Smartphone Imaging Trends

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Background

- B.S. - Optical Sciences & Engineering, University of Arizona
- Imaging Technology Lab with Steward Observatory
  - Worlds first curved front-illuminated CCD
  - ITL does BSI processing and characterization for CCDs used in astronomy, other photometric fields
- Thesis/Capstone: Terahertz GRIN Rapid prototyping
  - First THz GRIN objective cheaply fabricated on 3D printer

Background

- **AnandTech.com**, Founded in 1997 by Anand Lal Shimpi
  - Smartphones to Servers and Everything in Between
  - Everything is a Computer
  - Strong Background and Emphasis on Components
  - Understand the Pieces to Understand the Pie

Optics 101

$$n \equiv \frac{\text{Speed of Light in Vacuum}}{\text{Speed of Light in Medium}} = \frac{c}{v}$$

$$c = 2.99792458 \times 10^8 \text{ m/s}$$

$$\lambda = \frac{v}{\nu} \qquad \text{in vacuum: } \lambda = \frac{c}{\nu}$$

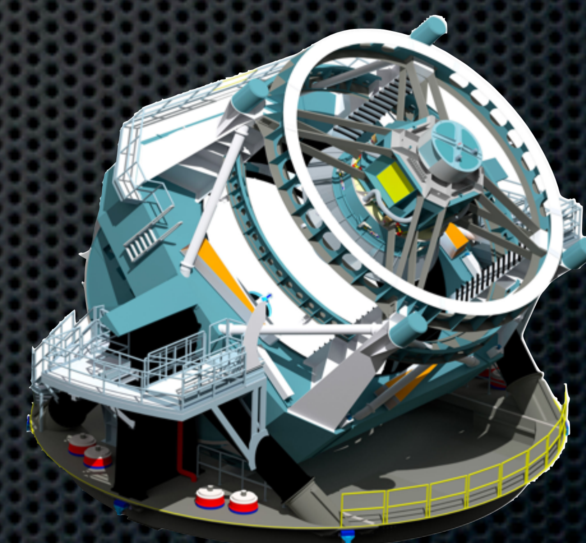
- **Index of refraction** - n (unitless)
  - Material property - ratio of how much the speed of light is slowed in a medium
- **Wavelength** - λ (m), **Frequency** - ν (Hz)
  - Essentially “Color”, Human Response 400 - 700 nm
- **Focal Length** - f (m), **Power** - ϕ (diopters)
  - Convergence or divergence of light from a system
  - Longer focal length - more magnification, lower focal length, less magnification

Optics 101

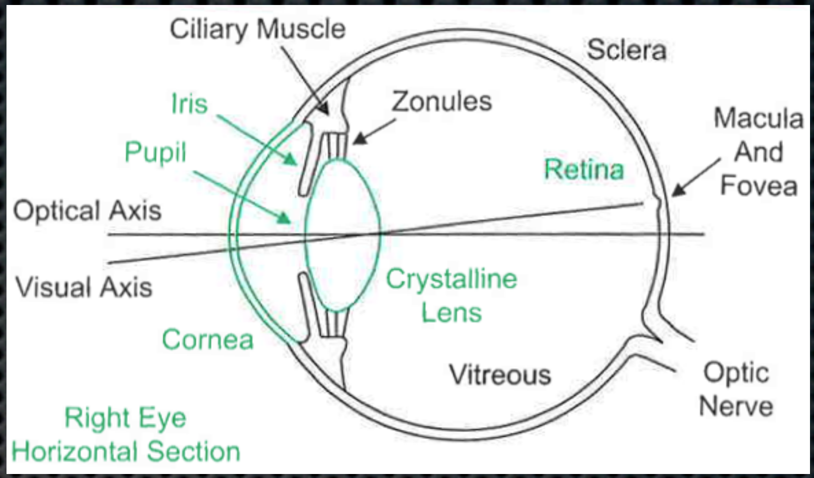
- **F-number** - F/# (unitless), F/#=f/d
  - Describes the size of the cone of light accepted by the system / light collection ability. Lower F/# - more light, equal to the ratio of the focal length to diameter of the entrance pupil
  - F-Stops - typically go in √2 steps (1.4, 2, 2.8, 4, 5.6) which changes light collection by factor of 2
- **Optical / Image Sensor Format** - eg. 1/3.2” (inches)
  - Sensor size, but nothing to do with sensor size. Originally vidicon glass tube diameter required for some other active imaging area size. Use table.

Optical Systems

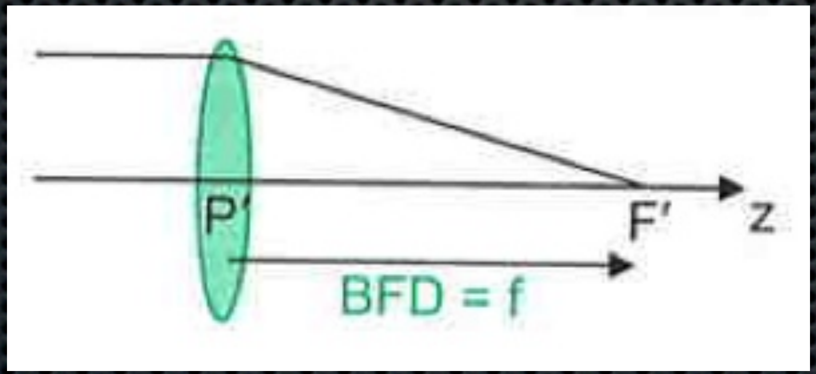
- Many different optical systems
  - Rifle Scopes
  - Telescopes
  - Microscopes
  - Viewfinders
  - Illumination / Projection
  - Industrial / Science
  - Internet (Fiber/EDFA)



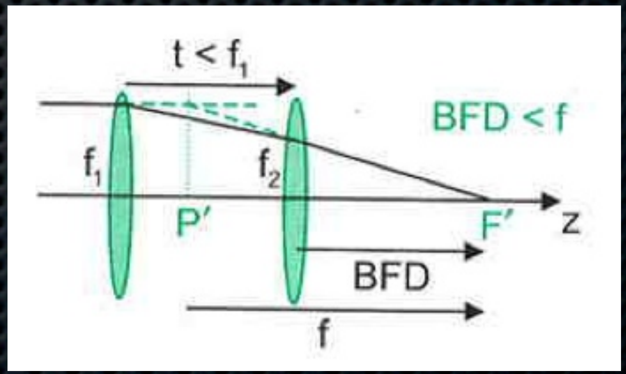
Camera Systems



- Approximation of the human eye
  - Human eye images field onto retina using crystalline lens which changes index as stretched (focus)
  - Objective system
    - Form an image of a scene onto some plane, image a distant object, hence objective



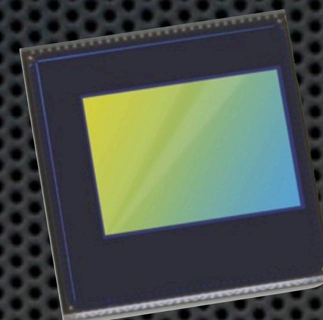
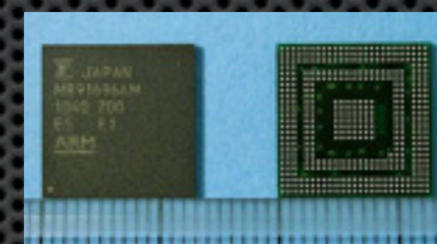
Simple Objective

