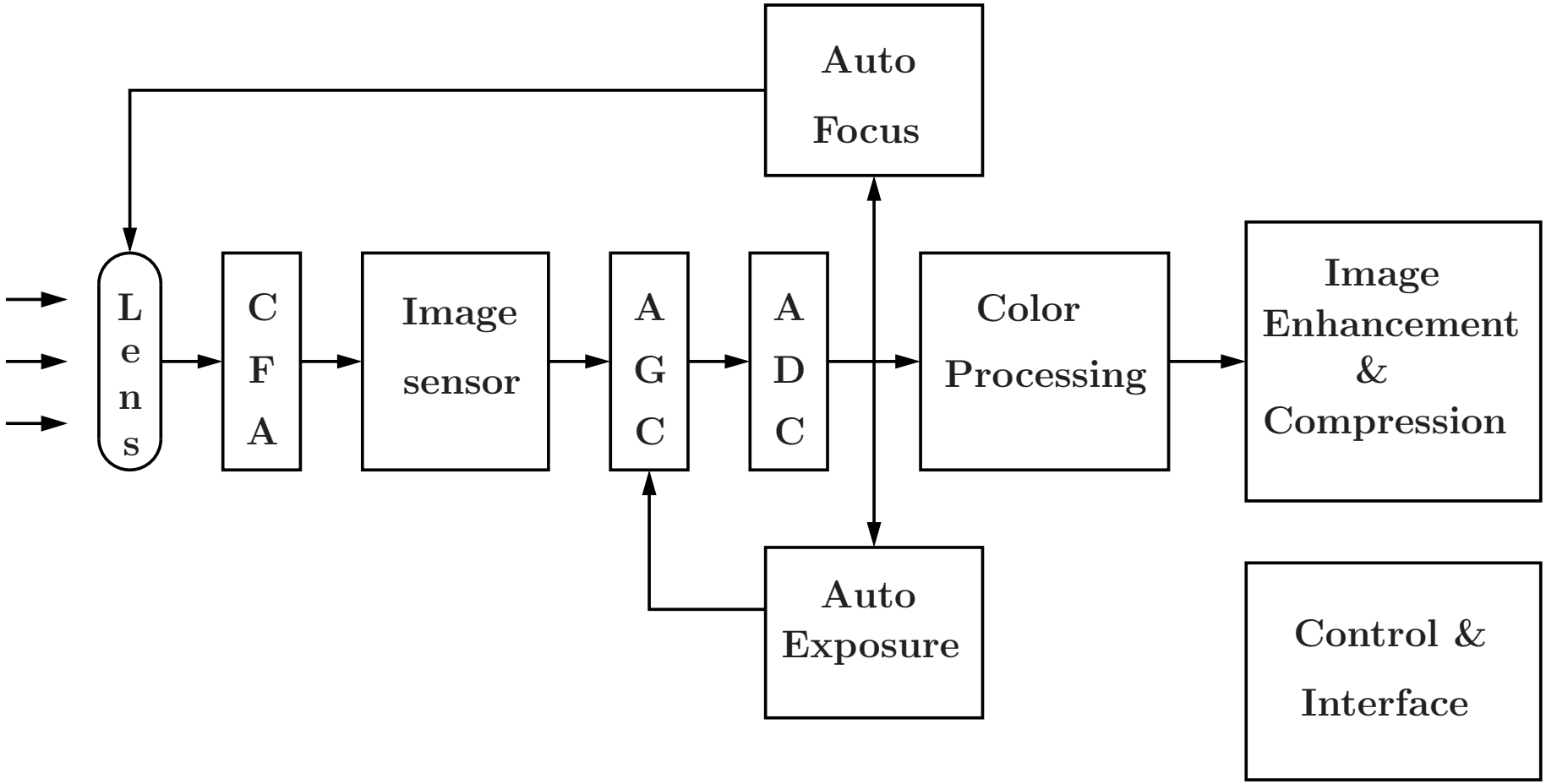
Motivation

- Sales of digital cameras has surpassed film cameras
- Emergence of CMOS image sensors making *camera-on-chip* possible – enabling new applications:
  - PC camera
  - cell phones and PDAs
  - toys and games
  - biometrics
  - camera arrays and networks
- More EEs are attracted to the field, but
  - Little teaching material available
  - Study of digital camera system requires working knowledge in many areas (photometry, optics, device physics, circuits, signal processing, color science . . .)

