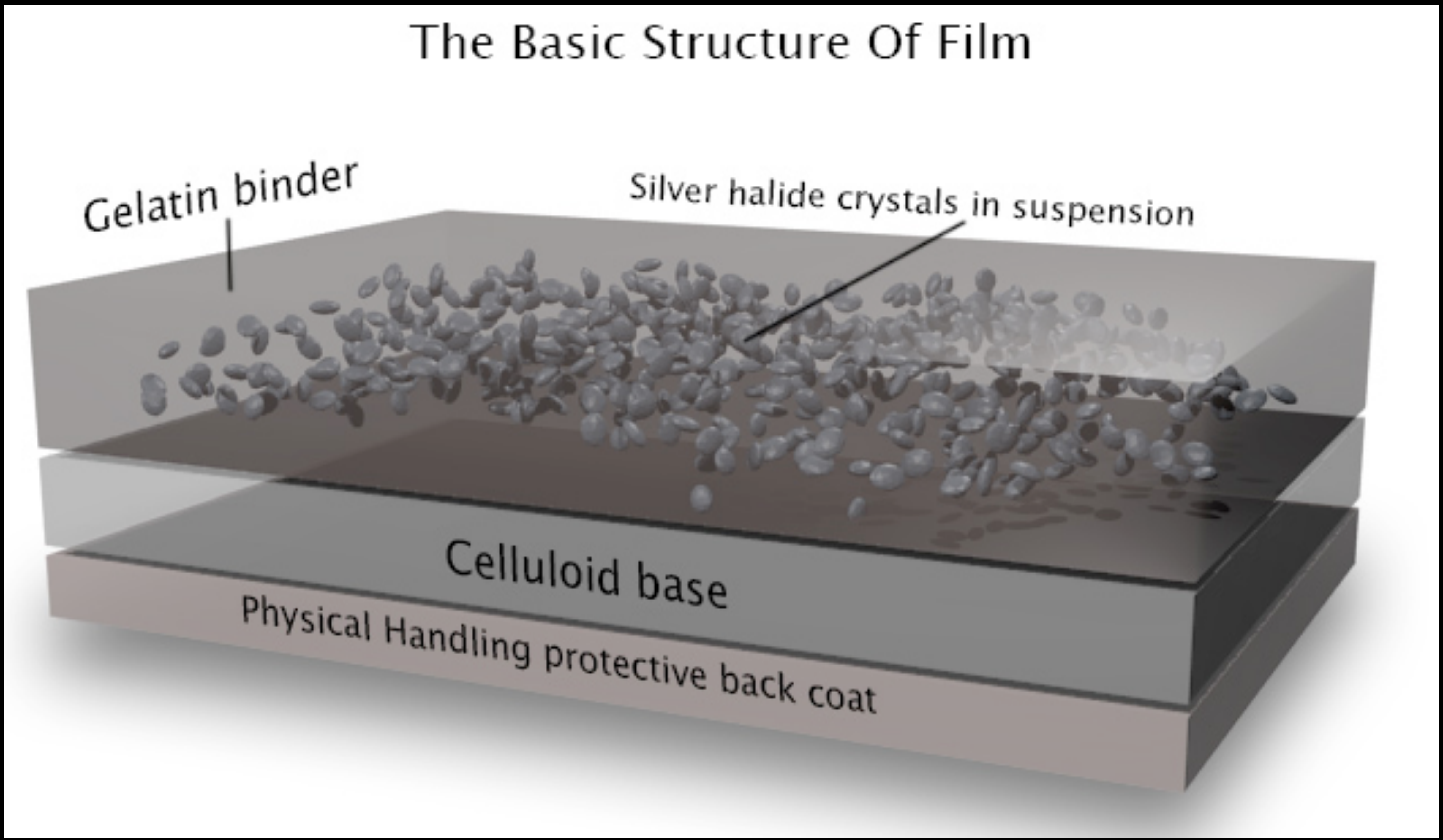
Image Sensors

- Super important part of the microscope
- Three major properties:
  - Size (Sampling Resolution)
  - Sensitivity
  - Speed

Image Sensors

- Historically, there was film.
- Now, almost everything is digital.
    - CCD
    - CMOS
    - PMTs and other fast, high-efficiency devices
- Also, some new really cool technology with nanowire *etc.* is being developed for extreme sensitivity and temporal resolution on every pixel

Photographic Film



$2AgBr + h\nu \rightarrow 2Ag + Br_2$

Photon energy

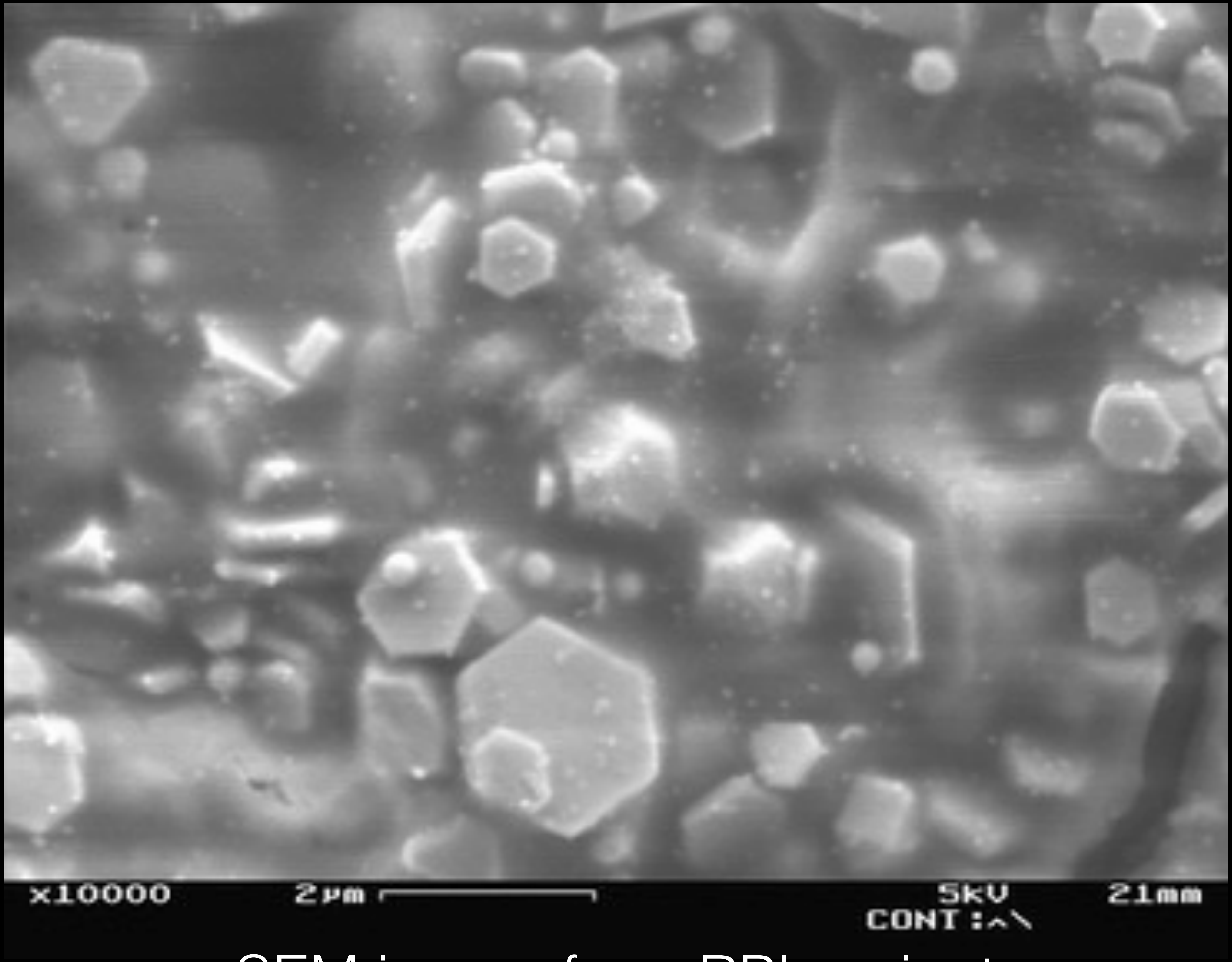
frequency of radiation, sometimes written as f giving expression $E = hf$.

$$E = h\nu$$

Quantum energy of a photon.