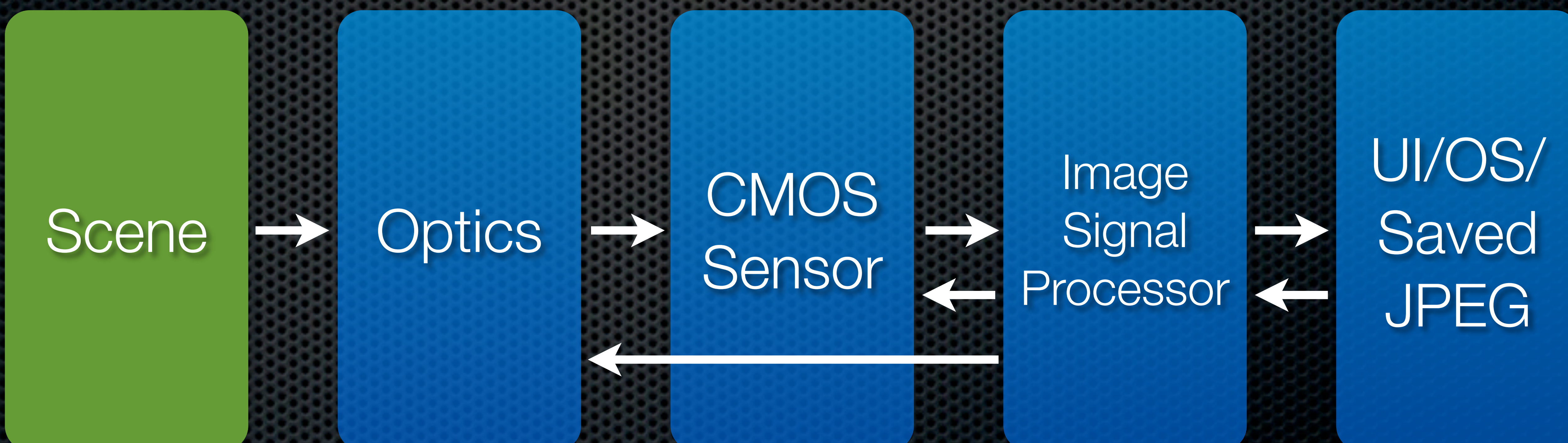


Telephoto Objective

Imaging Block Diagram

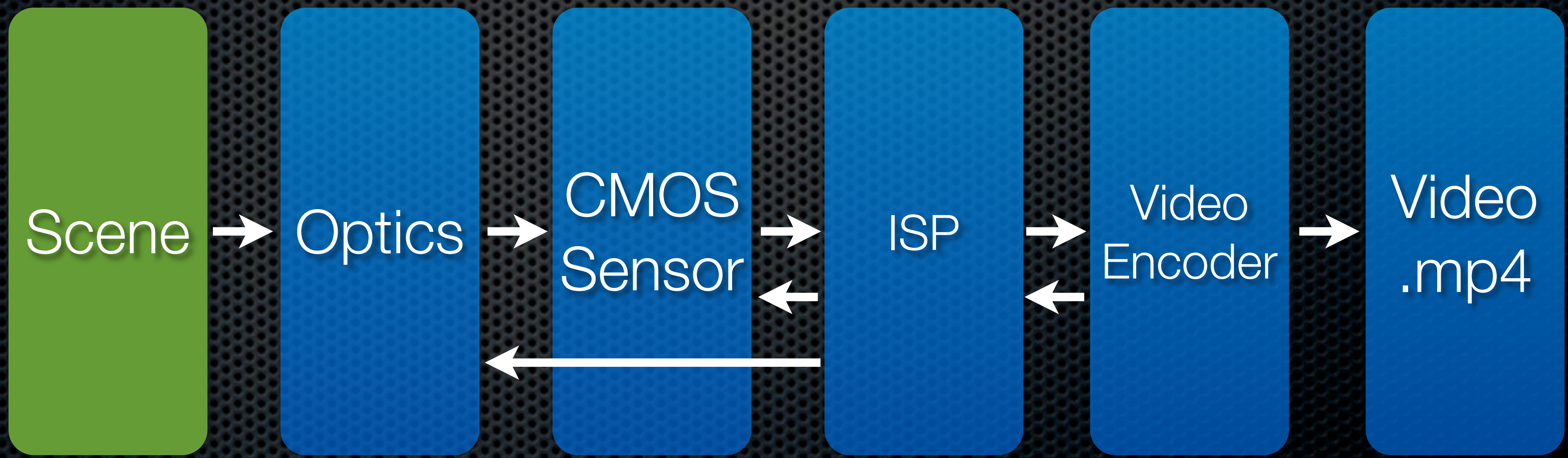


Video Block Diagram

- Same fundamental architecture, but with either a crop of the sensor or decimated version of output, then through an encoder for H.264/MPEG4. Encoder usually on SoC.

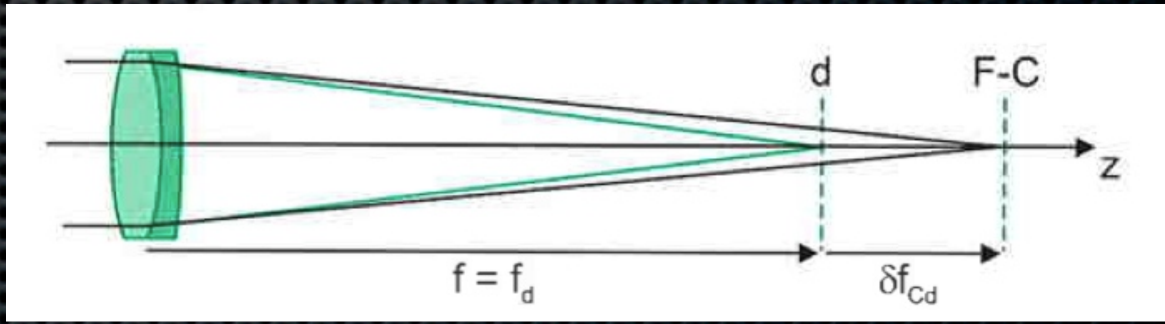


Smartphone Context

- Smartphone camera systems have unique constraints
  - Very small throw (z-stack, module often thickest part)
  - Cost ($5-15 for module)
  - Limited materials (Almost always plastic)
  - Unique manufacturing (Aspheres - injection molding)
  - Horrible operating conditions (Every type of scene)
  - Small aperture (Battling ID of phone)
  - All while imaging onto tiny pixels (Impossible problem)

Smartphone Optical System

- Optics usually made of plastic, injection molded into aspheres (complex, nonspherical shapes). Limited to 2-5 elements (2P-5P). Glass uncommon.
    - Optical plastics quite limited: Styrene, Polystyrene, ZEONEX, PMMA(Acrylic)
    - Doublet: PMMA as Crown Polystyrene as Flint



- Fixed focal length, fixed aperture (no iris), sometimes an ND filter, no shutter, usually not very fast (f/2.8, 2.4)
- Short focal length (wide), tiny image circle formed

Example Lens List

Lens Li

※Blue color is new information.　　※Parenthesis is temporary information.

Pixels	Sensor Size	Sensor Maker	Sensor	Lens Composition	Glass Thickness	Focal Length	CRA (H)	FOV (D)	F №	RI IH100%	Effective Image Circle	Mechanical		Screw Size	Study Design ES MP
												TTL	FB		
8.0Mega	1/2.9"	Samsung	3H3	5P	0.3	4.07	30.4°	73.7°	2.2	36.00%	6.50	5.2	1.1	M7.0×P0.35	Design
	1/3.2"	Omni Aptina SONY Samsung	OV-8820/30 AR0833 IMX105/175 3H2/3H7	5P	0.3	3.807	32.3	74.4	2.2	36.60%	6.17	4.45	0.94	M6.5×P0.25	ES
		Omni Aptina	OV-8820 AR0830/33	4P	0.3	4.50	24.6°	65.4°	2.8	45.00%	6.00	5.19	1.65	M6.0×P0.35	MP
		Omni Aptina SONY Samsung	OV-8820/30 AR0833 IMX105/175 3H2/3H7	5P	0.21	3.724	30.9	75.1	2.0	37.00%	6.10	4.60	0.83	M6.5×P0.25	Design
		Omni Aptina SONY	OV-8830 AR0833 IMX105/175	5P	0.3	4.36	27.8	66	2.4	39.50%	6.05	5.00	1.05	M6.5×P0.25	MP
12Mega	1/3.2"			5P	0.3	3.81	29.8°	72.4	2.5	41.90%	6.18	4.71	0.95	M7.0×P0.25	MP
		Samsung	3L1	5P	0.3	4.003	28.6°	70.2	2.4	45.00%	6.14	4.81	0.96	M6. 5×P0.25	MP
				5P	0.21	3.46	31.5°	76.4	2.4	35.40%	6.012	4.45	0.95	M6. 5×P0.35	Design
13Mega	1/3"	SONY	IMX091/135	5P	0.3	3.972	28.2	72.9	2.0	31.70%	6.167	5.0	1.0	M6.5×P0.25	Design
		SONY	IMX091/135	5P	0.3	3.807	32.3	75.3	2.2	36.00%	6.167	4.45	0.94	M6.5×P0.25	ES
		SONY	IMX091/135	5P	0.3	4.003	28.9	73	2.4	40.30%	6.14	4.81	0.96	M6.5×P0.25	MP
16Mega	1/2.5	Omni	OV16810	5P	0.3	5.556	27.2°	66.0°	2.0	47.80%	7.54	7. 454	1. 186	M9.0×P0.35	Design

Example System

- “Lens system having wide-angle, high resolution, and large aperture”
  US 8320061 B2, Chun-Cheng Ko, Hon Hai Precision Industry Co., Ltd. (aka Foxconn)
  - an aperture stop;
  - a first lens of positive refractive power having a subject-side surface and an image-side surface;
  - a second lens of negative refractive power having a subject-side surface and an image-side surface;
  - a third lens of positive refractive power having a subject-side surface and an image-side surface; and
  - a fourth lens of negative refractive power having a subject-side surface and an image-side surface;