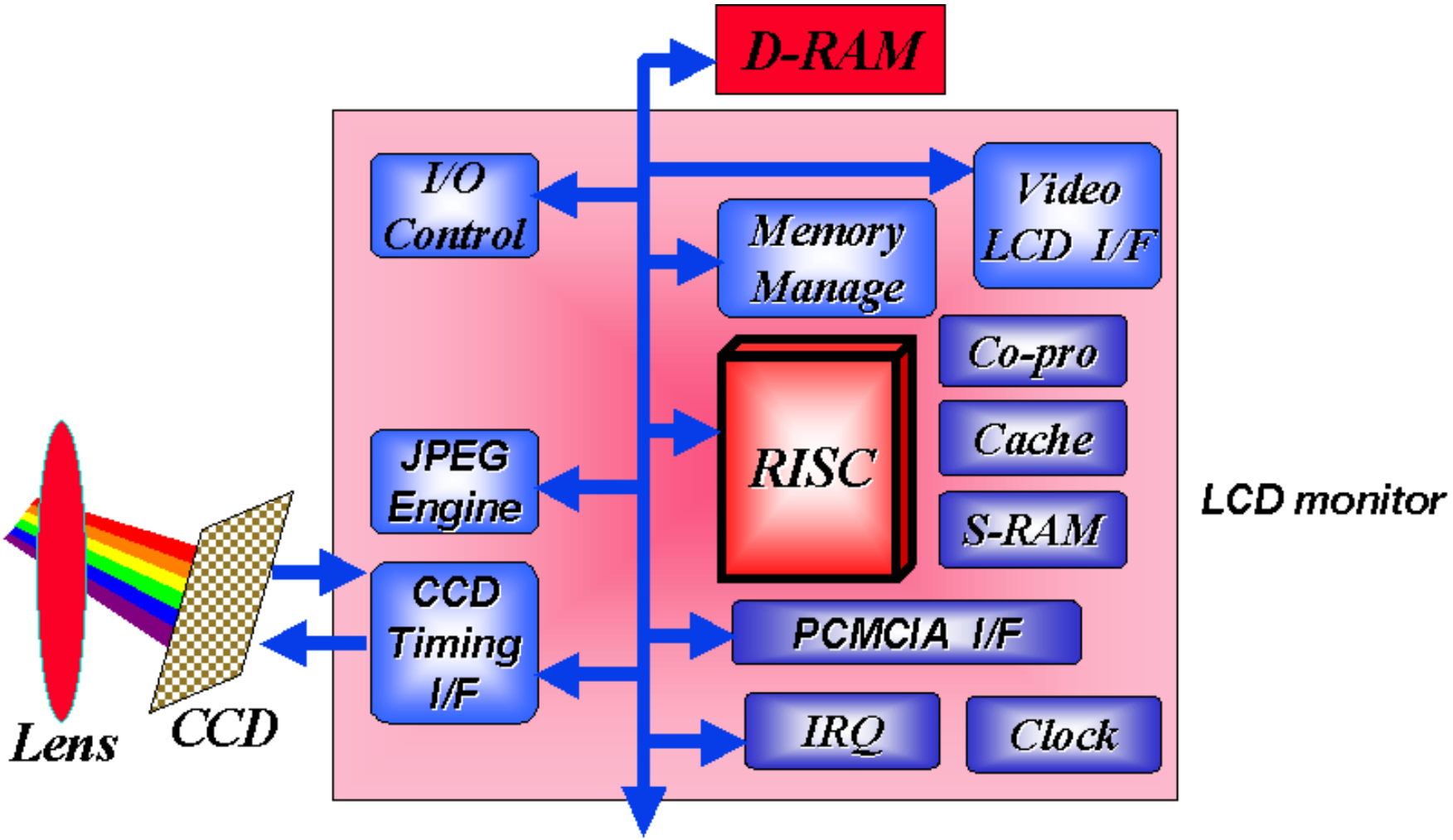
Outline

- Digital cameras and image sensors
- The course
  - Objectives
  - Requirements
  - Topics
  - Course history
- Digital camera simulator (vCam)
- Demo