h = Planck's constant = 6.626×10^{-34} Joule·sec = 4.136×10^{-15} eV·s

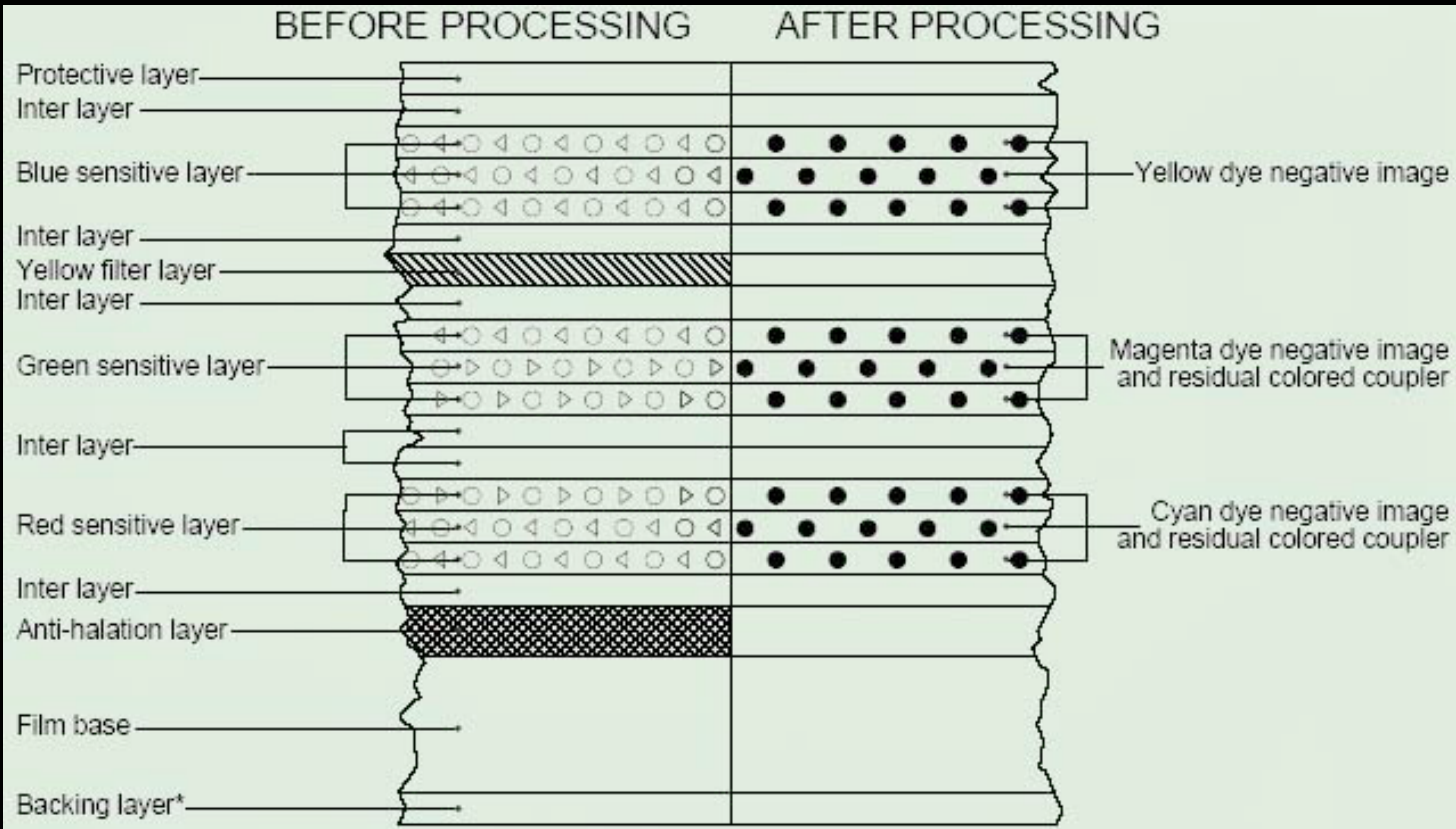
Silver grain size



SEM image from RPI project

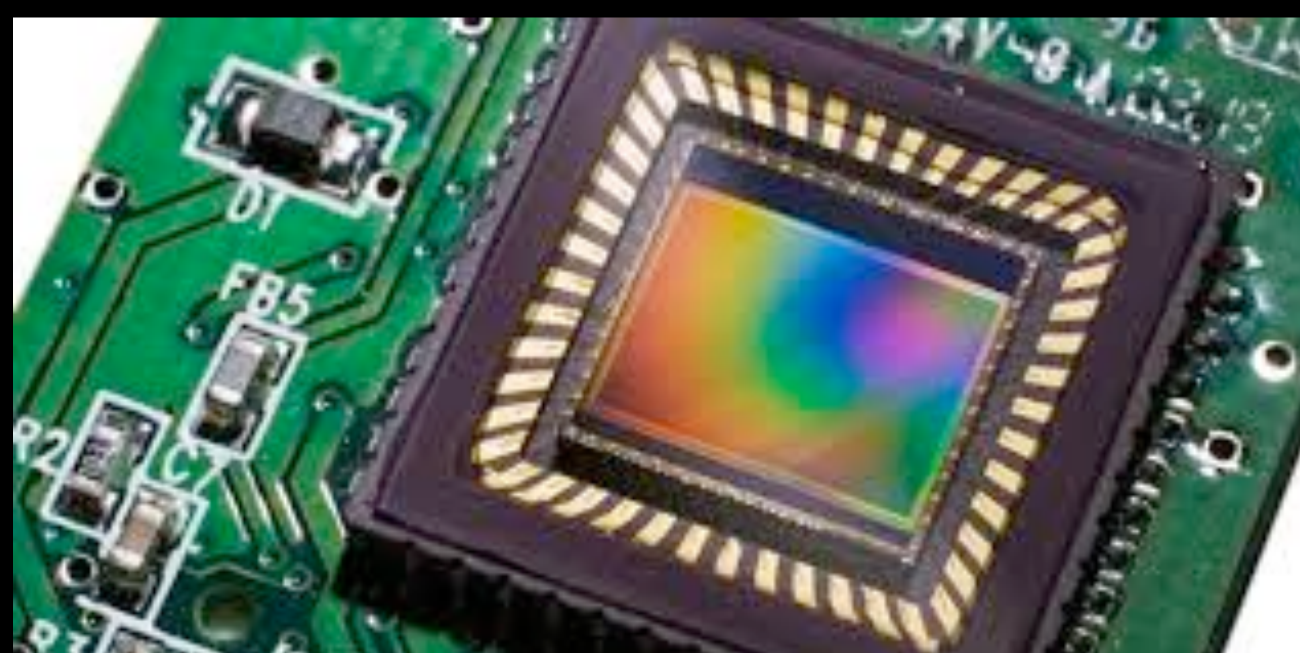

Nik Collection by Google: Silver Efex Pro (free)

Color film

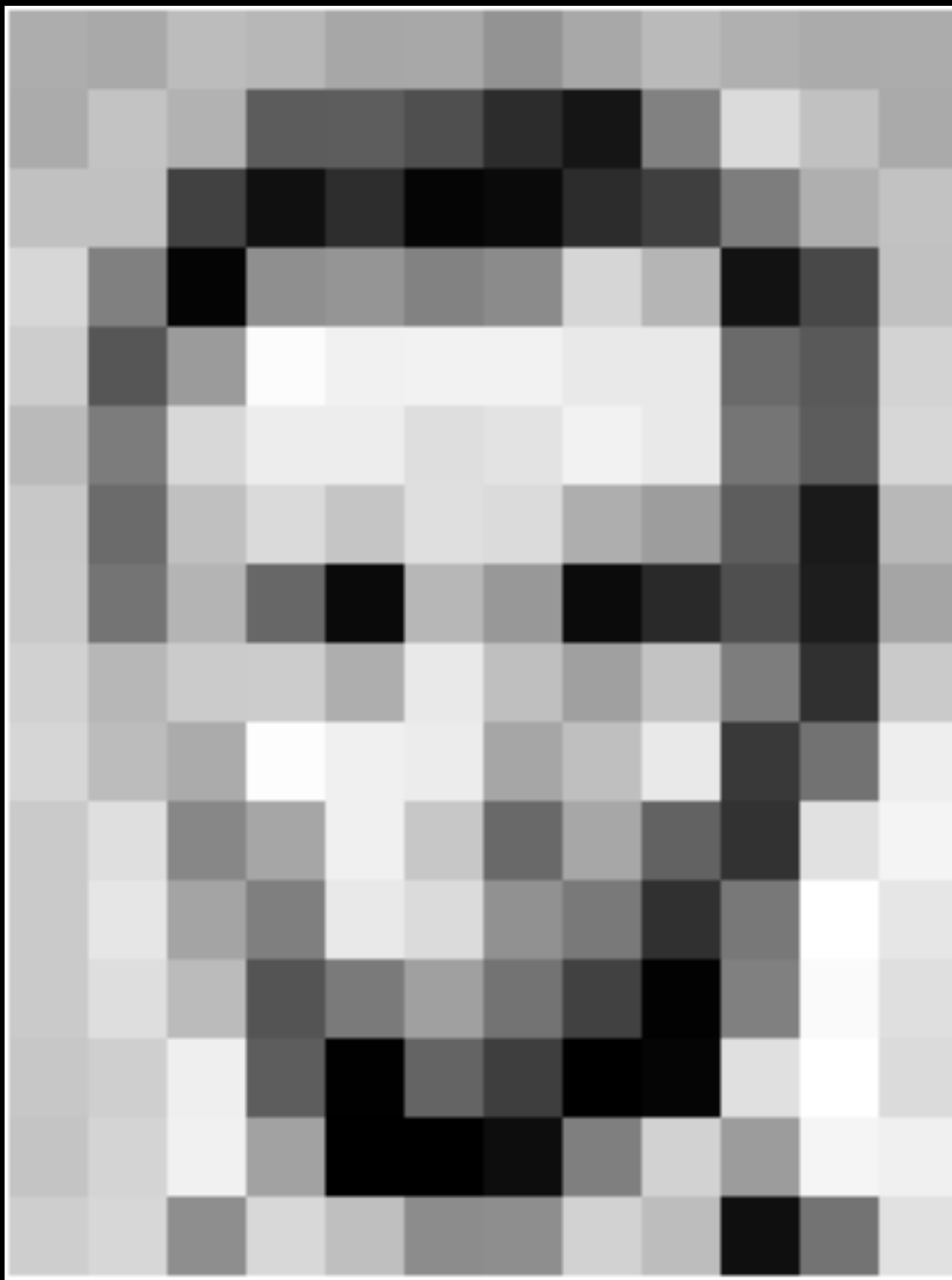

BEFORE PROCESSING
AFTER PROCESSING
Protective layer
Inter layer
Blue sensitive layer
Inter layer
Yellow filter layer
Inter layer
Green sensitive layer
Inter layer
Red sensitive layer
Inter layer
Anti-halation layer
Film base
Backing layer*
Yellow dye negative image
Magenta dye negative image and residual colored coupler
Cyan dye negative image and residual colored coupler

Digital Sensors

- Much more sensitive
- View and manipulate digitally



Digital Image



157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	106	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	95	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

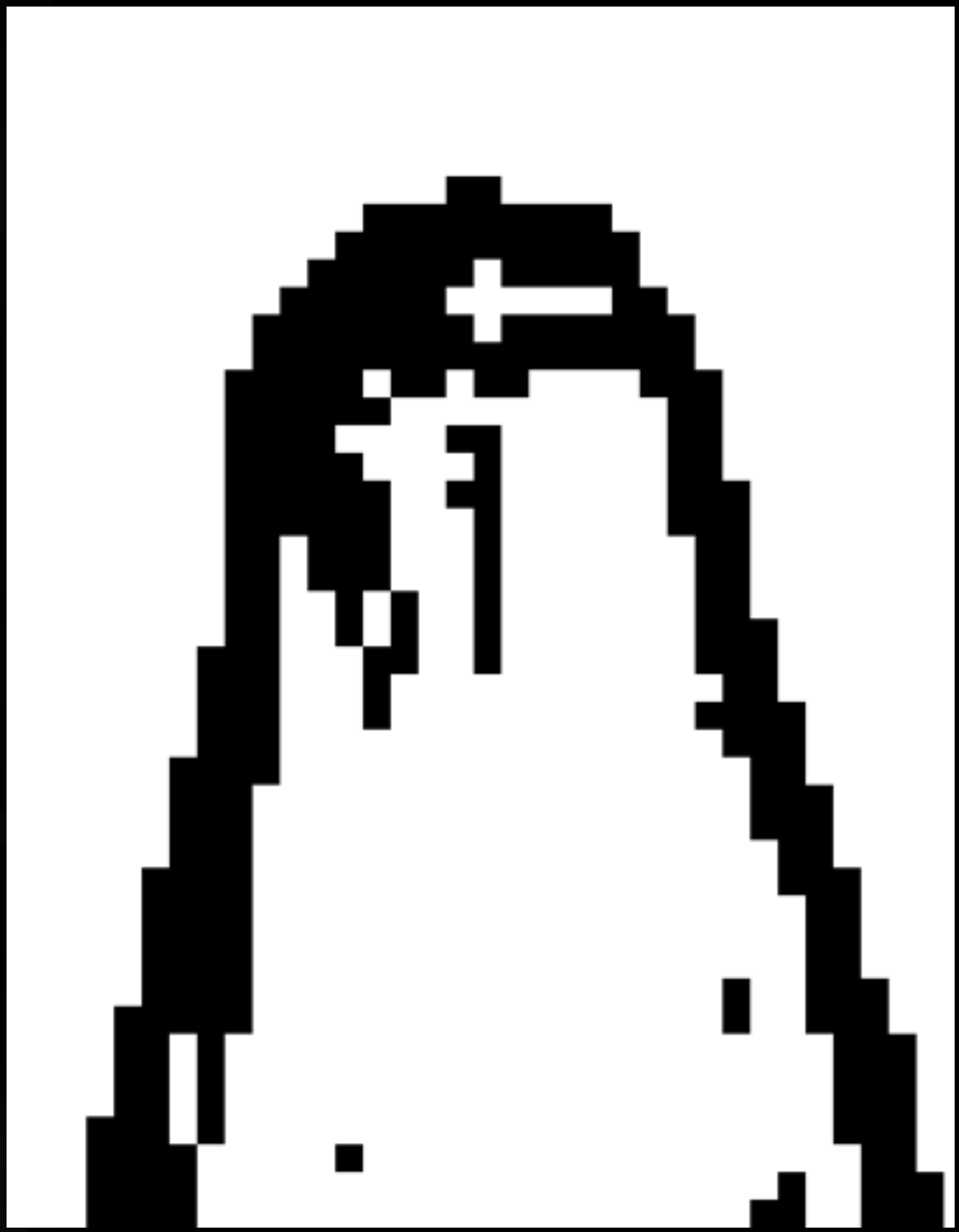
Matrix of gray-level values

157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

Bit depth

- Binary: 0 and 1
- 8 bit: 0 up to (2^8 =) 256
- 16 bit: 0 up to (16^2 =) 65,536
- 32 bit: 0 up to (32^2 =) 4,294,967,296