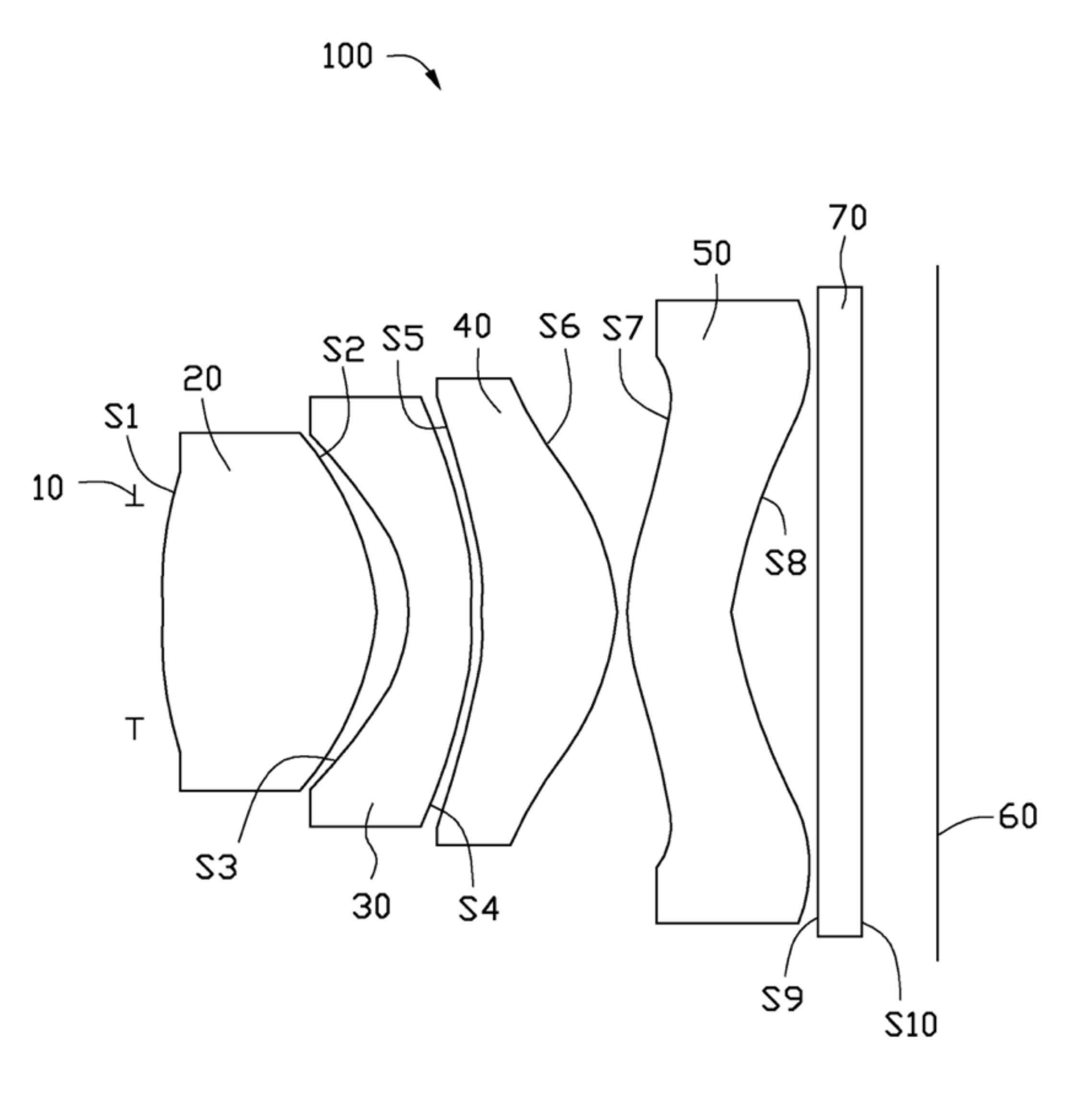


TABLE 3

F(mm)	F/No	2ω
2.10	2.05	74.85°

Example Prescription

Radius of Curvature

Separation

Index at d

Abbe # at d

Conic Constant (k)

TABLE 1

Surface	R(mm)	D(mm)	Nd	Vd	k
S0	infinity	0.13	—	—	—
S1	2.20	1.02	1.54	56.1	−10.6809
S2	−1.02	0.16	—	—	0
S3	−0.67	0.30	1.63	23.4	−0.5019
S4	−2.39	0.05		—	3.6355
S5	−1.89	0.65	1.53	56.0	0
S6	−0.77	0.05	—	—	−0.8953
S7	1.13	0.48	1.53	56.0	−5.4234
S8	0.67	0.42	—	—	−3.2770
S9	infinity	0.21	1.52	58.6	—
S10	infinity	0.36	—	—	—
Image plane 60	—	—	—	—	—

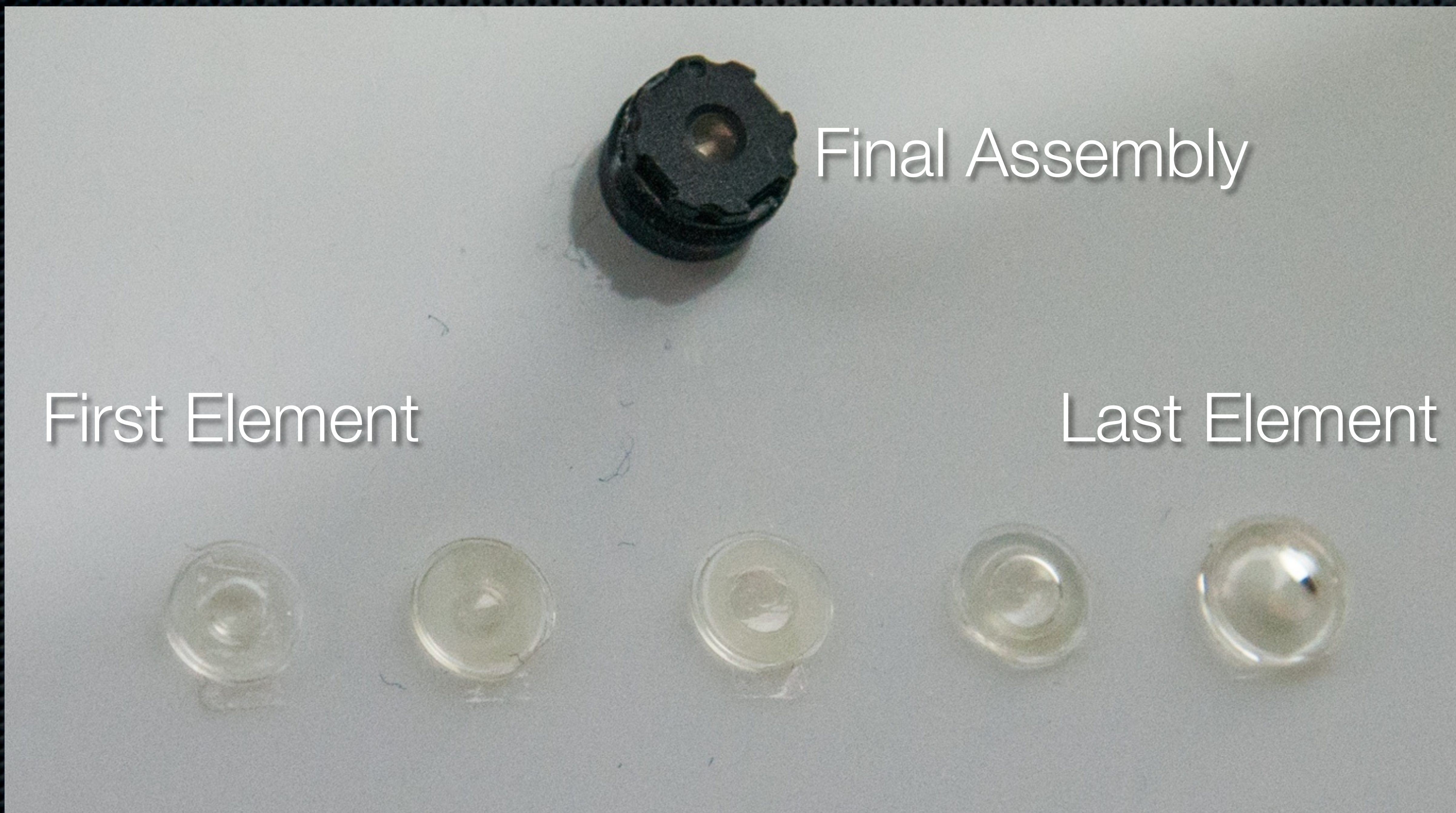
Polystyrene

http://refractiveindex.info/?group=PLASTICS&material=PS

Zeronex

http://refractiveindex.info/?group=PLASTICS&material=ZeonexE48

Example 5P System (LG)

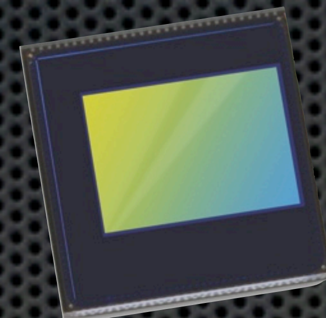


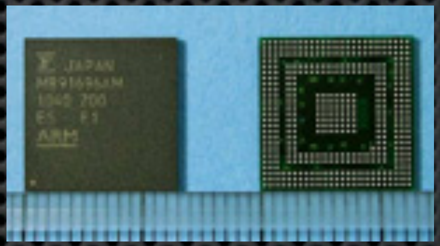
Lens then goes into a module

Camera Module

- Lens assembly
- VCM (Voice Coil Motor) - electromagnet / speaker which moves the lens to focus
- IR Filter / AA filter
- CMOS sensor
- Packaging and ribbon flex cable
  - Drop that module into a phone

Imaging Block Diagram





Scene → Optics → CMOS Sensor ⇄ Image Signal Processing ⇄ UI/OS/ Saved JPEG

CMOS Sensor Trends

Type	Diagonal (mm)	Width (mm)	Height (mm)	Area (mm^2)	Crop factor
1/4"	4	3.2	2.4	7.68	10.81
1/3.6"	5	4	3	12	8.65
1/3.2"	5.68	4.54	3.42	15.5	7.61
1/3"	6	4.8	3.6	17.3	7.21

- Rear CMOS size commonly around 1/3.2” or 1/4”
- Front CMOS smaller, but lower resolution 1/6”, 1/7”
- Size of CMOS sensors are relatively fixed, trend is more of smaller pixels