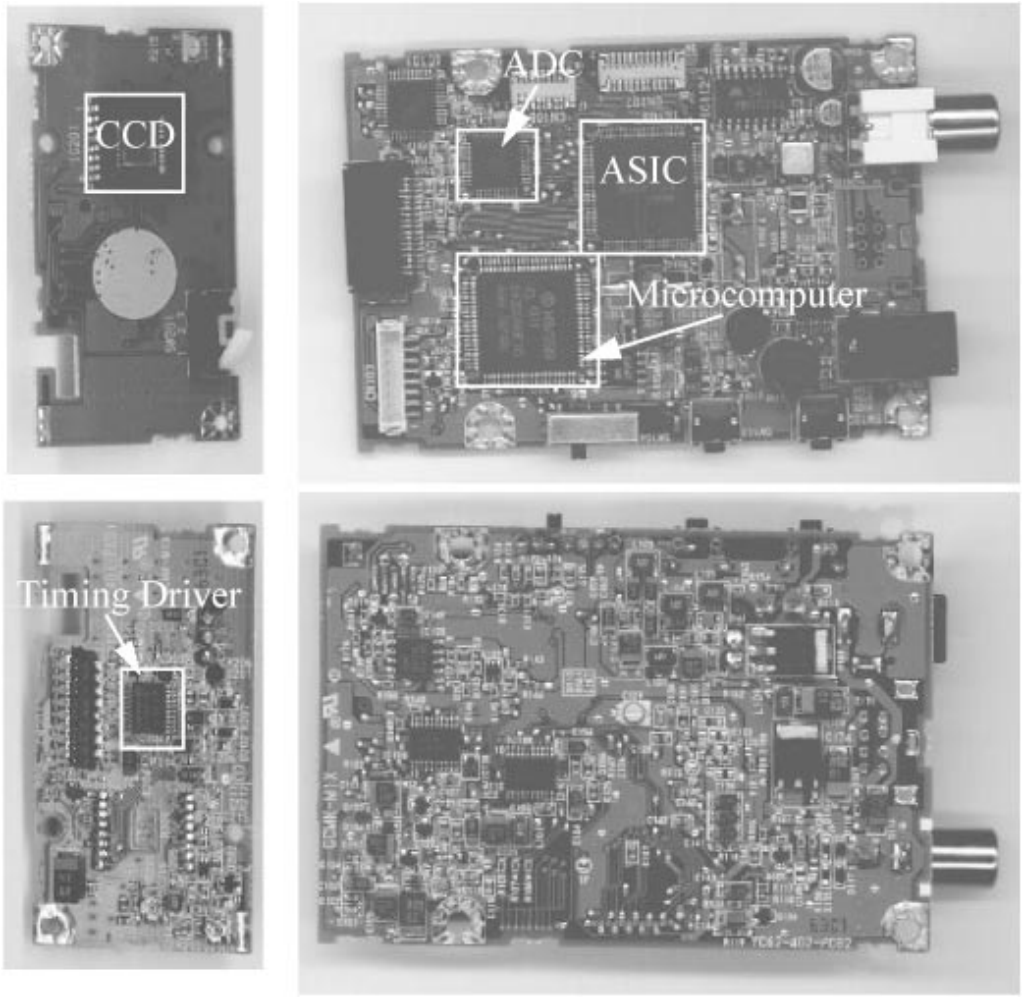
Digital Camera System



Architecture of Olympus Camera

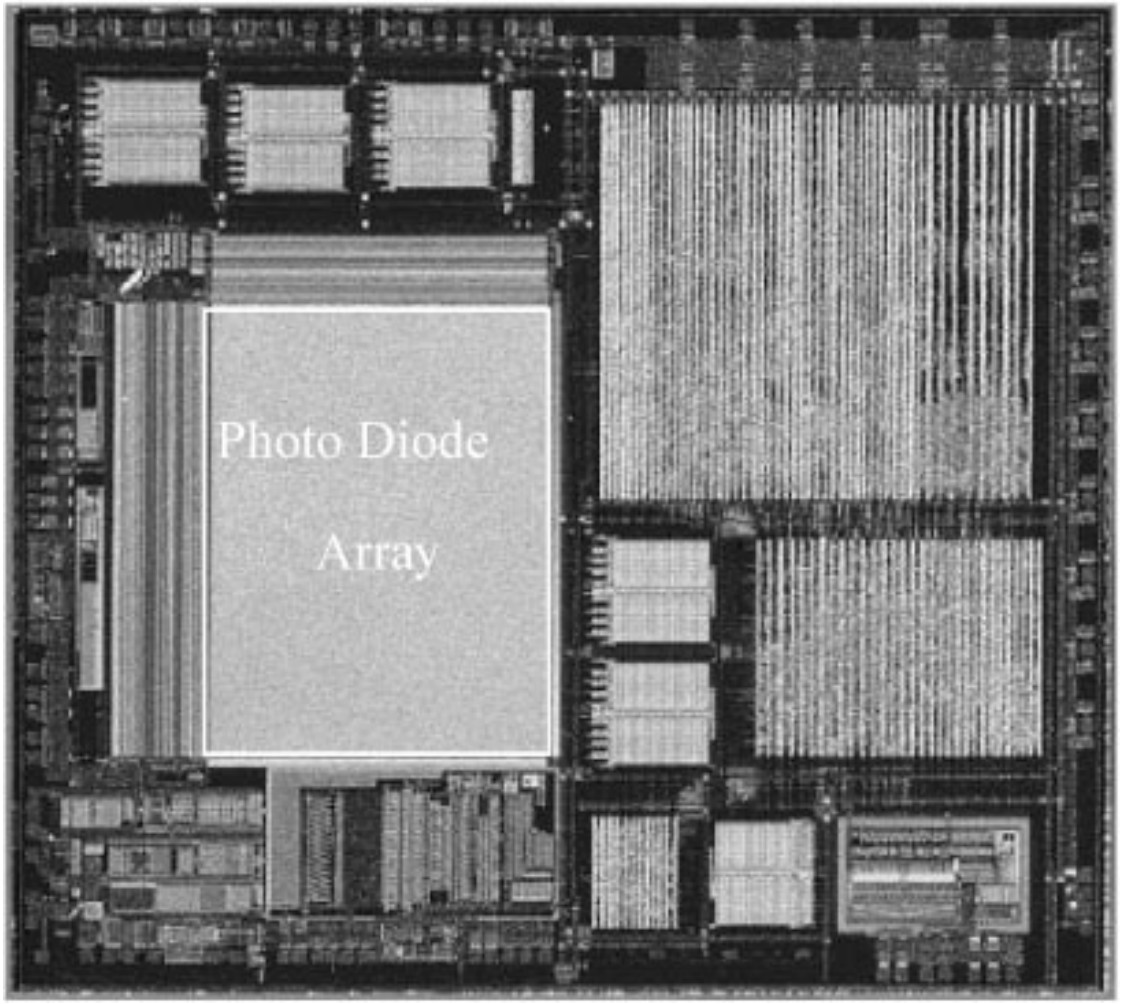