8-bit *vs.* Binary



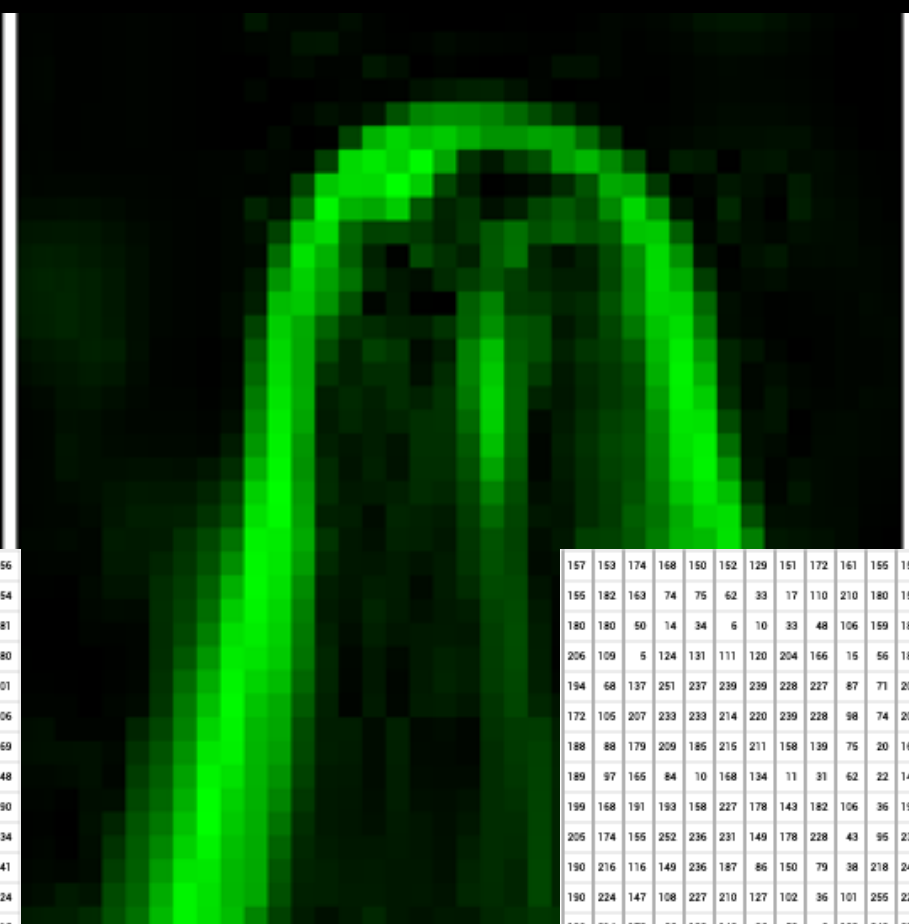
Digital Color Image

Digital Color Image

R

157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

G



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180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
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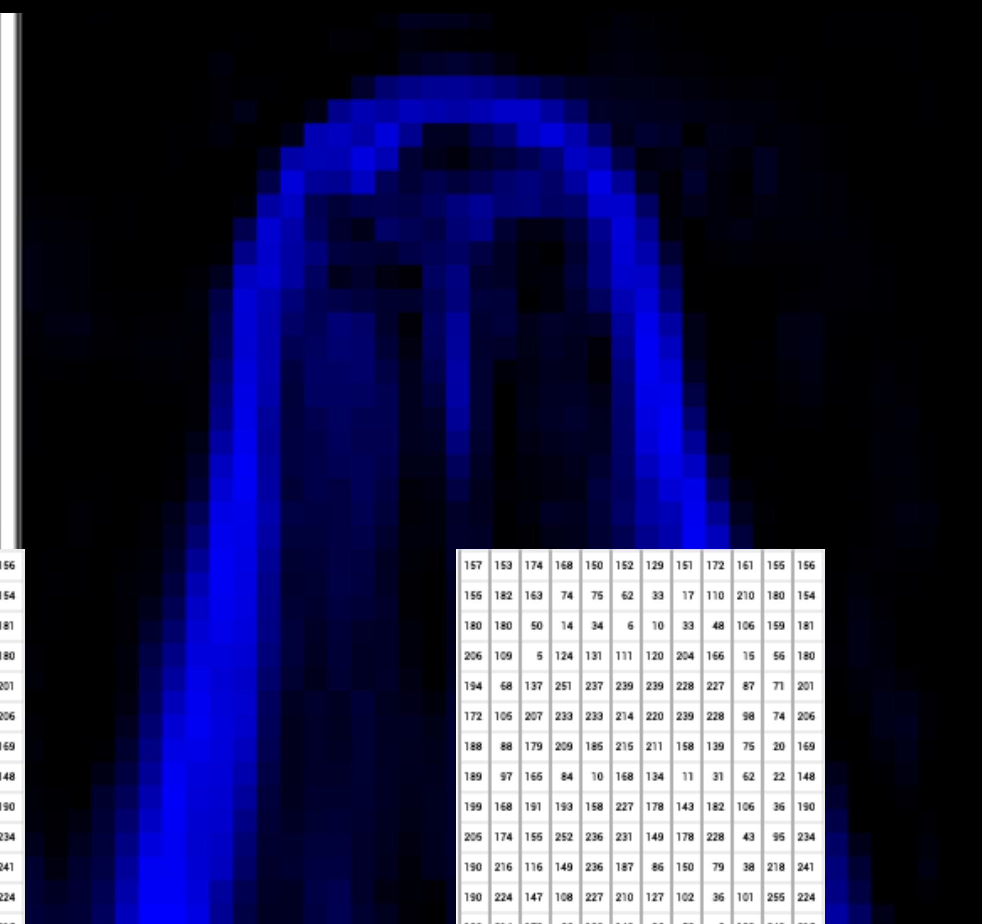
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

B



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180	180	50	14	34	6	10	33	48	106	159	181
206	109	5	124	131	111	120	204	166	15	56	180
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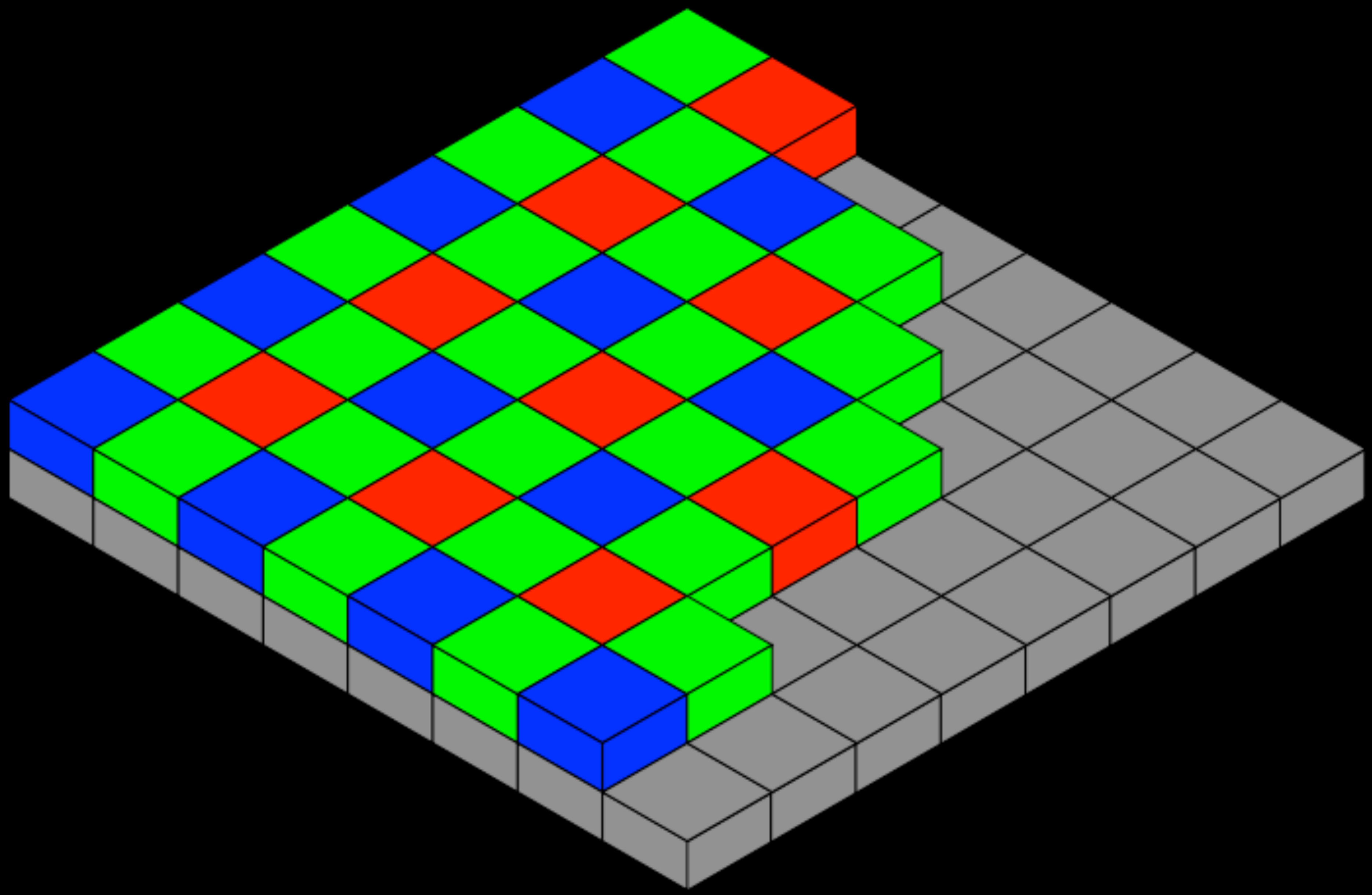
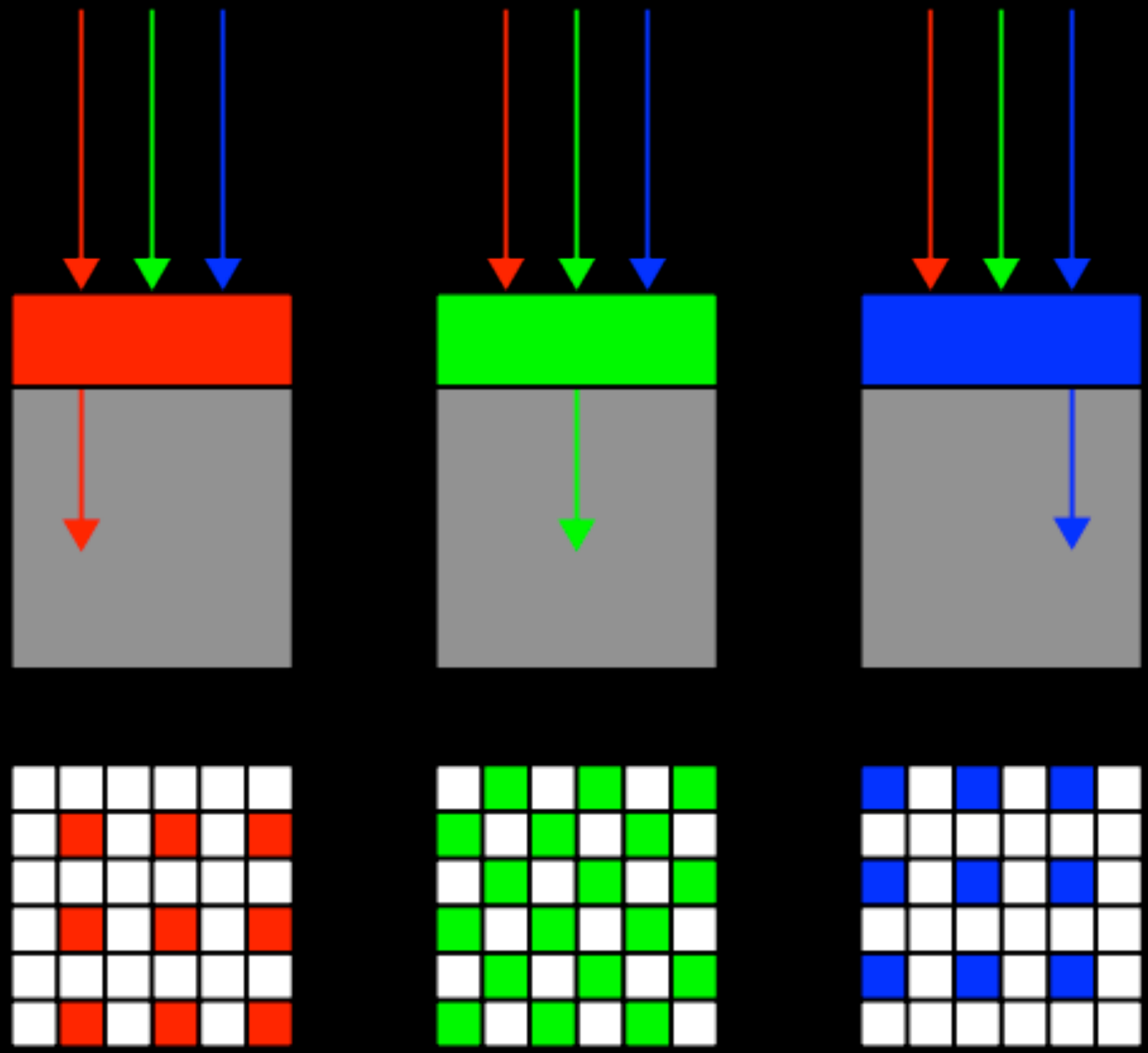
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