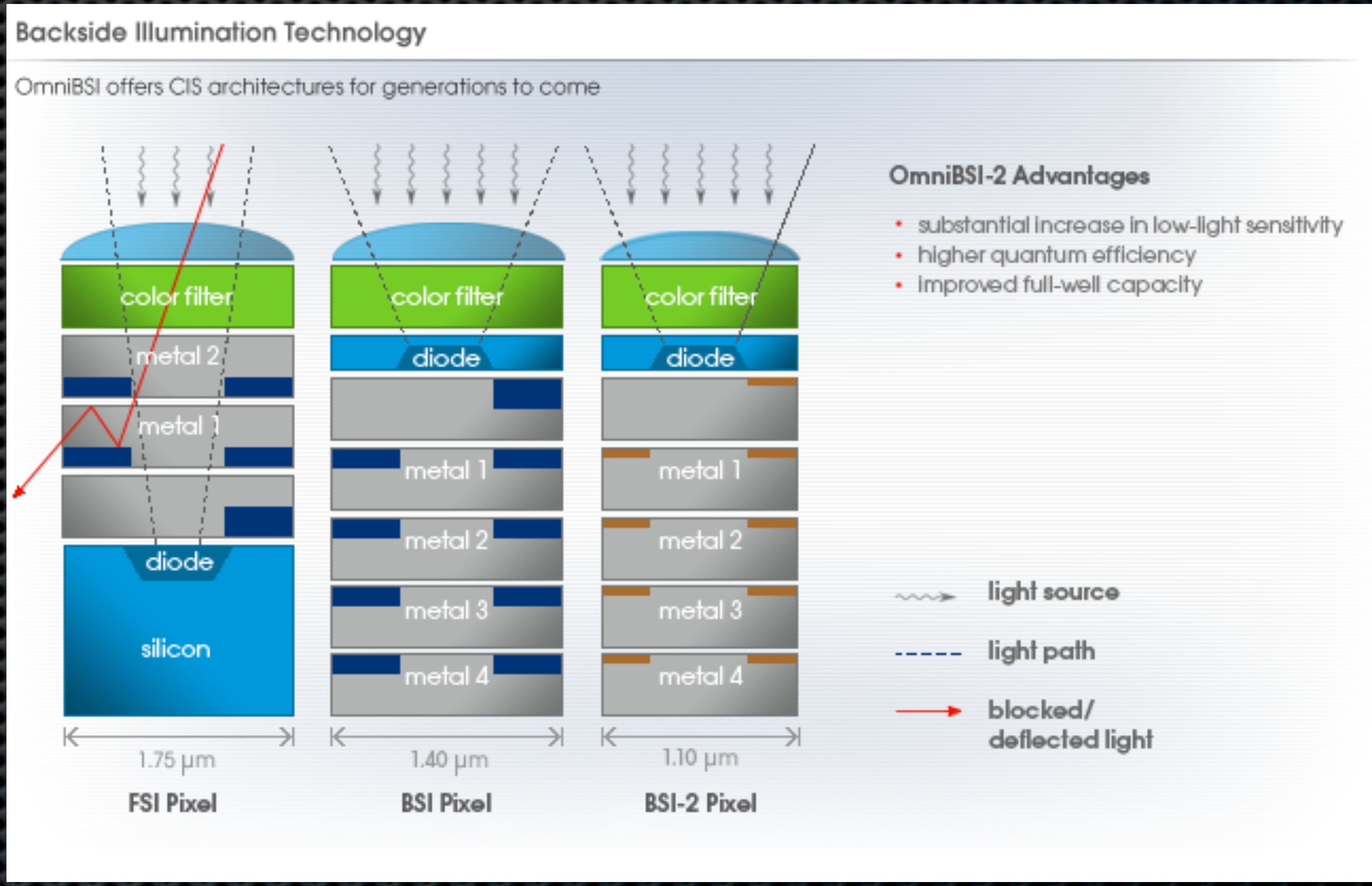
CMOS Sensor Trends

Generation	n-3	n-2	n-1	n	Future (?)
Pixel Size (µm)	2.2	1.75	1.4	1.1	0.7
Area (µm^2)	4.84	3.06	1.96	1.21	0.49
Area Ratio	1.00	0.63	0.40	0.25	0.10
Waves, λ (@ 700 nm)	~3	~2.5	~2	~1.5	~1

- Pixels : CMOS :: MHz : CPU - (MHz race, pixels)
- Pixels can't get much smaller, or they'll be sub one wave in size (weird quantum effects begin)
- >=5 MP (1.4µm), BSI is a necessity not just for sensitivity

BSI / FSI

- FSI - Traditional way of imaging onto a CCD/ CMOS, through metal gating, incurring reflections
- BSI - Requires removing material using wafer scale chemical or abrasive lapping, image directly into active region of sensor. Significantly higher QE.

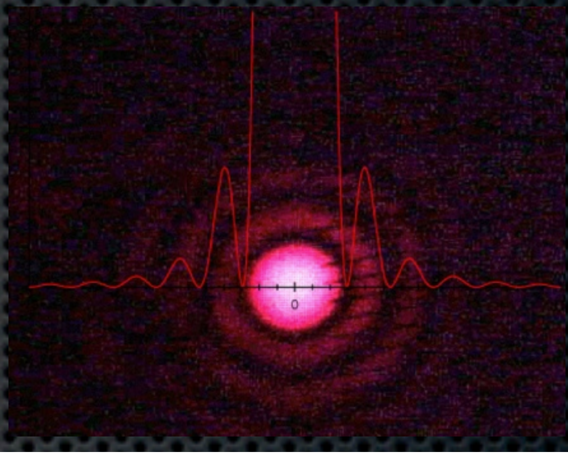


Dirty Secret - IT'S A LIE

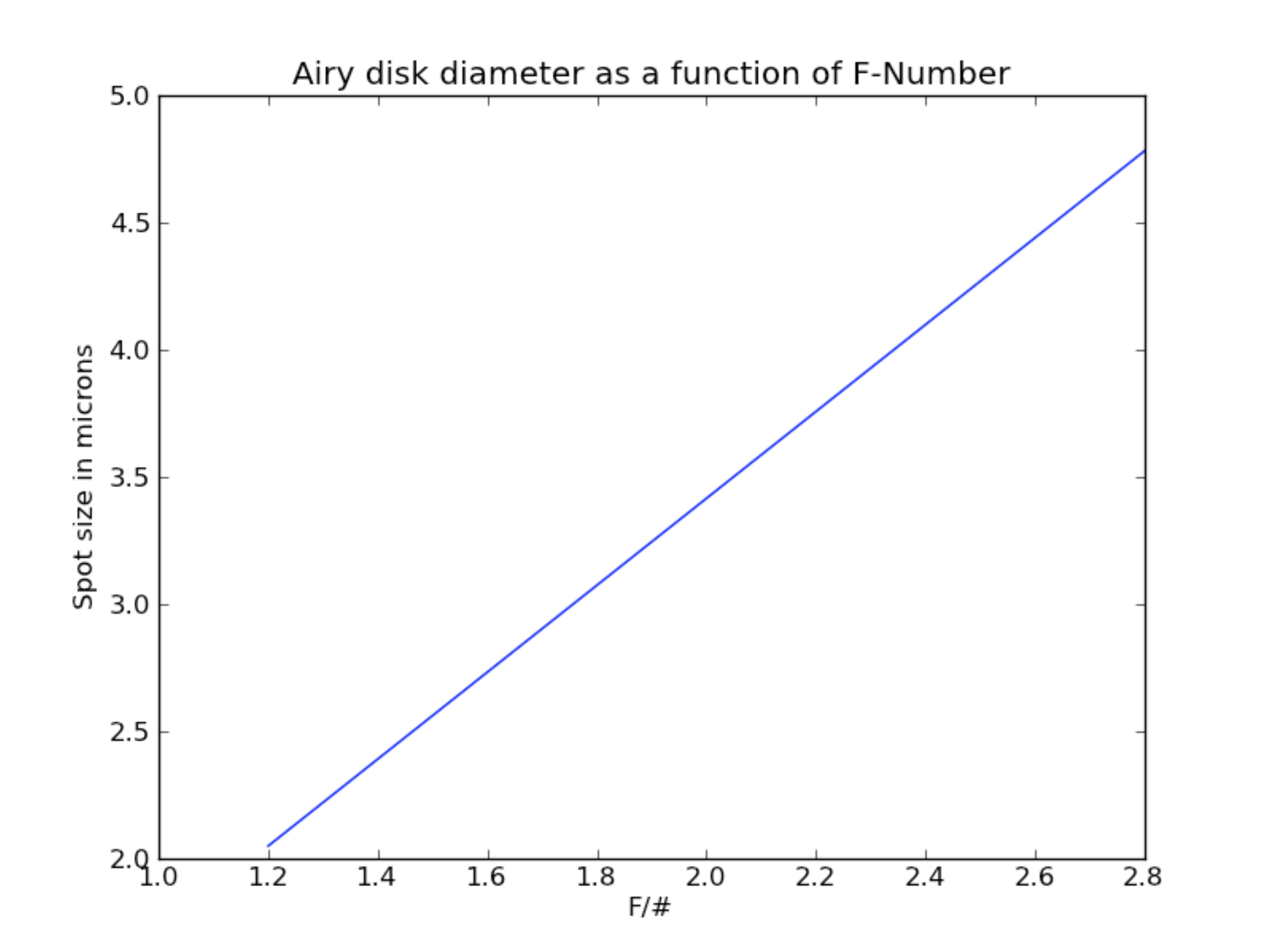
- We can't resolve pixels that small to begin with... Oops....

```
from numpy import *
from scipy import *
from pylab import *

f = 3.63E-3 ## 3.63 mm focal length HTC One system
b = 1.4E-6 ## 1.4 micron standard modern pixel size, 1.1 newer, 1.65 micron older
fno = 2.0 ## HTC One S F/2.0

fnos = linspace(1.2,2.8,100) ## HTC One - F/2.0, iPhone 4S - F/2.4, SGS3 - F/2.6
bscale = linspace(0.7E-6,1.65E-6,100) ## Range of pixel sizs

zh = - f**2 / (b * fnos); ## hyperfocal distance
zn = zh / fno ## nearest point in focus (hyperfocal/2)

diff = (2.44 * 700E-9 * fnos)/1.0E-6 ## airy disk first zero diameter 84% energy here

deltazprime = 4.88*700E-9 * fno ** 2
deltaz = (4 * deltazprime * f ** 2) / ((deltazprime)**2 - 4*(f - 3.7E-3)**2)

cla()
clf()
plot(fnos,diff)
title('Airy disk diameter as a function of F-Number')
xlabel('F/#')
ylabel('Spot size in microns')
savefig('fnosspotsize.png')

cla()
clf()
plot(fnos,zn)
title('Hyperfocal distance as F/#')
xlabel('F/#')
ylabel('Hyperfocal dist')
savefig('hyperfocalfixedpixel.png')

cla()
clf()
zh2 = - f**2 / (bscale * fno); ## hyperfocal distance fixed f=2.0
plot(bscale/1.0E-6,zh2/2)
title('Hyperfocal distance as pixel size')
xlabel('Pixel size (microns)')
ylabel('Hyperfocal dist')
savefig('hyperfocalfixedfnos.png')
```