CCD Camera



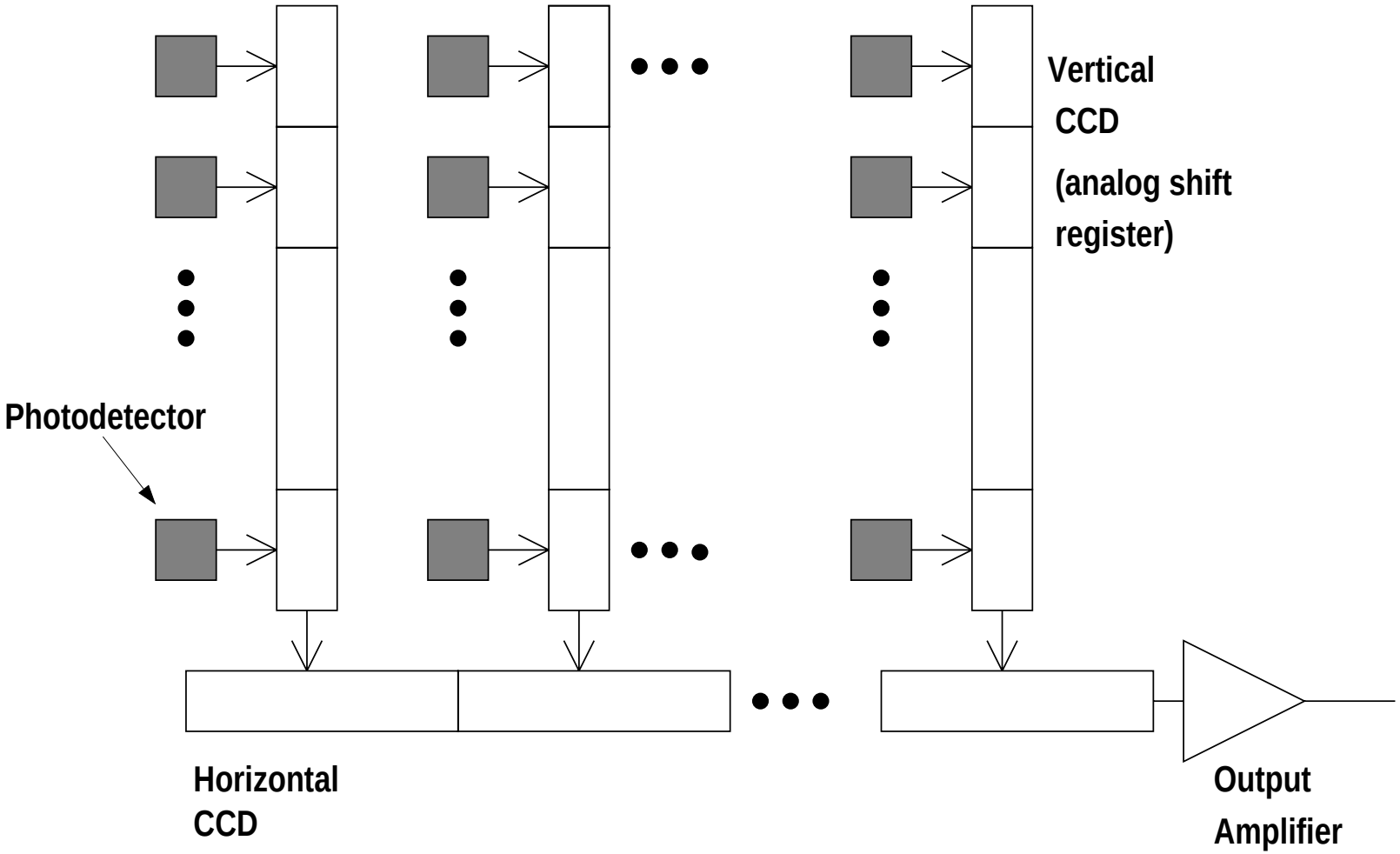
Many chips — CCD, ADC, ASICs, memory, . . .