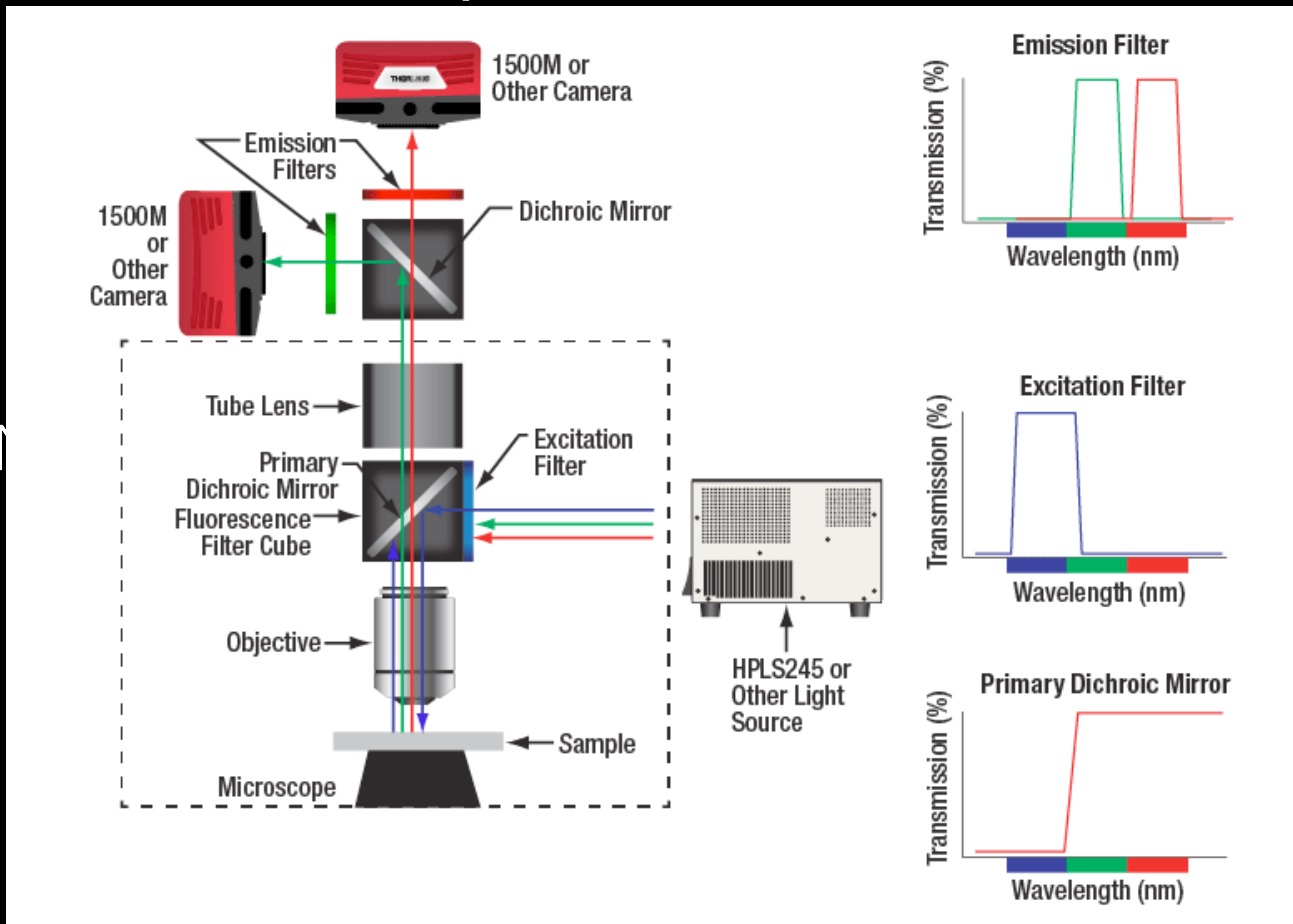
Bayer pattern



We lose light



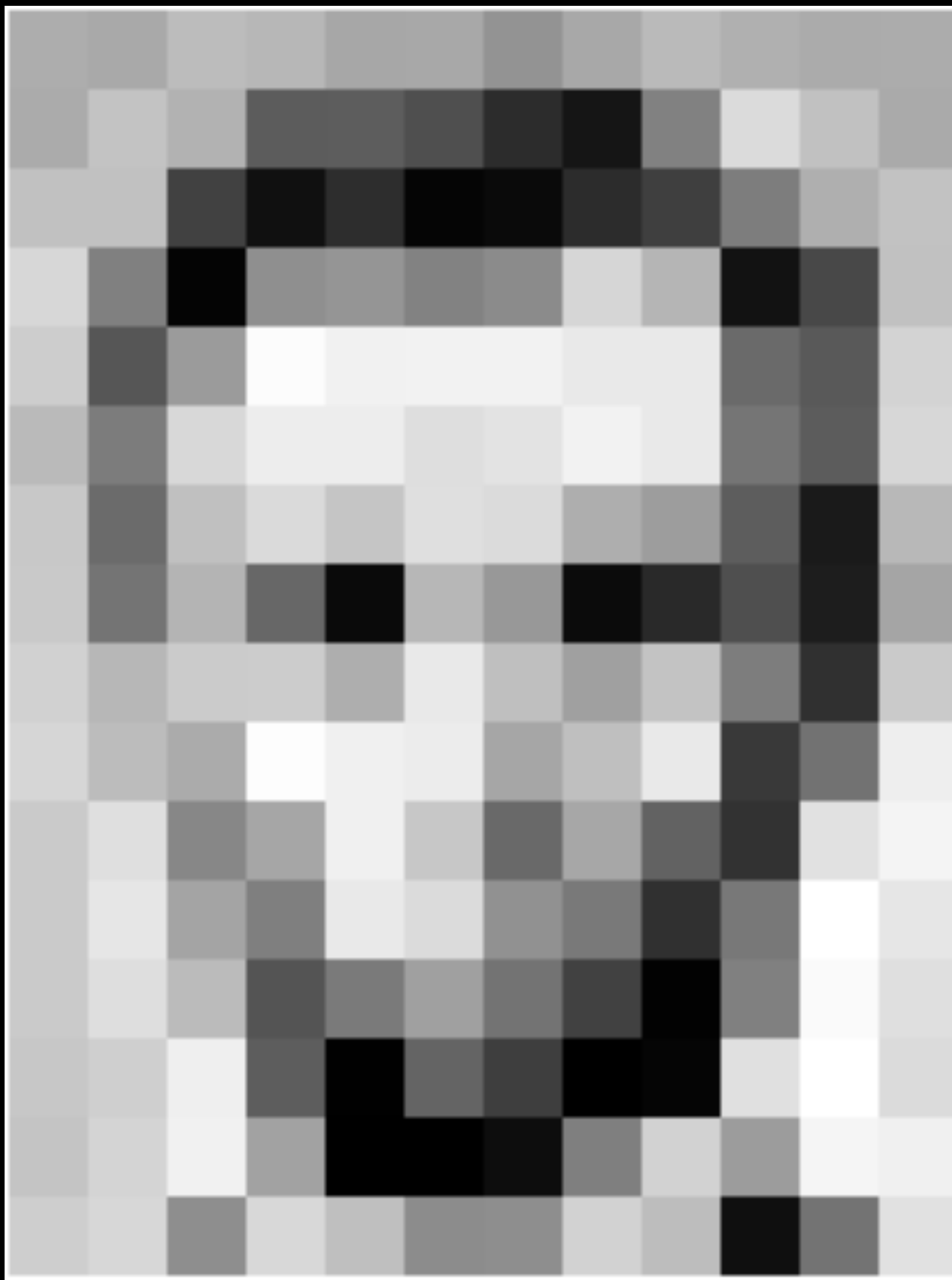
Dichroic Mirrors, Multiple Cameras



Digital Cameras

Break Time

Recording a Digital Image



157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
180	180	50	14	34	6	10	33	48	105	159	181
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199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
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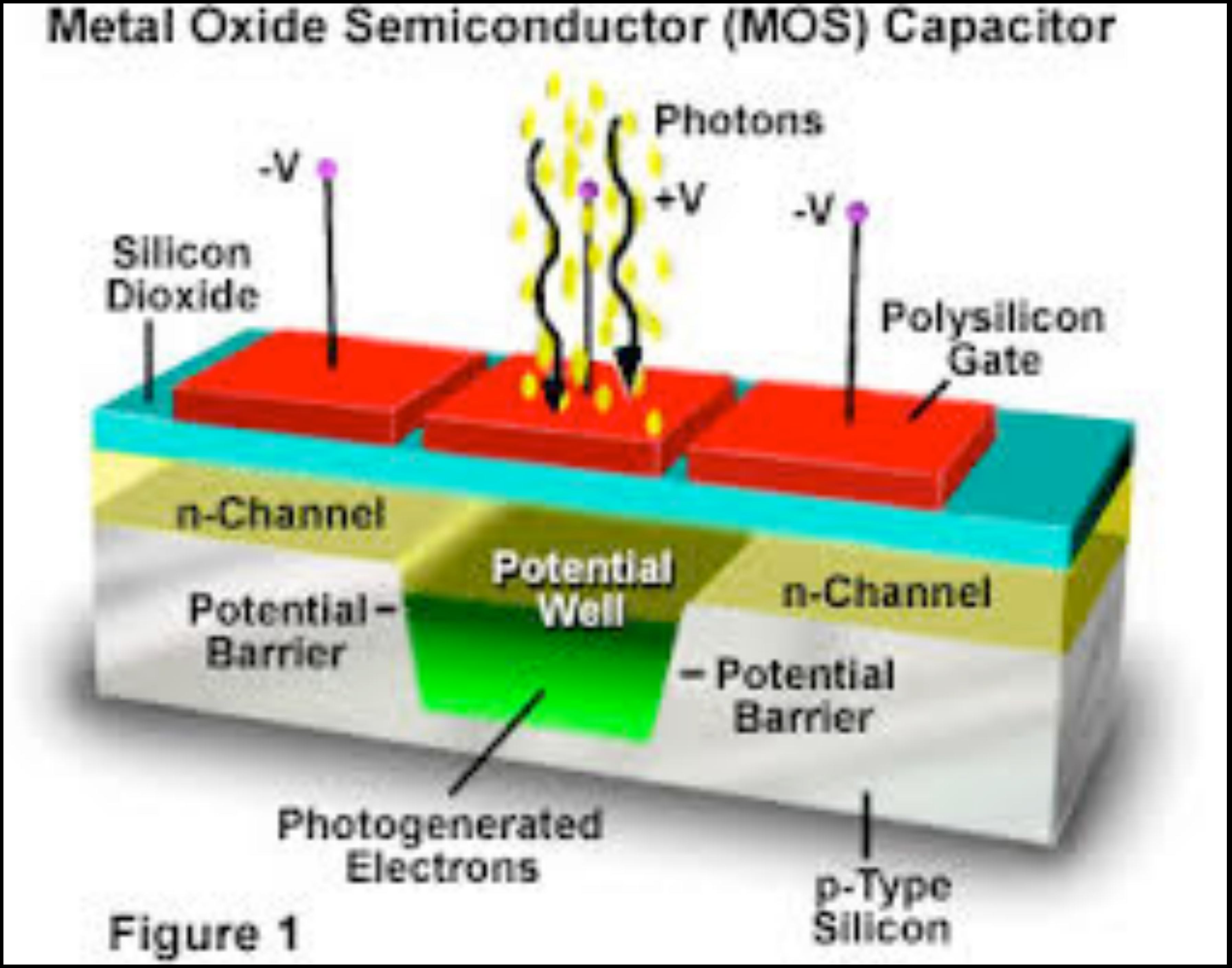
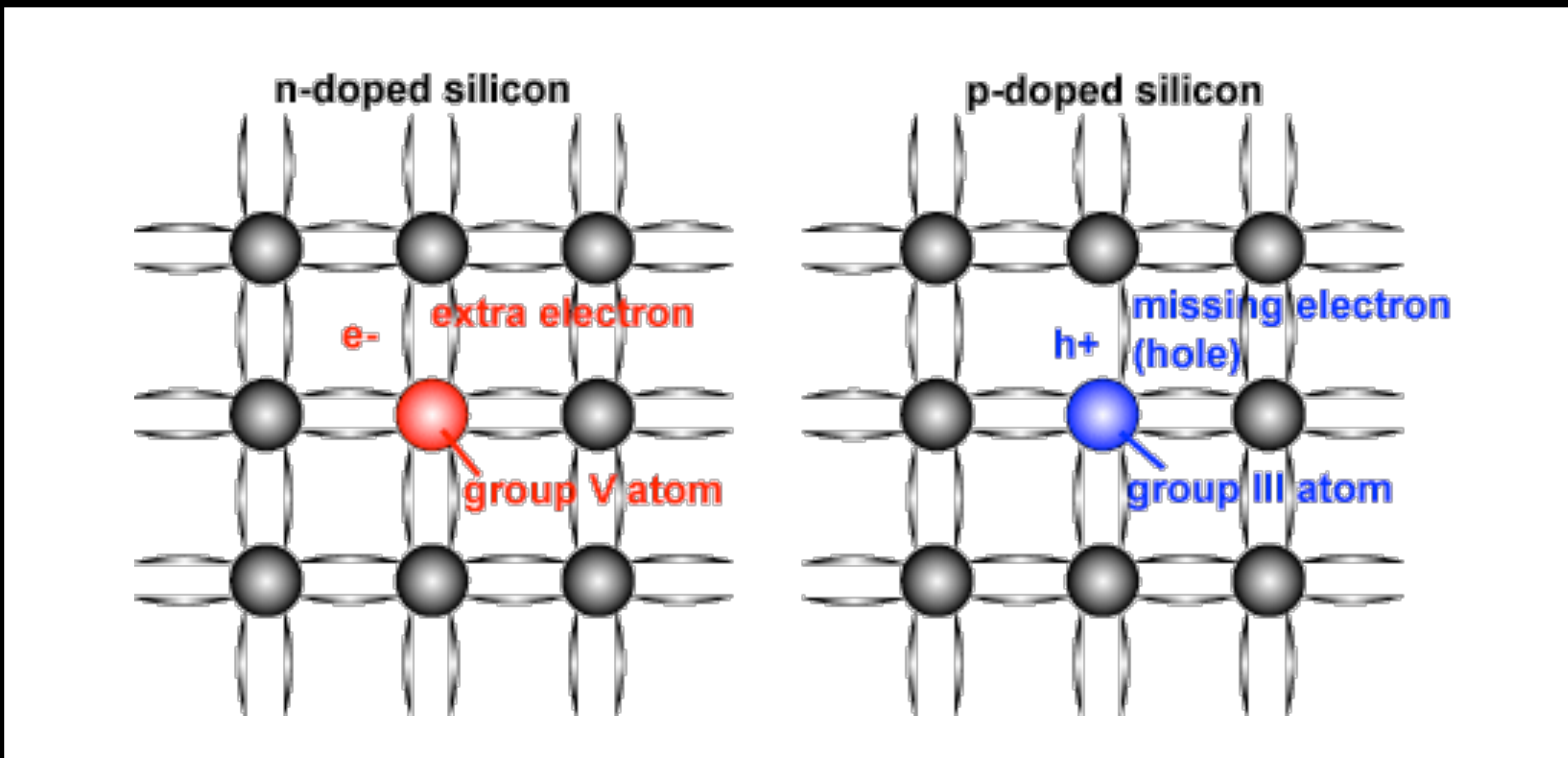
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