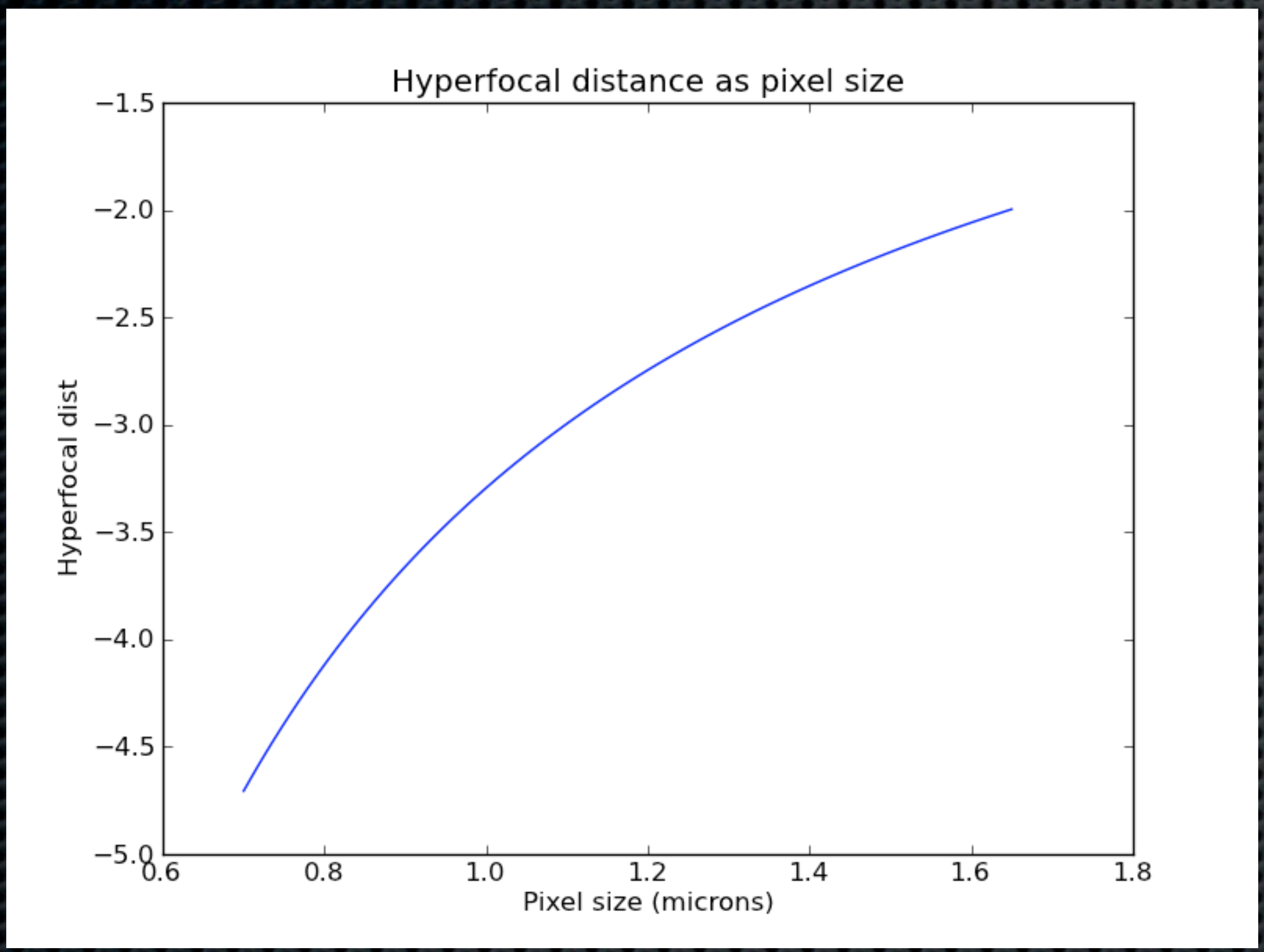
Dirty Secret - IT'S A LIE

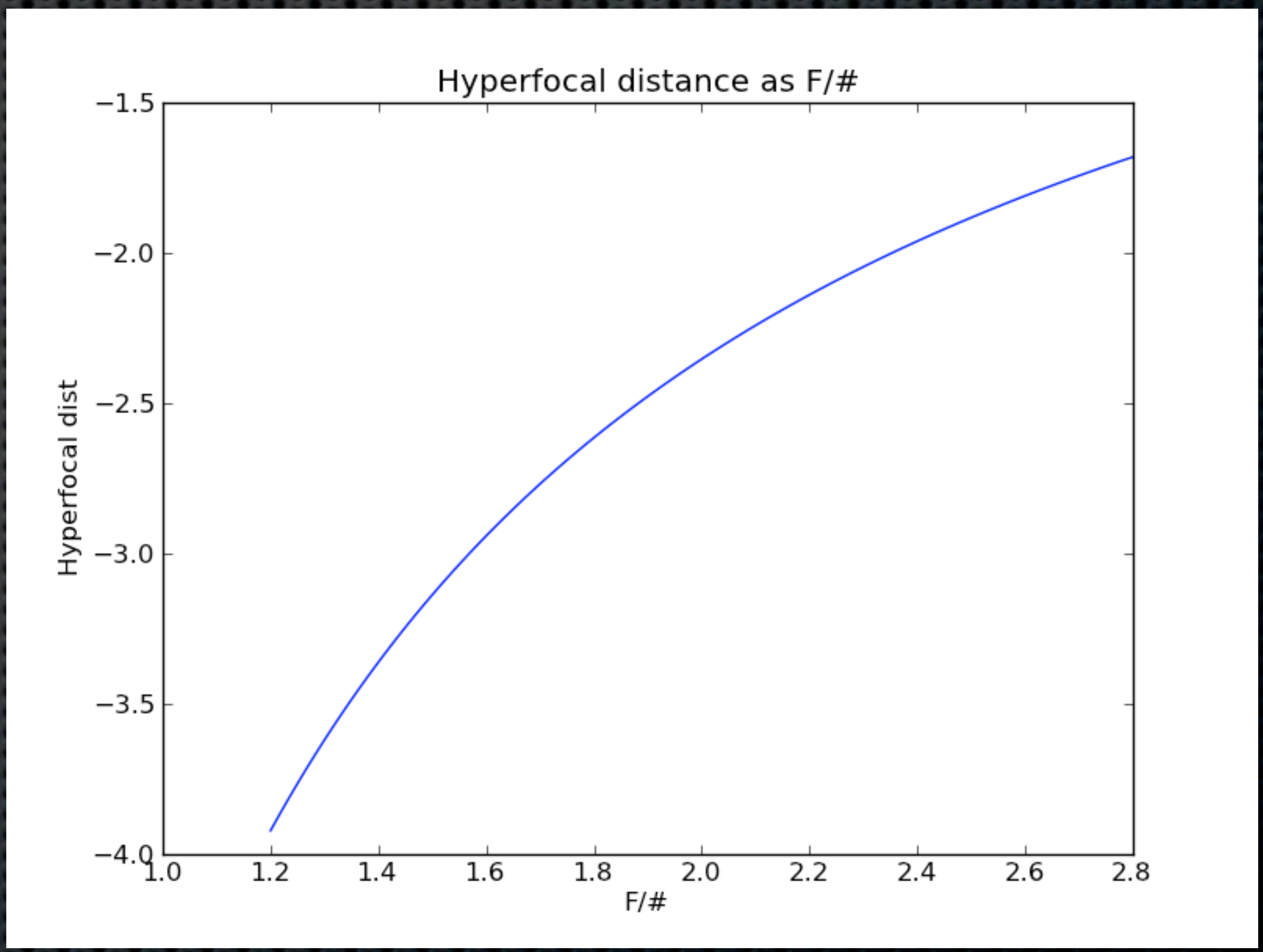


- Airy Disk - Assumes perfect optics, limited only by diffraction (ideal system)
- Rayleigh Criterion - camera example, before two points blur together
- Can't resolve that pixel size! Oops.