Sub-micron CMOS Enables Camera-on-Chip



VLSI Vision Ltd. (ISSCC '98)

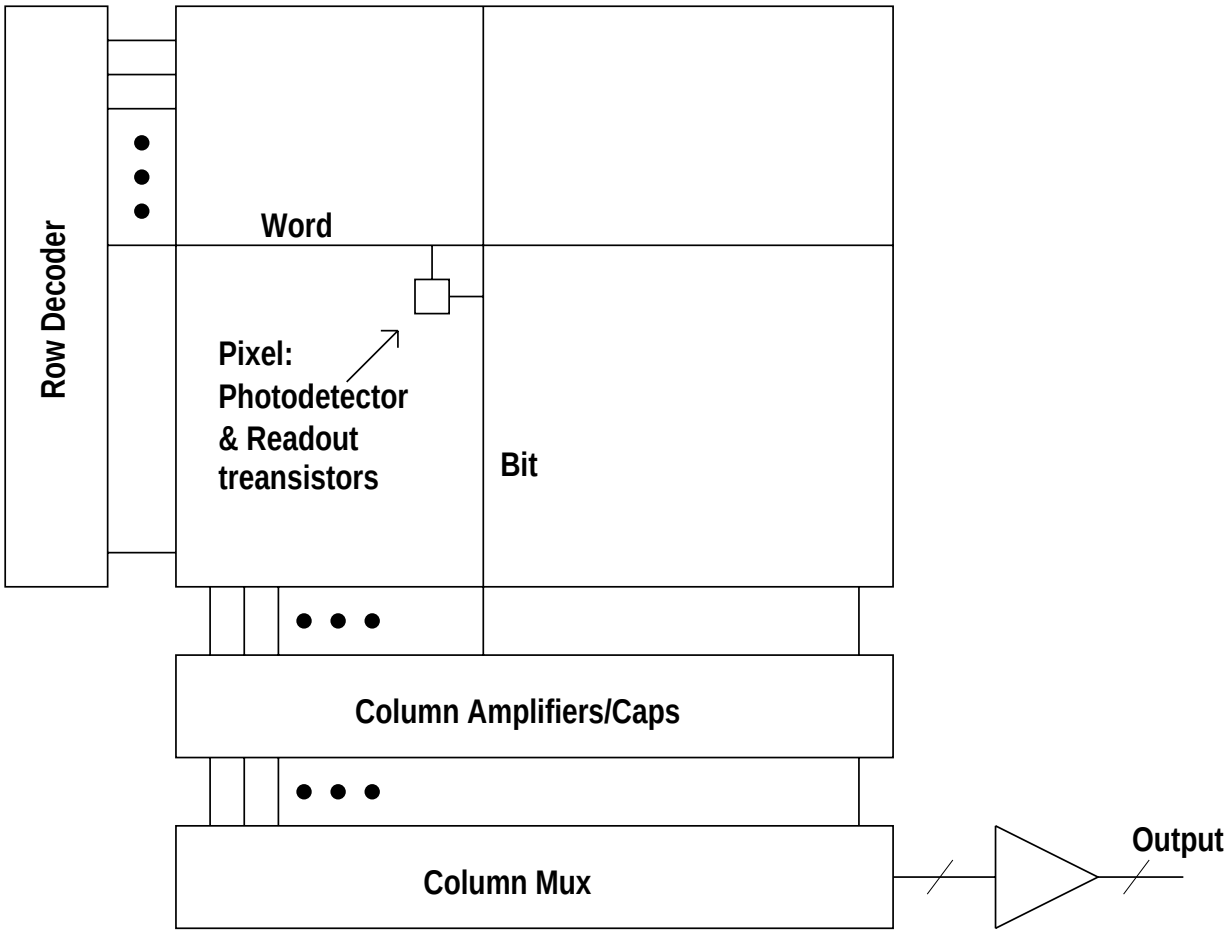
CCD Image Sensors (Interline Transfer)