The Pixel


Metal Oxide Semiconductor (MOS) Capacitor
Photons
-V
+V
-V
Silicon Dioxide
Polysilicon Gate
n-Channel
Potential Well
n-Channel
Potential Barrier
Potential Barrier
Photogenerated Electrons
p-Type Silicon
Figure 1

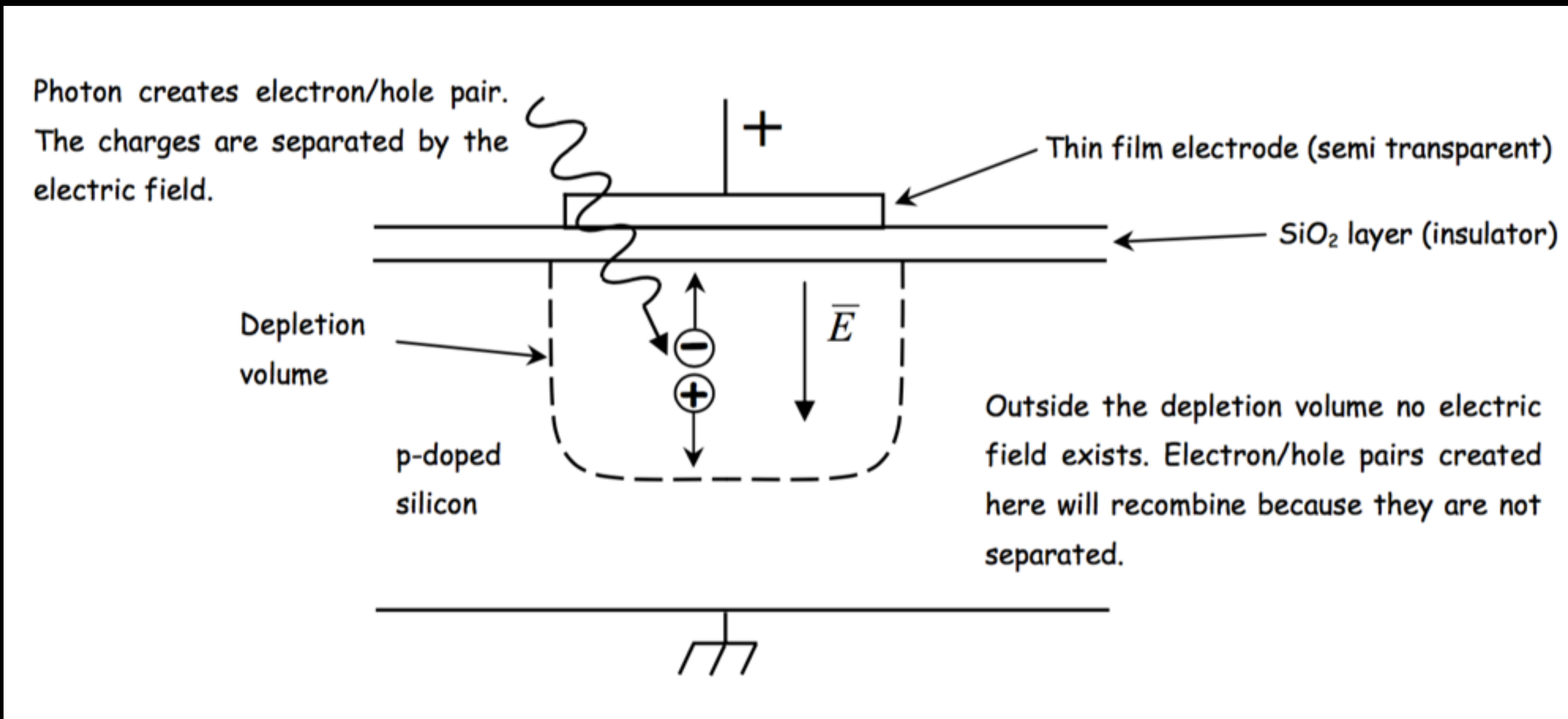
Doped Silicon



Donors, Group V impurities:
Phosphorous, Arsenic and Antimony

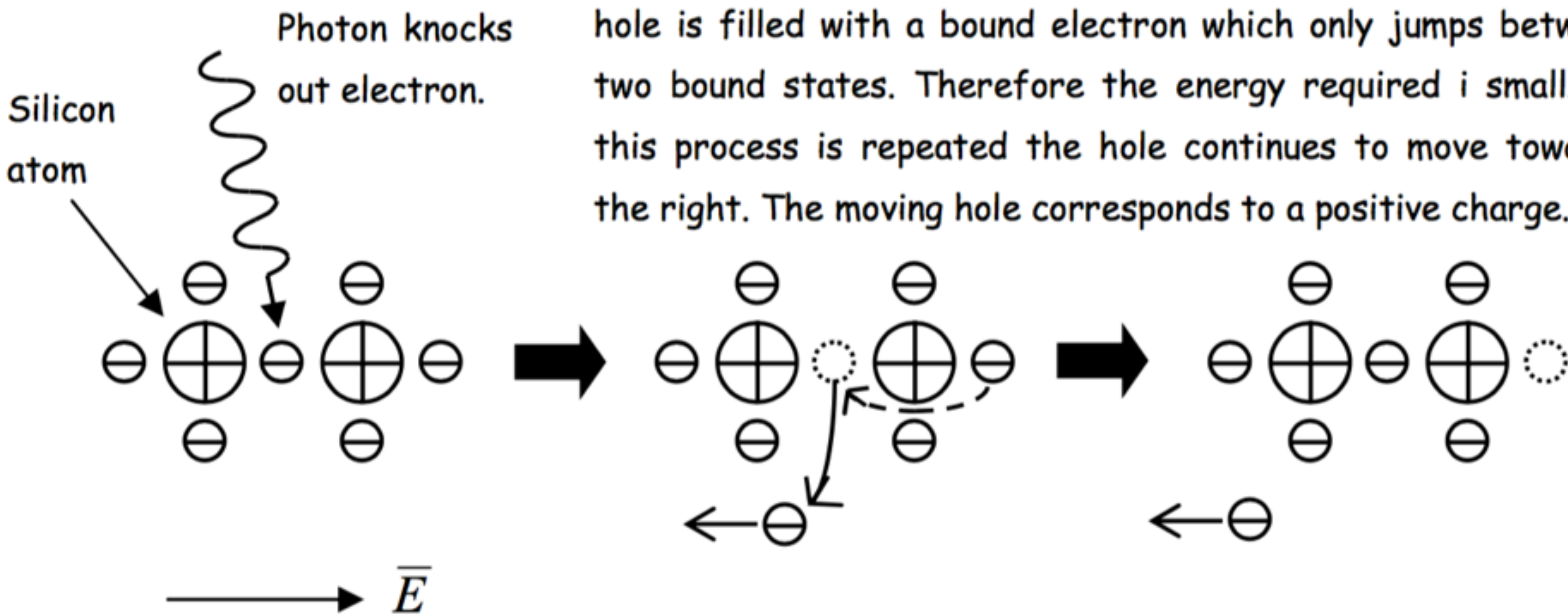
Acceptors, Group III impurities:
(e.g. Boron, Gallium and Indium)

Photogate


Photon creates electron/hole pair. The charges are separated by the electric field.
+
Thin film electrode (semi transparent)
SiO2 layer (insulator)
Depletion volume
$\overline{E}$
p-doped silicon
Outside the depletion volume no electric field exists. Electron/hole pairs created here will recombine because they are not separated.

Holes move

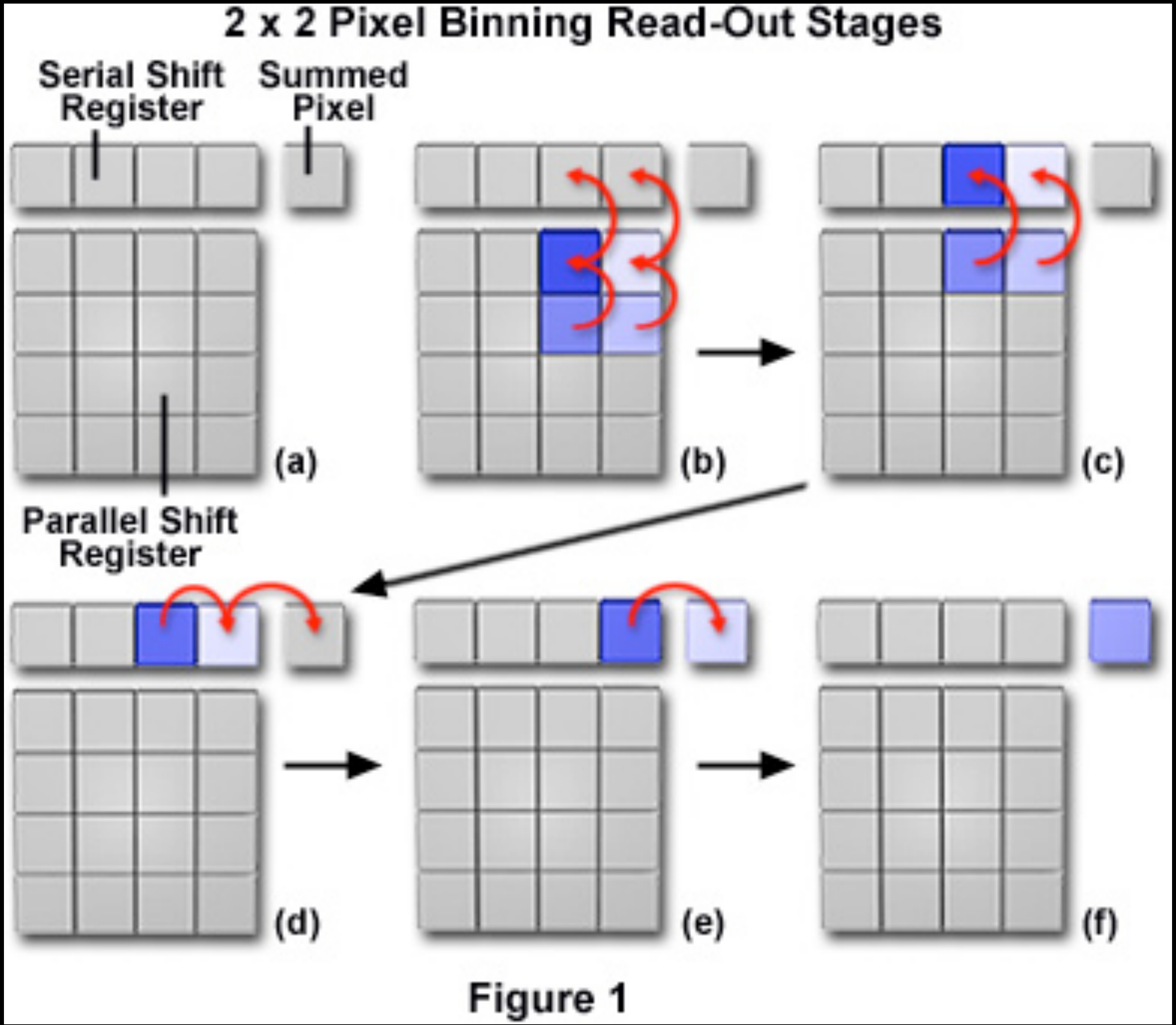
The free electron moves to the left in the electric field. The hole is filled with a bound electron which only jumps between two bound states. Therefore the energy required i small. As this process is repeated the hole continues to move towards the right. The moving hole corresponds to a positive charge.