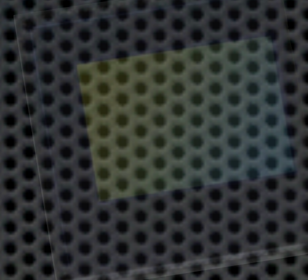
Hyperfocal distance

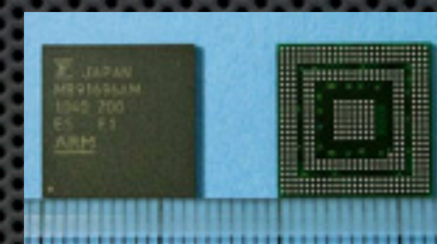




Distance after which everything is in focus

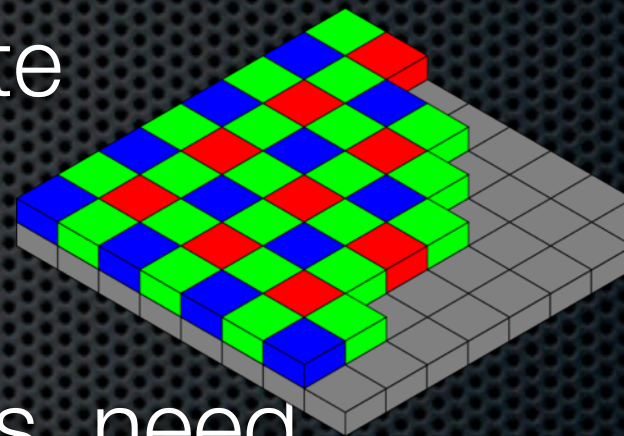
Imaging Block Diagram





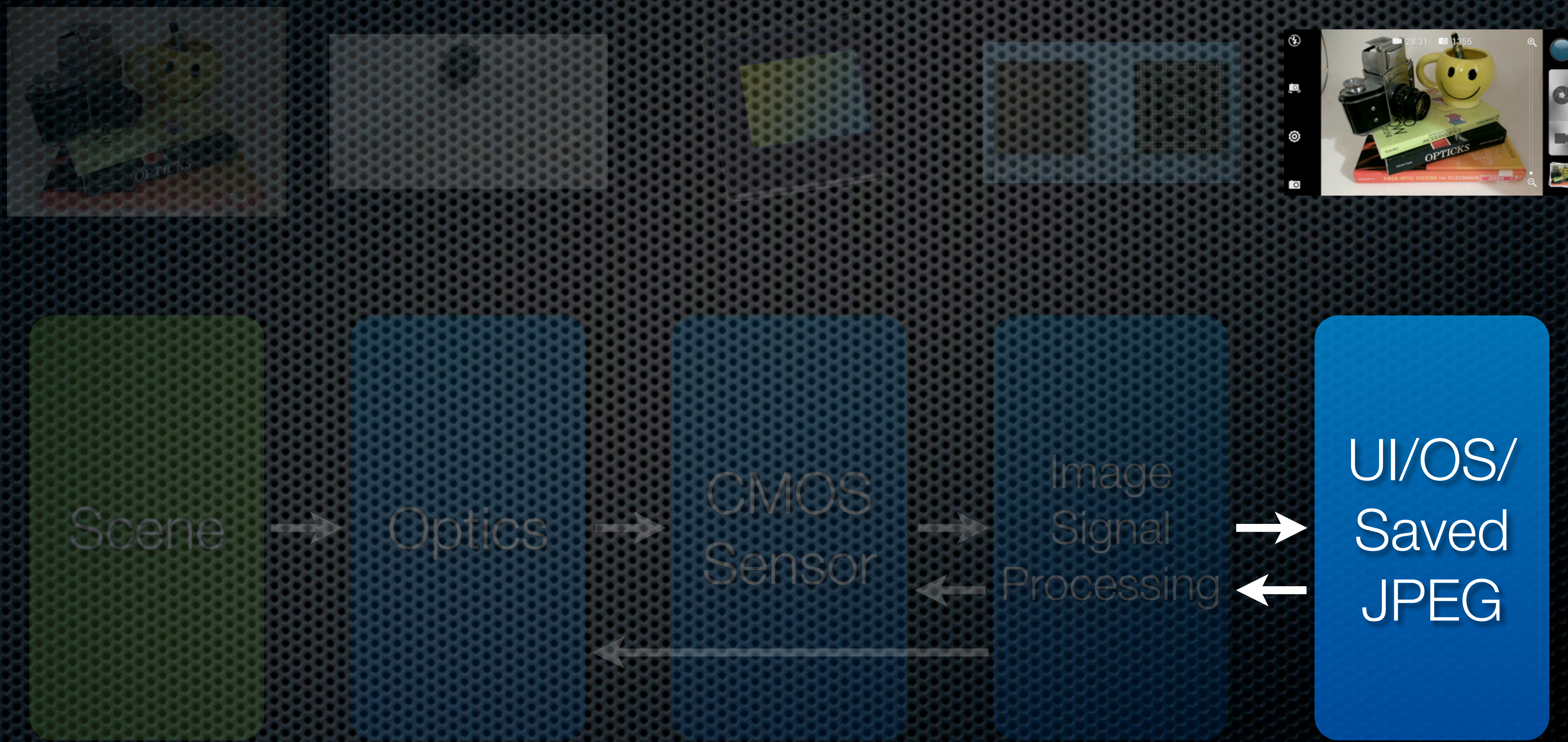
Scene → Optics → CMOS Sensor ⇄ Image Signal Processing ⇄ UI/OS/ Saved JPEG

ISP - Image Signal Processor



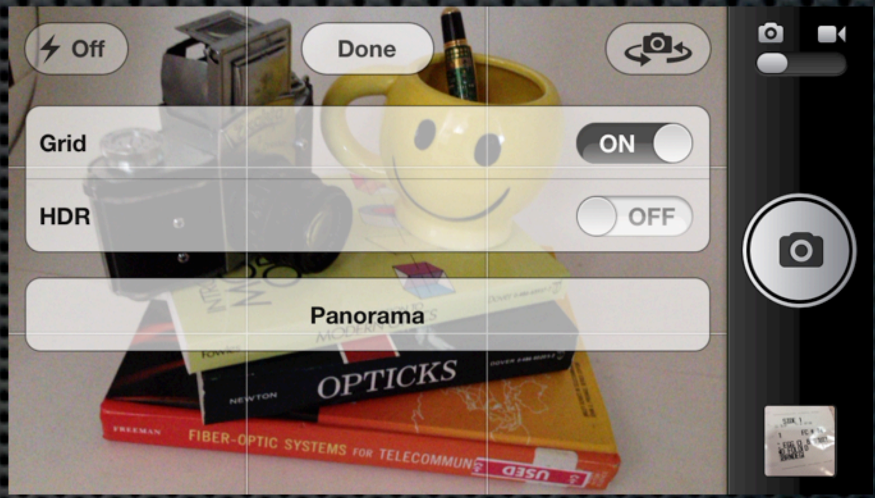
- ISP usually onboard SoC, sometimes discrete
- ISP Roles
  - Demosaicing - Sensor just senses photons, need Bayer color filter atop sensor to determine color. RGBG / GRGB, interpolate to RGB for each pixel.
  - 3A - Autofocus, Autoexposure, Autowhitebalance
  - Correction for lens imperfections - Lens shading, geometry/distortion, vignetting, try to fix image
  - Noise reduction, filtering, HDR, cleaning up, JPEG
  - This is the controller for CMOS / Focus assembly

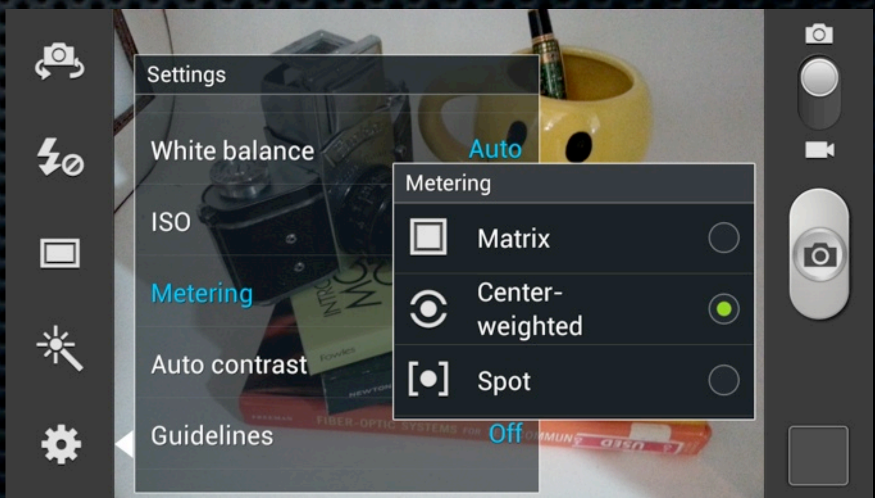
Imaging Block Diagram



Camera UI/UX

- Minimalist to highly customizable
- Still evolving, Many still making horrible mistakes
  - Low res/fps preview, wrong preview, broken UI, not enough controls, laggy
- Smartphone platform again unique - needs balance of speed and simplicity to be successful