CCD image sensors

- Advantage: High quality
  - optimized photodetectors (high QE, low dark current)
  - low noise and nonuniformity (CCDs do not introduce noise or nonuniformity)
- Disadvantages:
  - inability to integrate other camera functions on same chip with image sensor
  - high power (due to high speed shifting clocks)
  - limited frame rate (due to analog serial readout)

CMOS Image Sensors



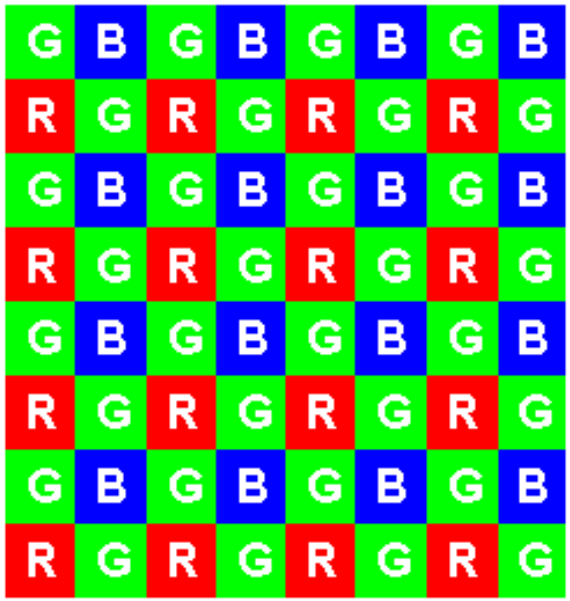
Most popular type called Active Pixel Sensor (APS), pixel has photodiode and 3 transistors

CMOS Image Sensors

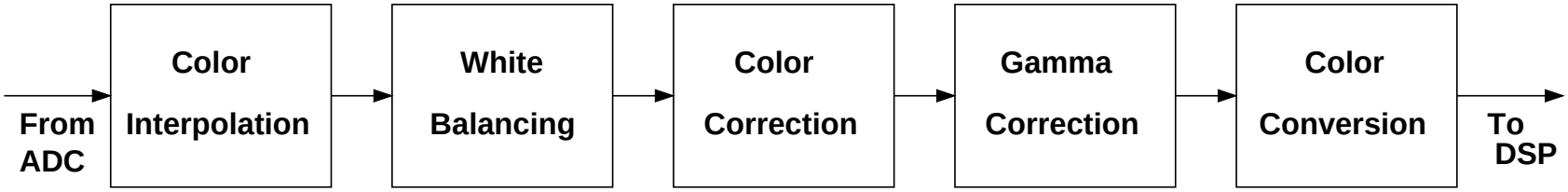
- Advantages:
  - unlimited ability to integrate other camera functions with image sensor on same chip
  - lower power consumption than CCDs (10X)
  - potential for very high frame rates
- Disadvantages: lower quality than CCDs
  - nonoptimized photodetectors (process often modified to optimize the photodetector)
  - high noise and nonuniformity due to multiple levels of amplification (pixel, column, and chip)

Color Imaging

- Color filter array (Bayer pattern)



- Color processing



Course Objectives

- Provide an introduction to design and analysis of image sensors (especially CMOS)
- Develop basic understanding of signal path through digital camera
- Develop understanding of the performance measures and tradeoffs involved in the design of image sensors and digital cameras
- Have fun using many basic EE (and some non EE) stuff to understand a "cool" system

Course Requirements

- **Prerequisites:** Undergrad device, circuit, system courses
- **Reading:** Lecture notes and research papers handed out
- **Students:** MS or PhD level (EE, CS, Applied Physics)
- **Homeworks:** Six weekly homeworks
- **Exams:** Take home midterm
- **Project:**
  - 1-2 project topics proposed
  - performed in 1-2 student groups
  - two weekly progress reports/ meetings and final report
  - Most projects used the camera simulator