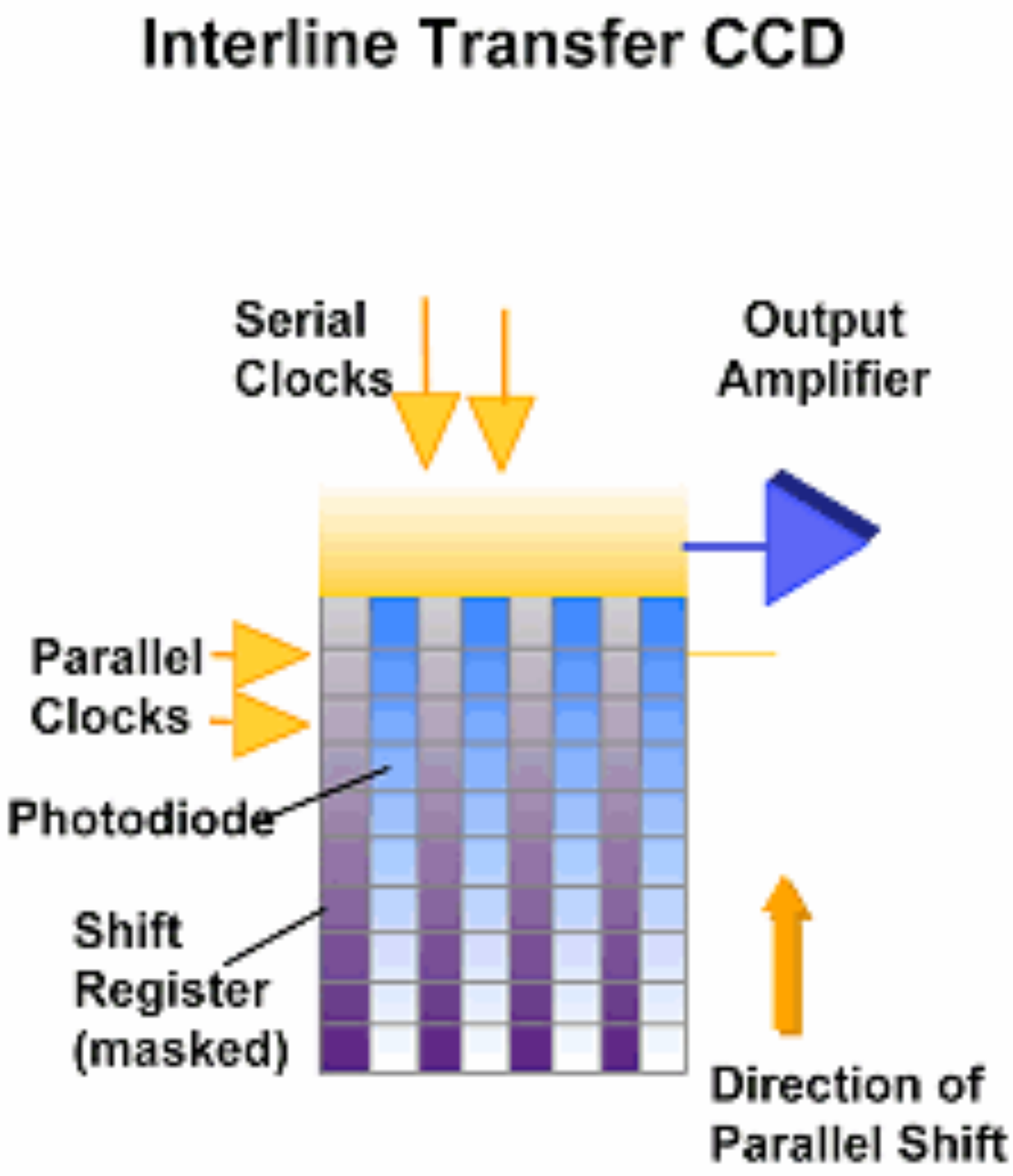


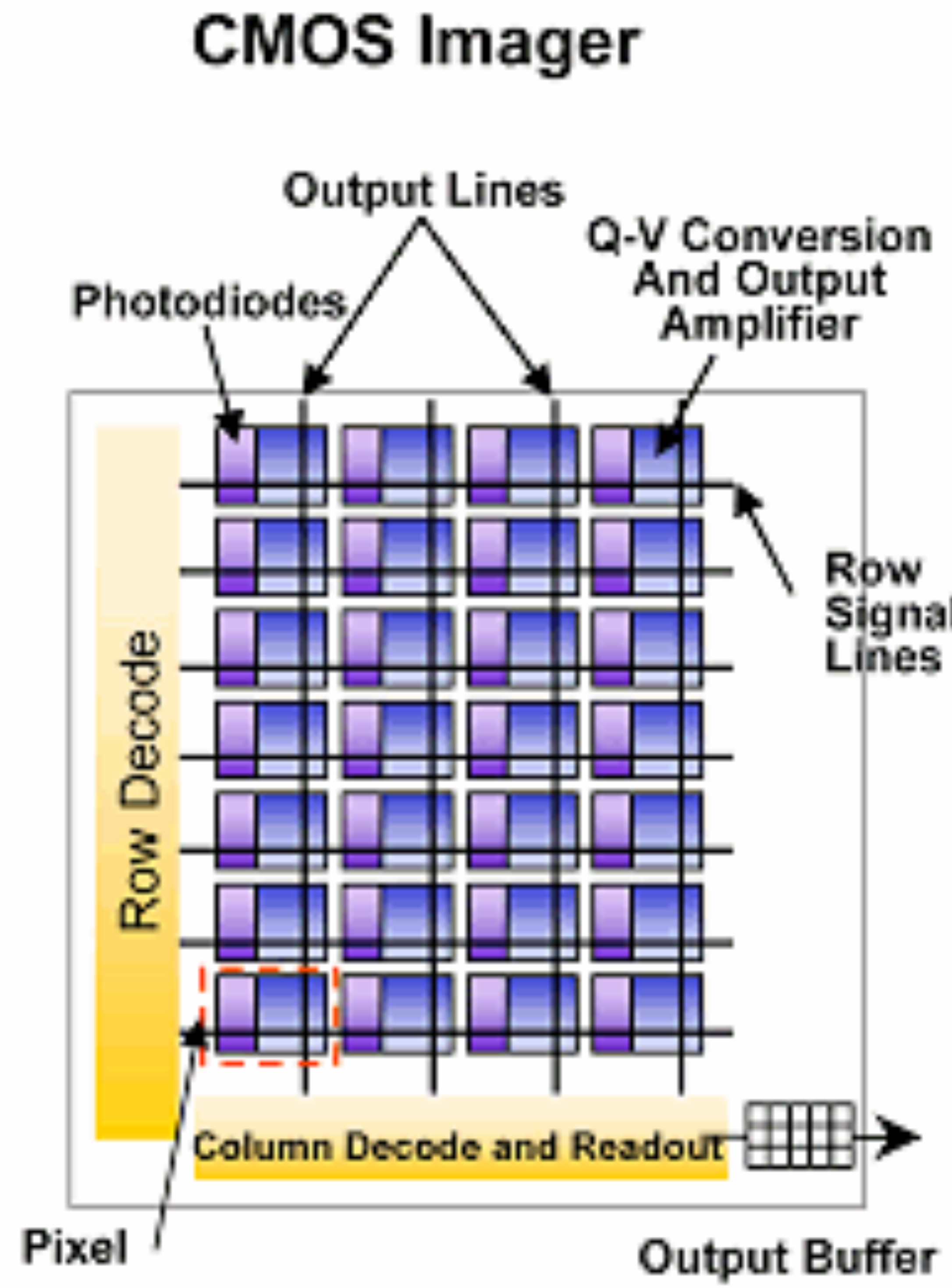
Energy required to knock it: ~1.2 eV ~ 1 μm wavelength

- Infrared
- Now commercially available
- Different material lenses (e.g. Gallium Arsenide)

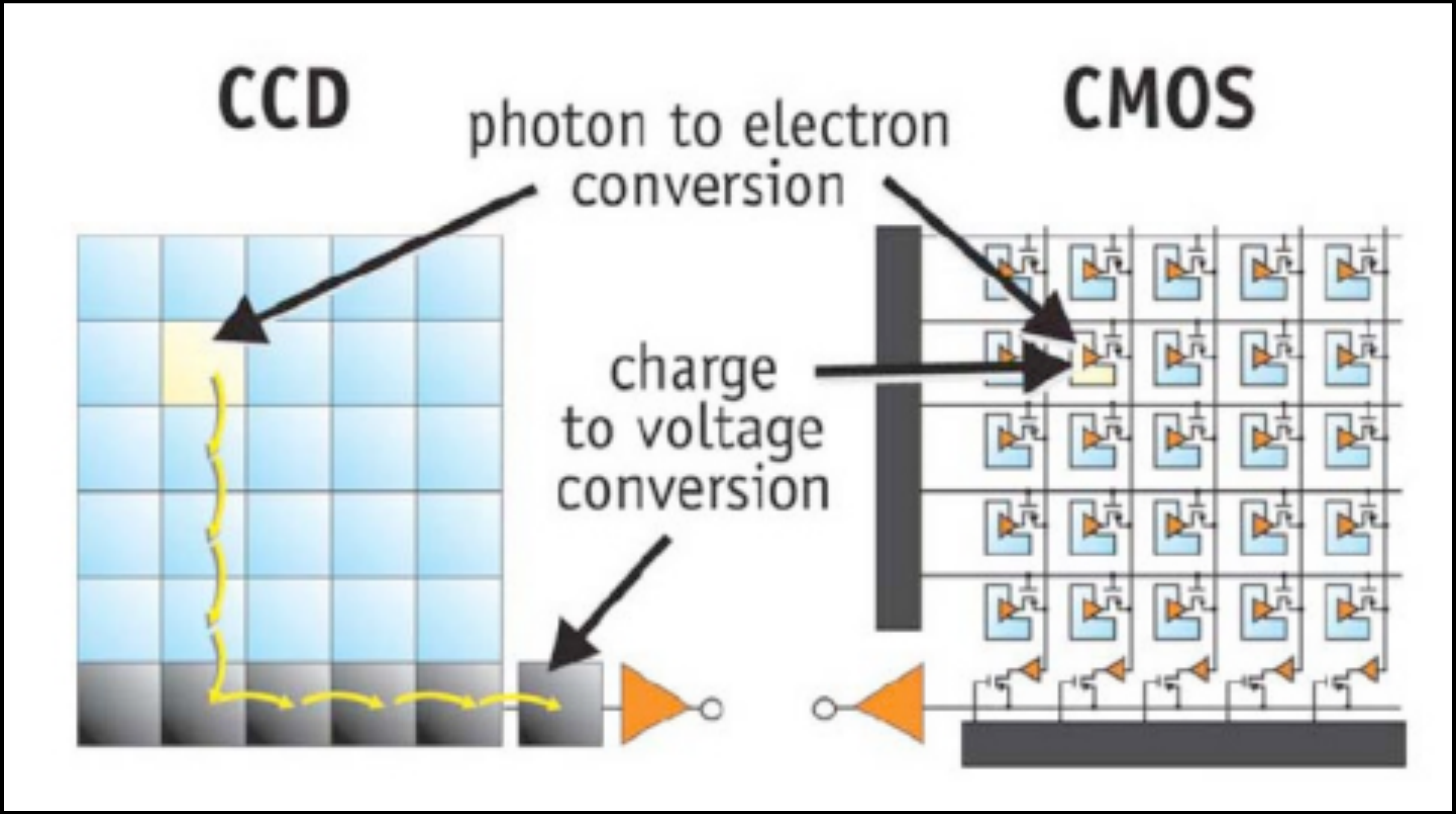
CCD read-out


2 x 2 Pixel Binning Read-Out Stages
Serial Shift Register
Summed Pixel
Parallel Shift Register
(a)
(b)
(c)
(d)
(e)
(f)
Figure 1


Interline Transfer CCD
Serial Clocks
Output Amplifier
Parallel Clocks
Photodiode
Shift Register (masked)
Direction of Parallel Shift