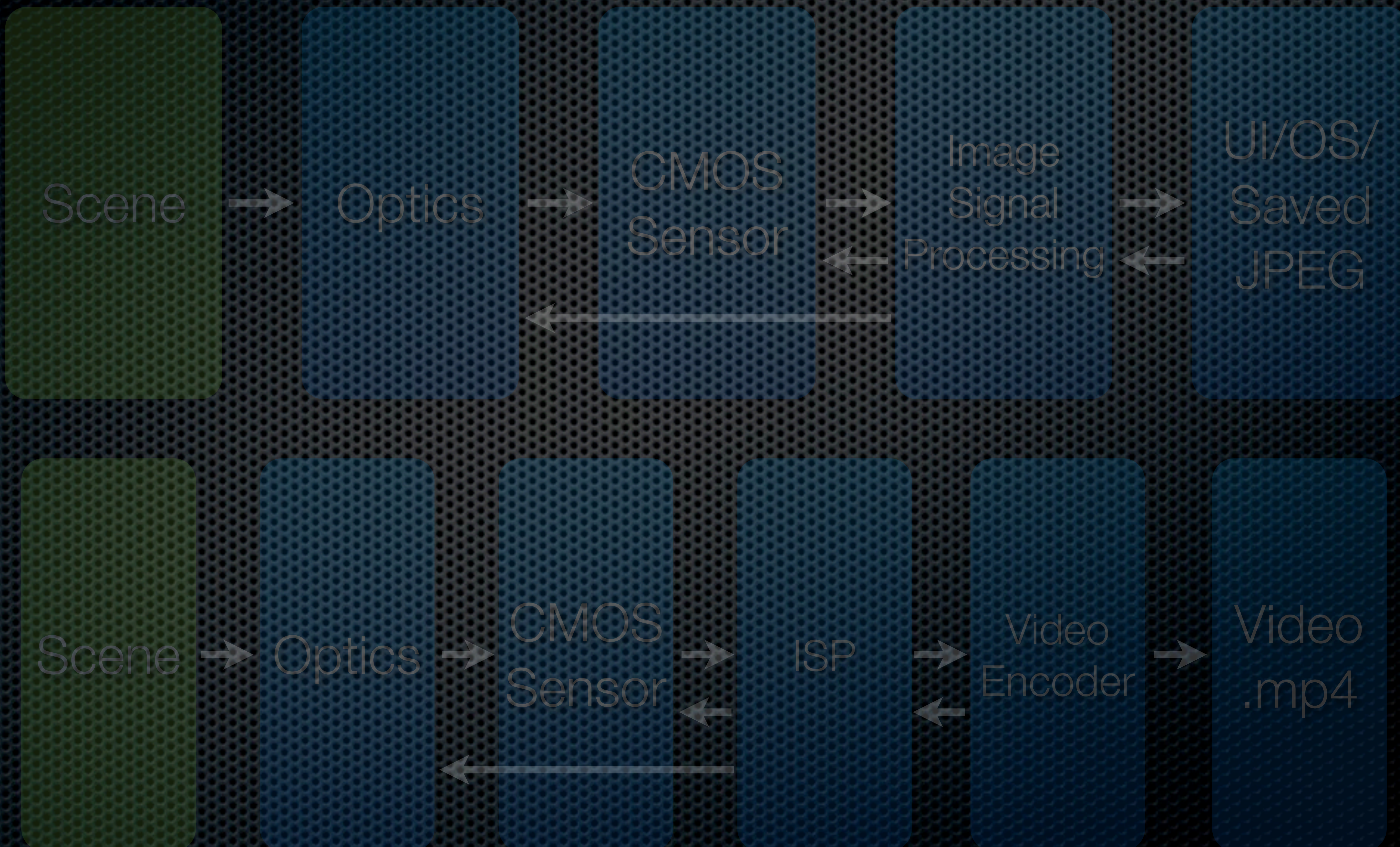
Video Block Diagram

- Same fundamental architecture, but with either a crop of the sensor or decimated version of output, then through an encoder for H.264/MPEG4. Encoder usually on SoC.

Video Encoder

- Usually on SoC, sometimes external
- Takes frames from CMOS, encodes to format of choice
    - Example Exynos 5 Dual: Multi-format Video Hardware Codec: 1080p 60fps (capable of decoding and encoding MPEG-4/H.263/H.264 and decoding only MPEG-2/VC1/VP8)
    - Imagination Technologies, Qualcomm, TI, Others
    - Not all are born equal. OEMs frequently not using full potential
- 15-20 Mbps H.264 1080p30 High Profile = Current

Video Block Diagram



Quality - What do you mean?

- Image "sharpness" - MTF (Modulation Transfer Function) or FT of PSF (Point Spread Function)
  - What is the highest frequency that can make it through the optical system before contrast reverses
- Aberrations - 3rd order and higher (wavefront error)
  - Spherical
  - Coma
  - Astigmatism
  - Field Curvature
  - Distortion

Cutoff frequency $\nu_0 = \dfrac{2NA}{\lambda} = \dfrac{1}{\lambda(F/\#)}$

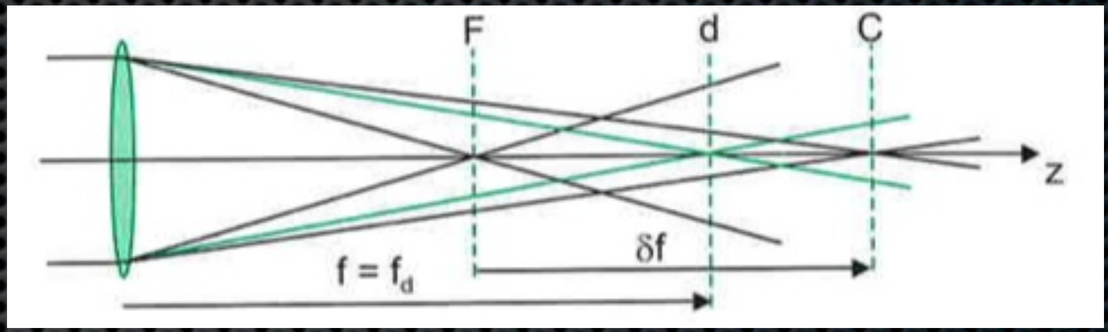
Aberrations

- No system is perfect - good design balances out aberrations with other aberrations
- Center of field is easy, most aberrations blow up strongly at edge of field (by square or cube)
- Sphere not the perfect shape, ellipse is

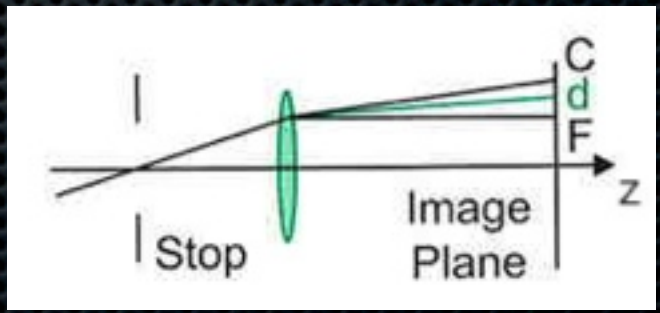
		y_ρ Depend	x_ρ Depend	Field Depend
Tilt	111	Constant	None	H
Distortion	311	Constant	None	H^3
Defocus	020	Linear	Linear	None
Field Curvature	220	Linear	Linear	H^2
Astigmatism	222	Linear	None	H^2
Coma	131	Quadratic	None	H
Spherical Aberratin	040	Cubic	Cubic	none

Chromatic Aberration

- Axial chromatic aberration
    - Each color comes to focus at a different point, because materials refract different colors differently



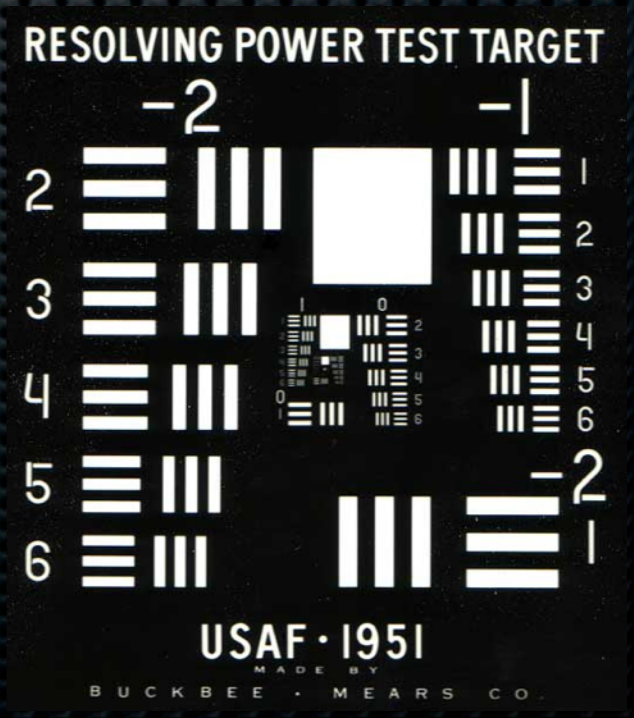
- Transverse chromatic aberration
    - Each color is deviated differently laterally on the image plane



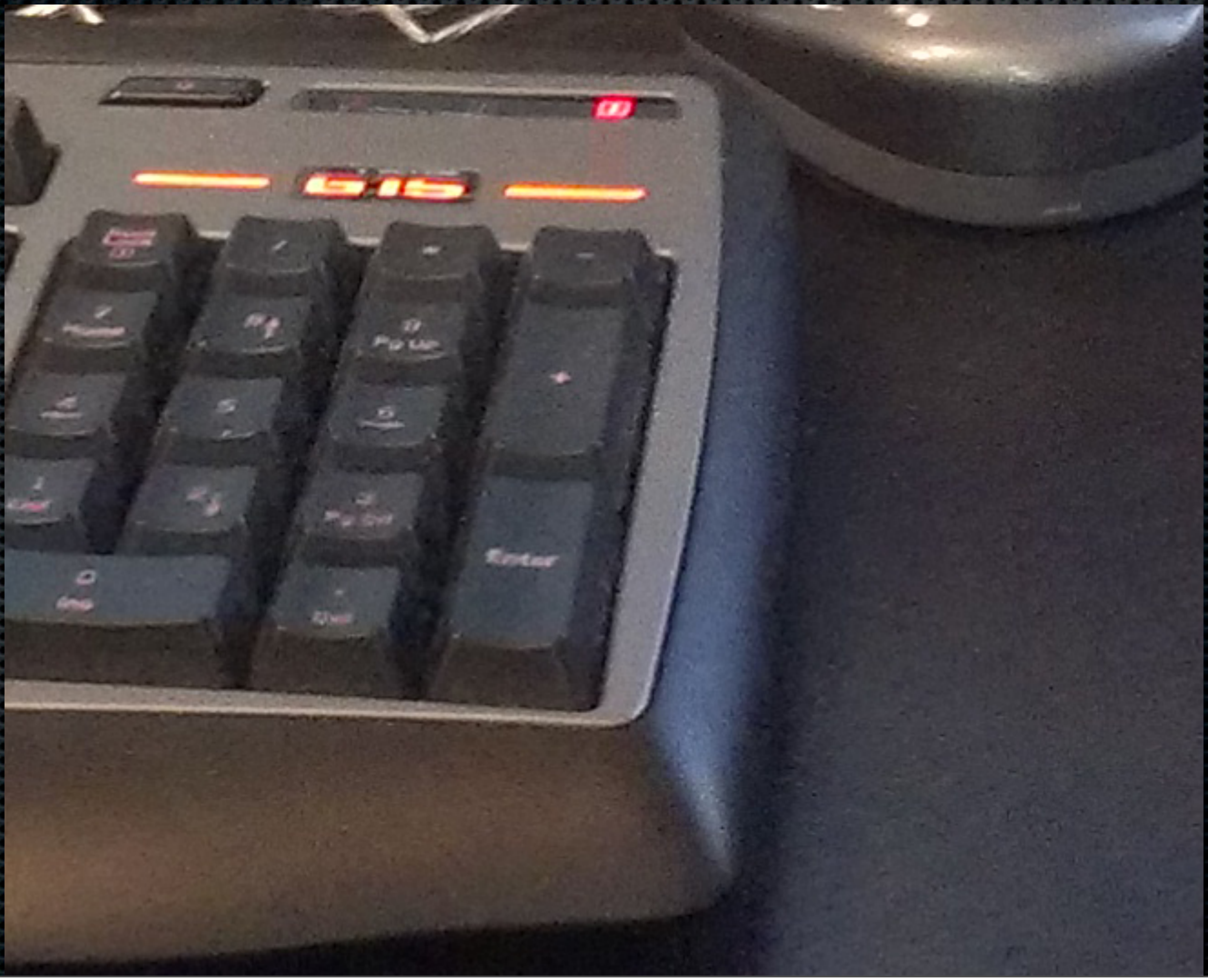
- Fix with Achromatic doublet

Things to look for

- Scrutinize extreme field angles
  - Distortion
  - Chromatic fringing
  - Loss of contrast (MTF falling off)
  - Vignetting
  - Lens shading correction errors
- Test charts - objective measures
  - Don't always tell full story