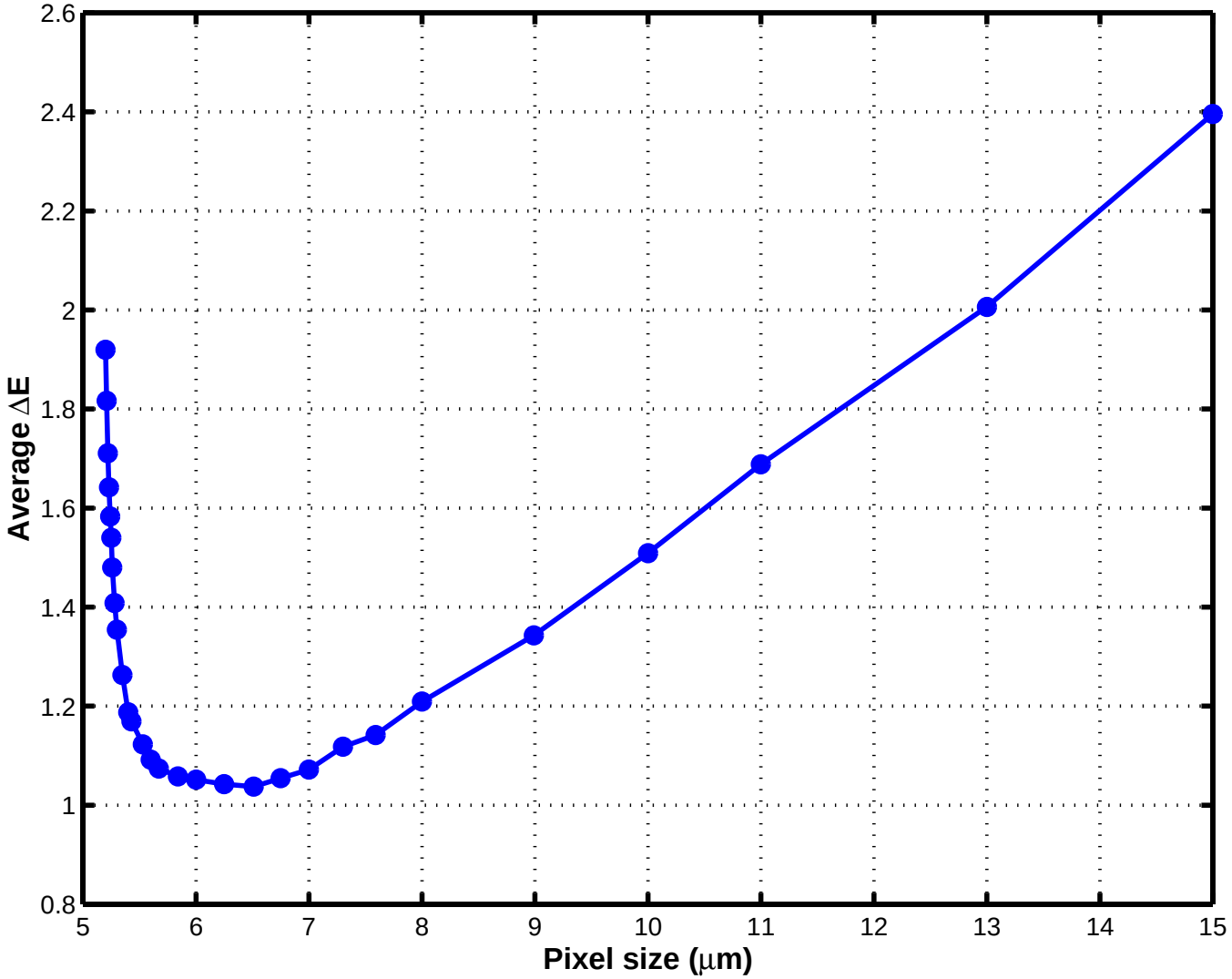
Course Topics

- Imaging optics (1 lecture)
- Photodetector operation, QE, dark current (3 lectures)
- CCD and CMOS image sensor operation (3 lectures)
- Noise analysis, SNR, and dynamic range (3 lectures)
- Fixed pattern noise (FPN) (1 lecture)
- Spatial resolution, MTF (1 lecture)
- Color imaging and color processing (1 lecture)
- Camera simulator (1 lecture)
- Recent developments (1 lecture)