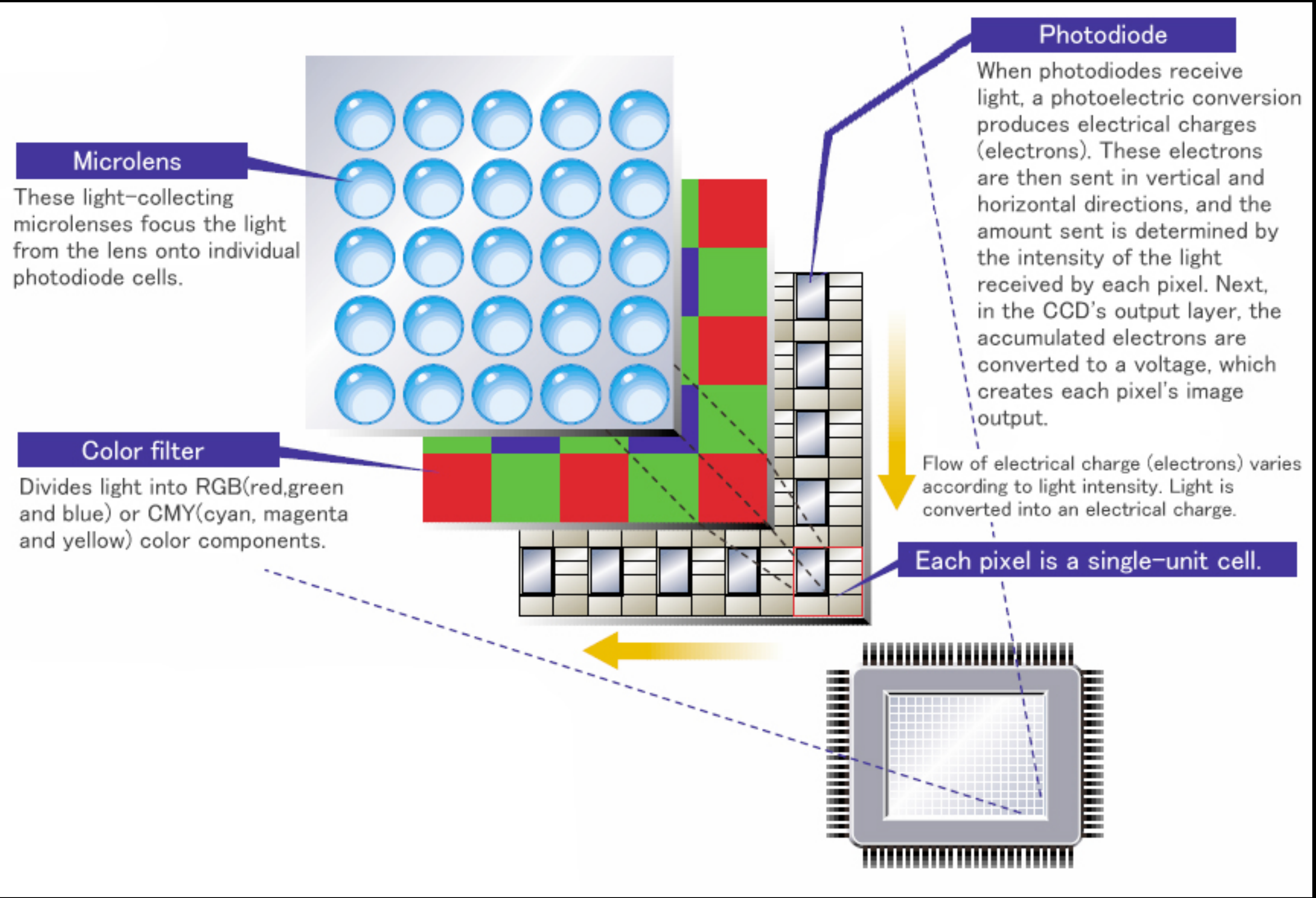

CMOS Imager
Output Lines
Q-V Conversion And Output Amplifier
Photodiodes
Row Signal Lines
Row Decode
Column Decode and Readout
Pixel
Output Buffer

CCD vs CMOS

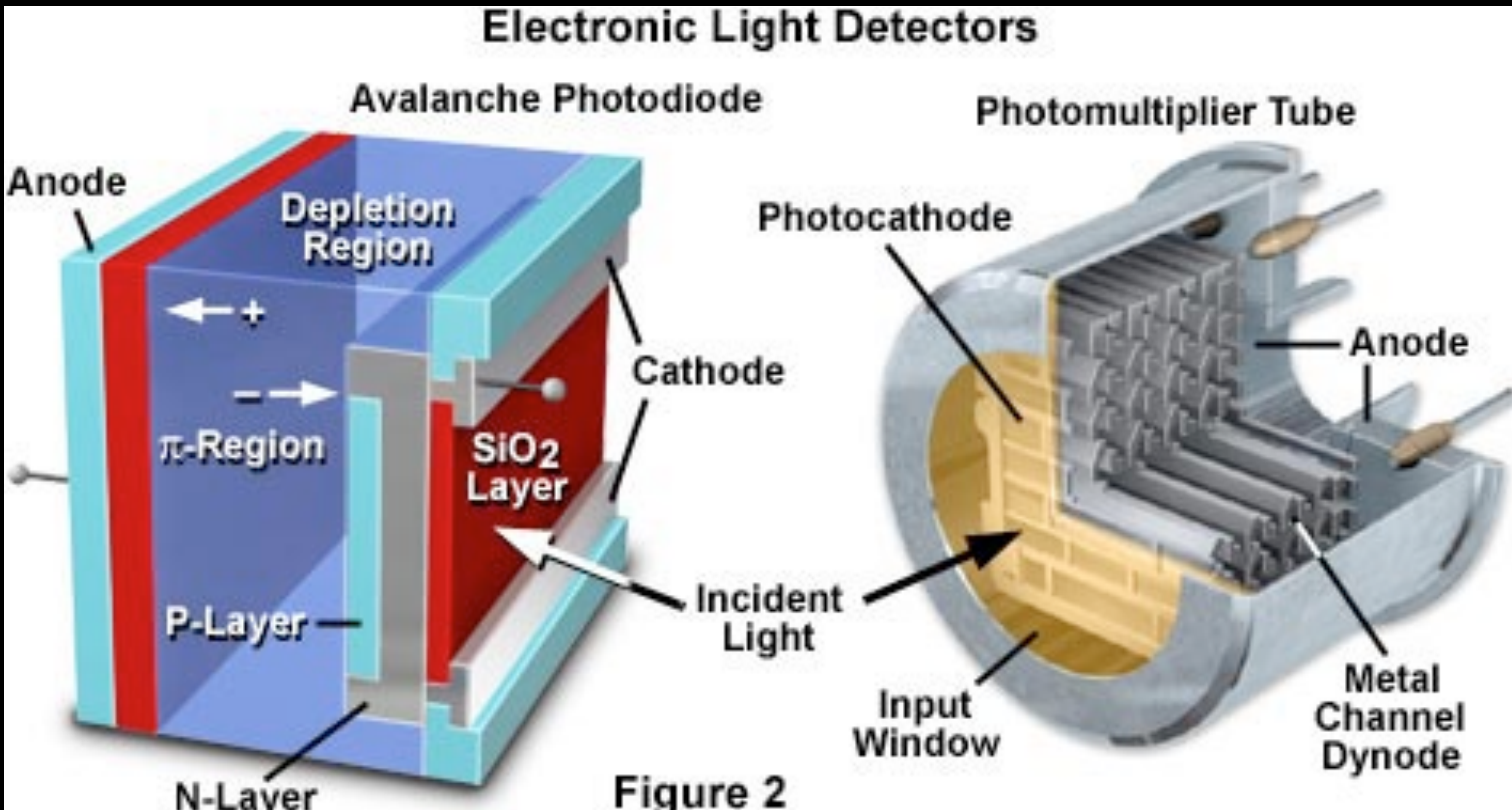


CCD
photon to electron conversion
CMOS
charge to voltage conversion

Increase effective fill factor

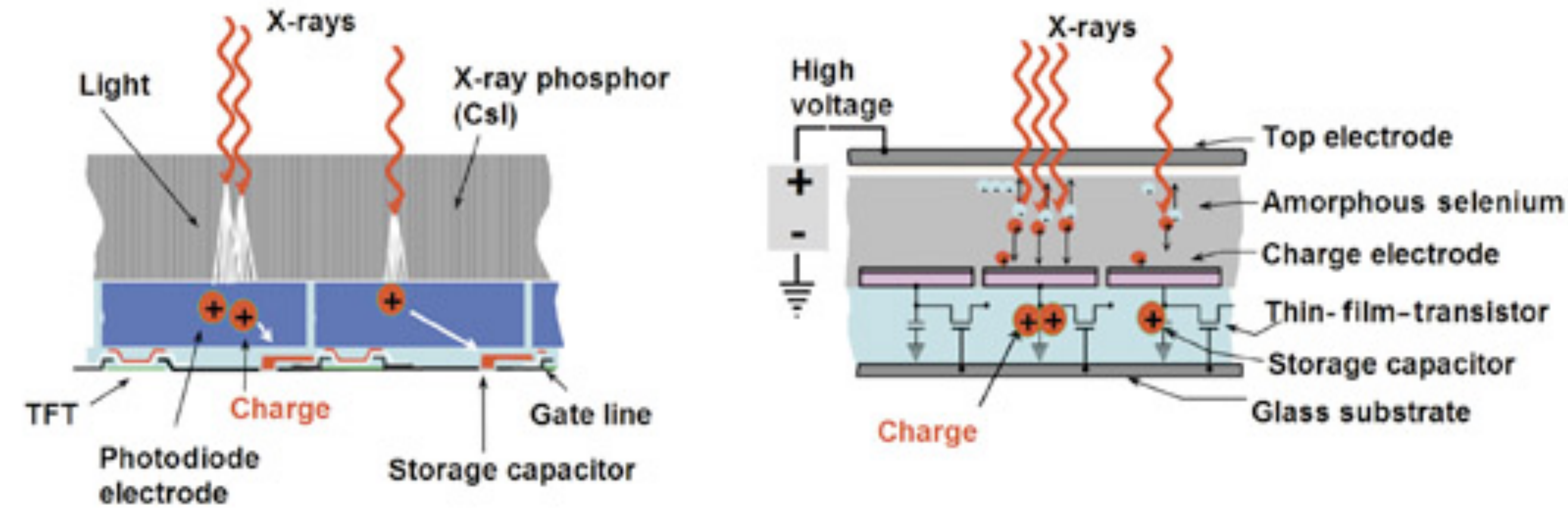


Other imaging modes (PMTs)



https://www.olympus-lifescience.com/de/microscope-resource/primer/techniques/confocal/detectorsintro/