Things to look for



Things to look for

Things to look for

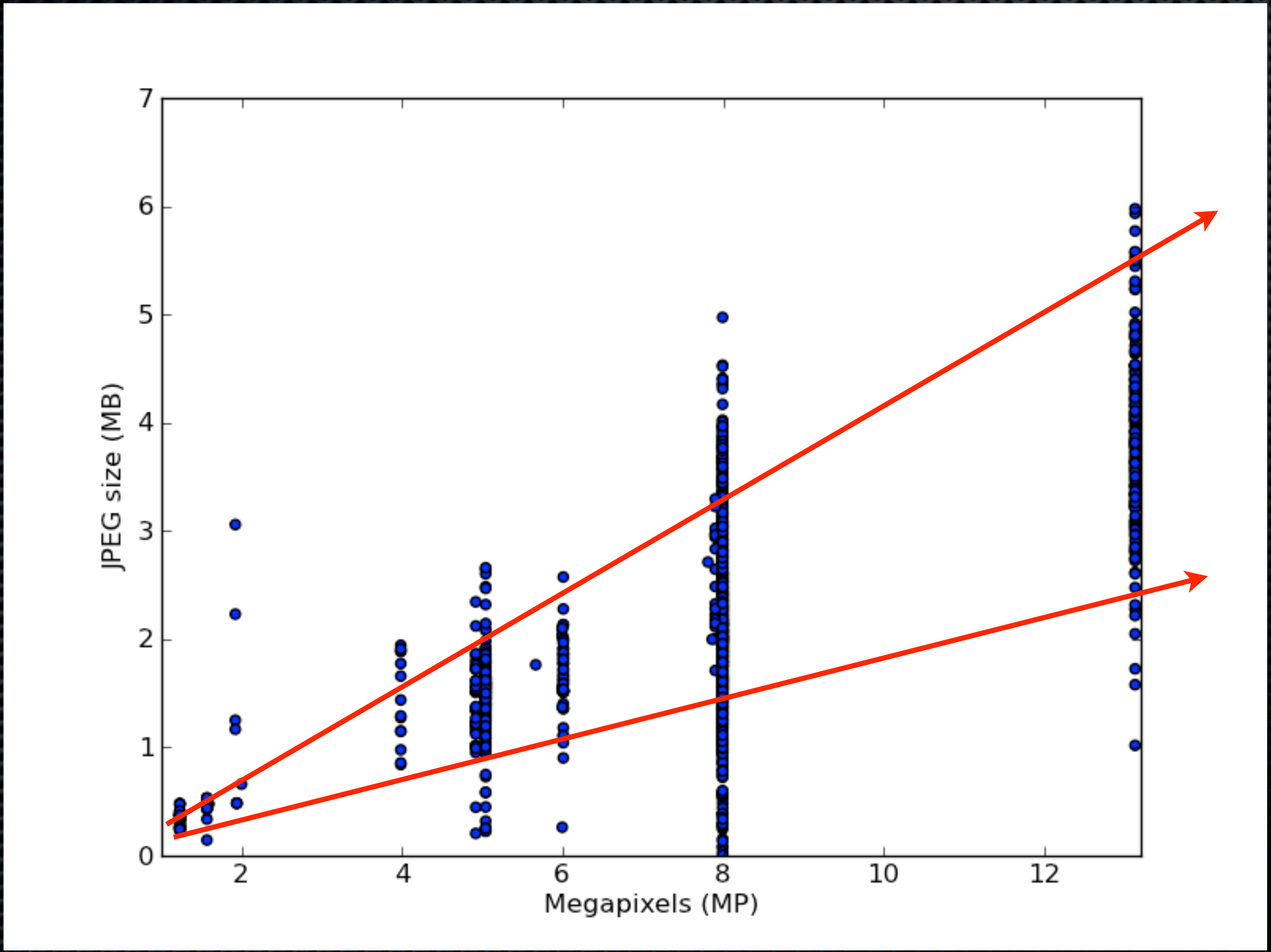
Things to look for

Things to look for

Things to look for

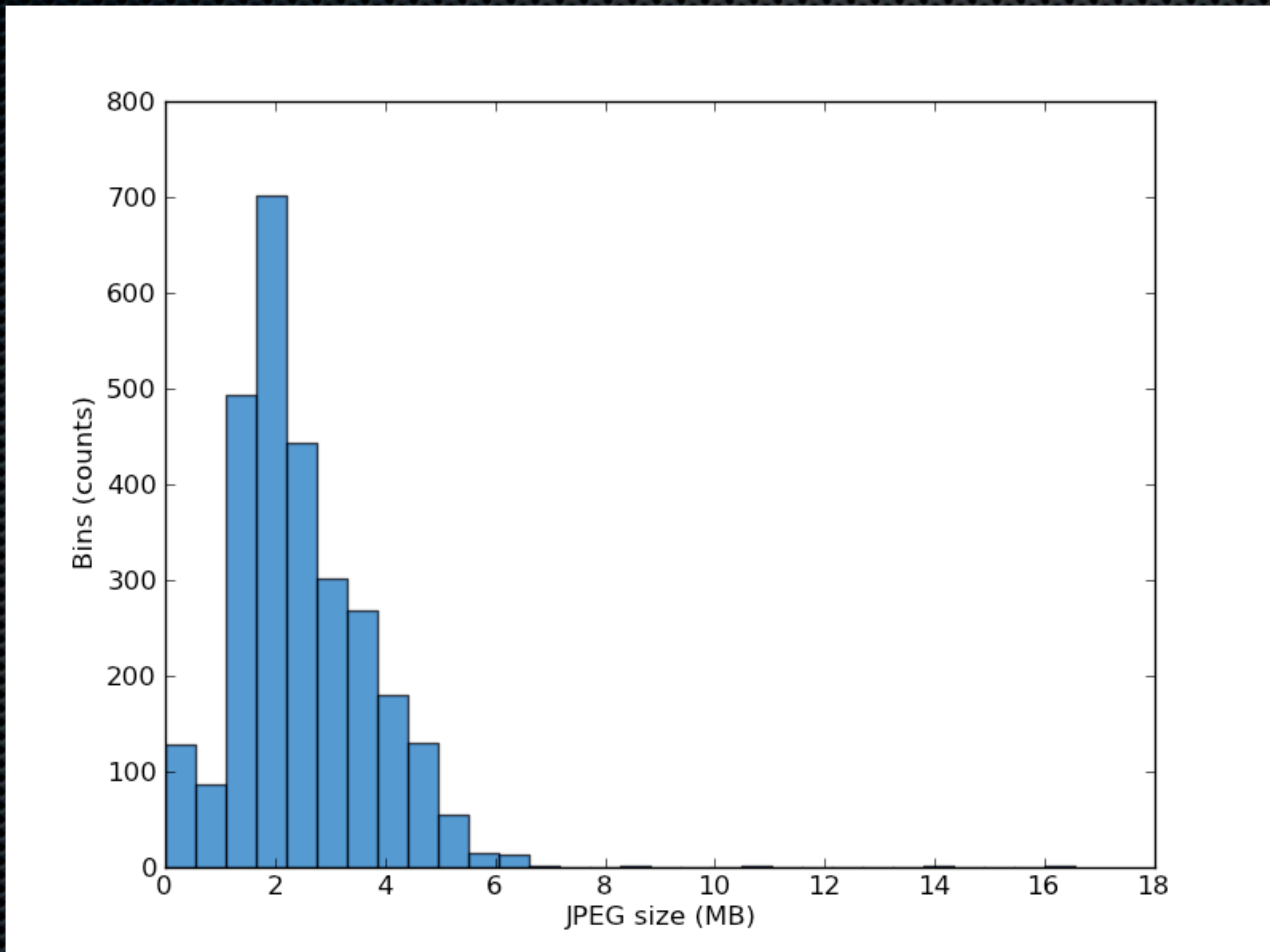
- Processing related
  - Aggressive noise reduction (loss of high frequency details to smooth regions of chroma/luma noise)
  - Sharpening kernels (halos around high frequency regions to artificially increase sharpness)
  - Moire (artifact of bad demosaicing algorithms)
  - Too much compression (artifacts)
  - Missed focus
  - Bad AWB, unnatural colors

MB vs MPs



- 4000+ images from smartphones - statistical analysis

MB vs MPs



800
700
600
500
400
300
200
100
0
Bins (counts)
0
2
4
6
8
10
12
14
16
18
JPEG size (MB)

Smartphone Imaging

- Smartphones rapidly displacing and disrupting traditional P&S market. Connected camera and smartphone blurring together
    - Smartphone OEMs without P&S business at disadvantage
- Imaging performance still volatile, changing each gen.
- Miniaturization approaching limits of physics
    - Needs computational photography techniques to improve beyond limits
- It's incredible smartphone cameras are as good as they are now