Course History

- Course offerred four times (Spring 98-01)
- Class enrollment: 16 MS and PhD students (mostly EEs, some CS and Applied Physics)
- Example projects:
  - How large should pixel size be ?
  - Honey-comb versus square pixel array
  - High dynamic range image sensor schemes
  - Auto-exposure algorithms

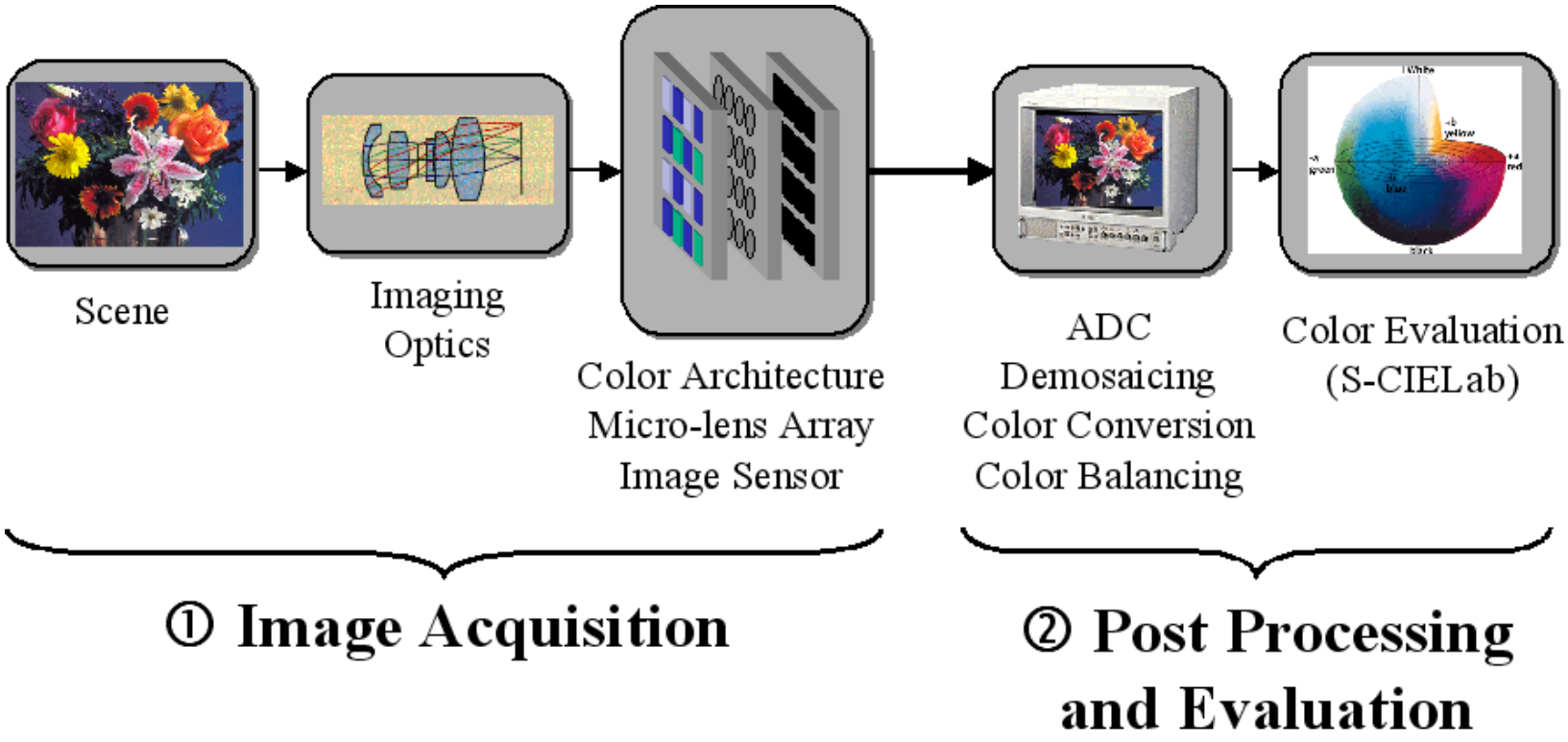
Optimal Pixel Size



Conclusion

- Graduate level course on image sensors and digital cameras
- Course only requires undergraduate EE level background
- Course uses a "system approach":
  - builds a model for the signal path through digital camera
  - discusses sensor architectures and operation
  - introduces important performance measures
- Example of how the study of a complex system can be made accessible to MS level EEs
- Example of the bidirectional flow of ideas between research and teaching

vCam: Digital Camera Simulator



- Set of MATLAB routines modeling light source, object, optics, sensor, ADC characteristics, and for performing color and image processing
- Developed for research on image sensors and digital cameras