Digital X-ray



A. Indirect AMFPI: X-rays to light to charge

B. Direct AMFPI: X-rays to charge

SPEED

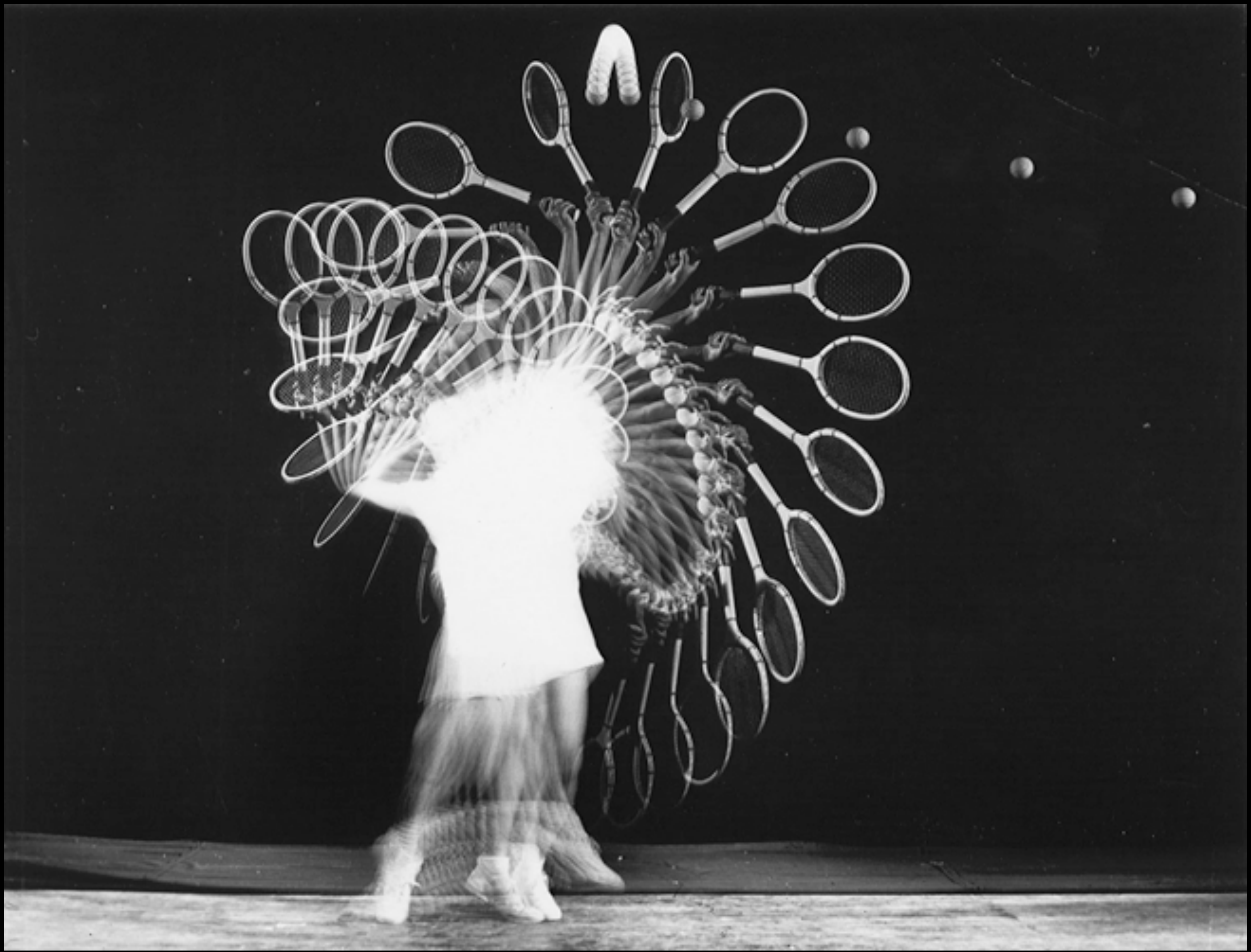
Temporal Sampling

Rolling Shutter/Global Shutter and Artifacts

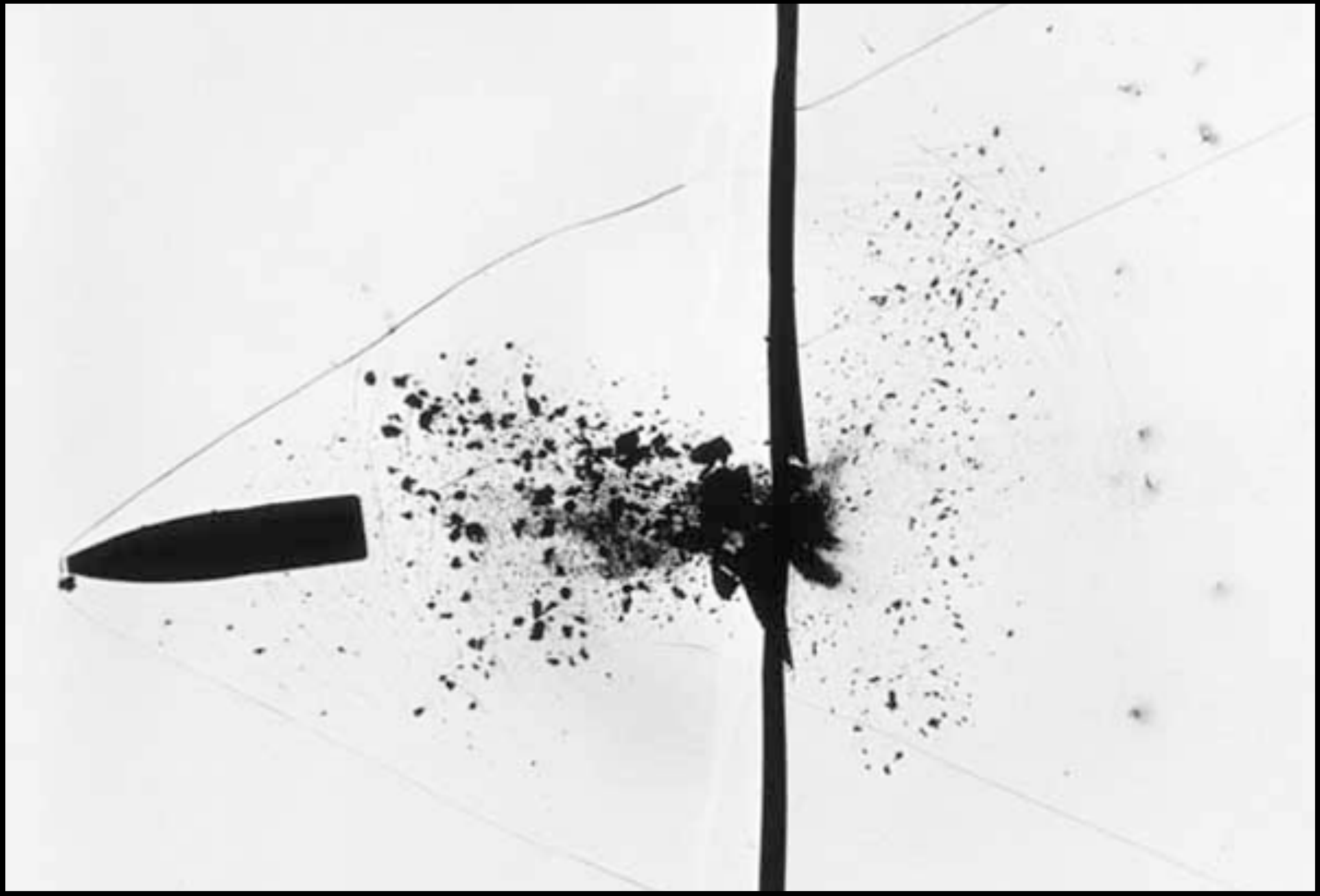
Stopping Time

Harold Edgerton's Kodatron strobe (1/3,000s)

Flash Strobe

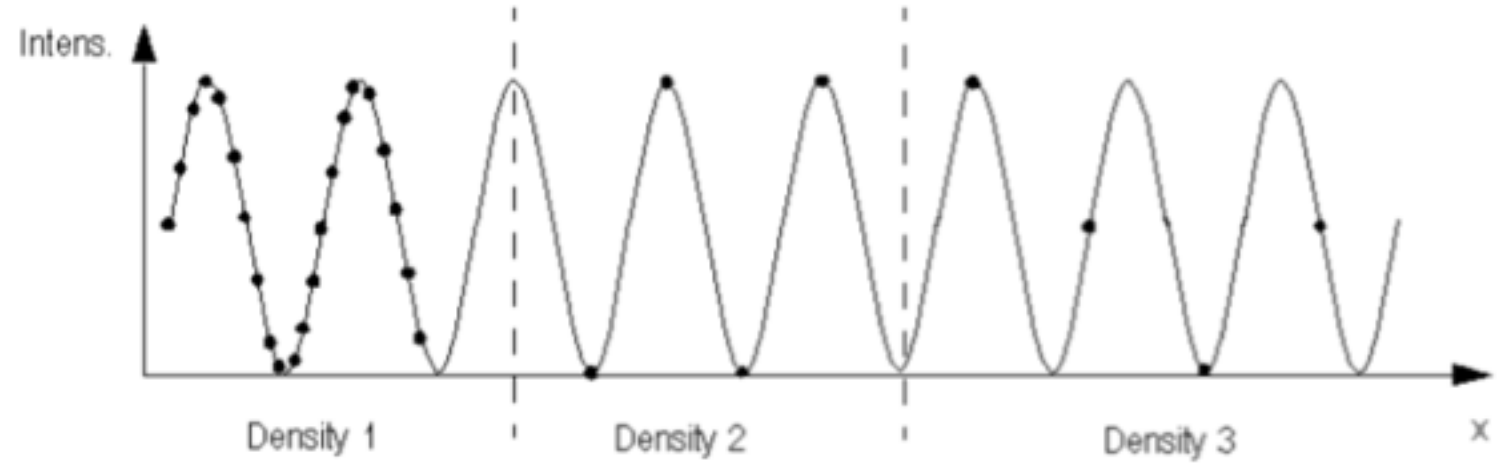


Shadow Photography

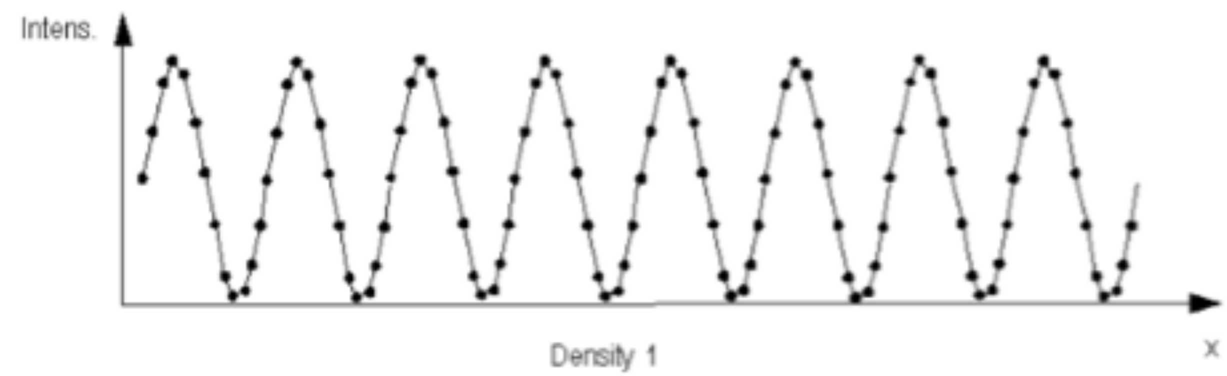


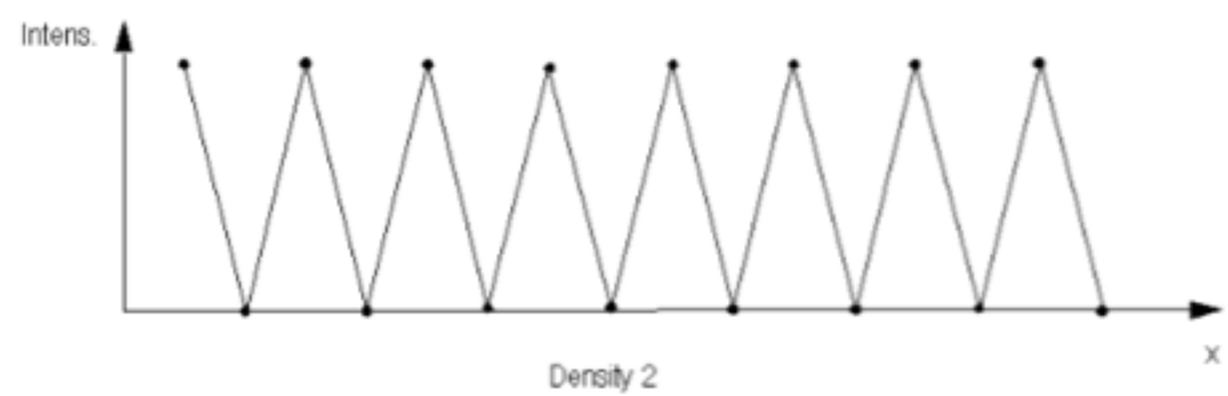
http://edgerton-digital-collections.org/techniques/shadow-photography

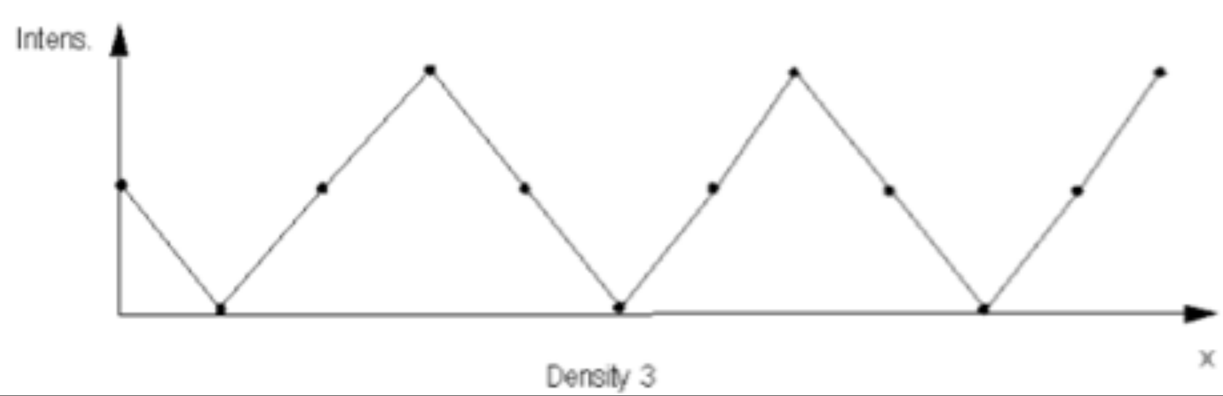
Spatial Sampling



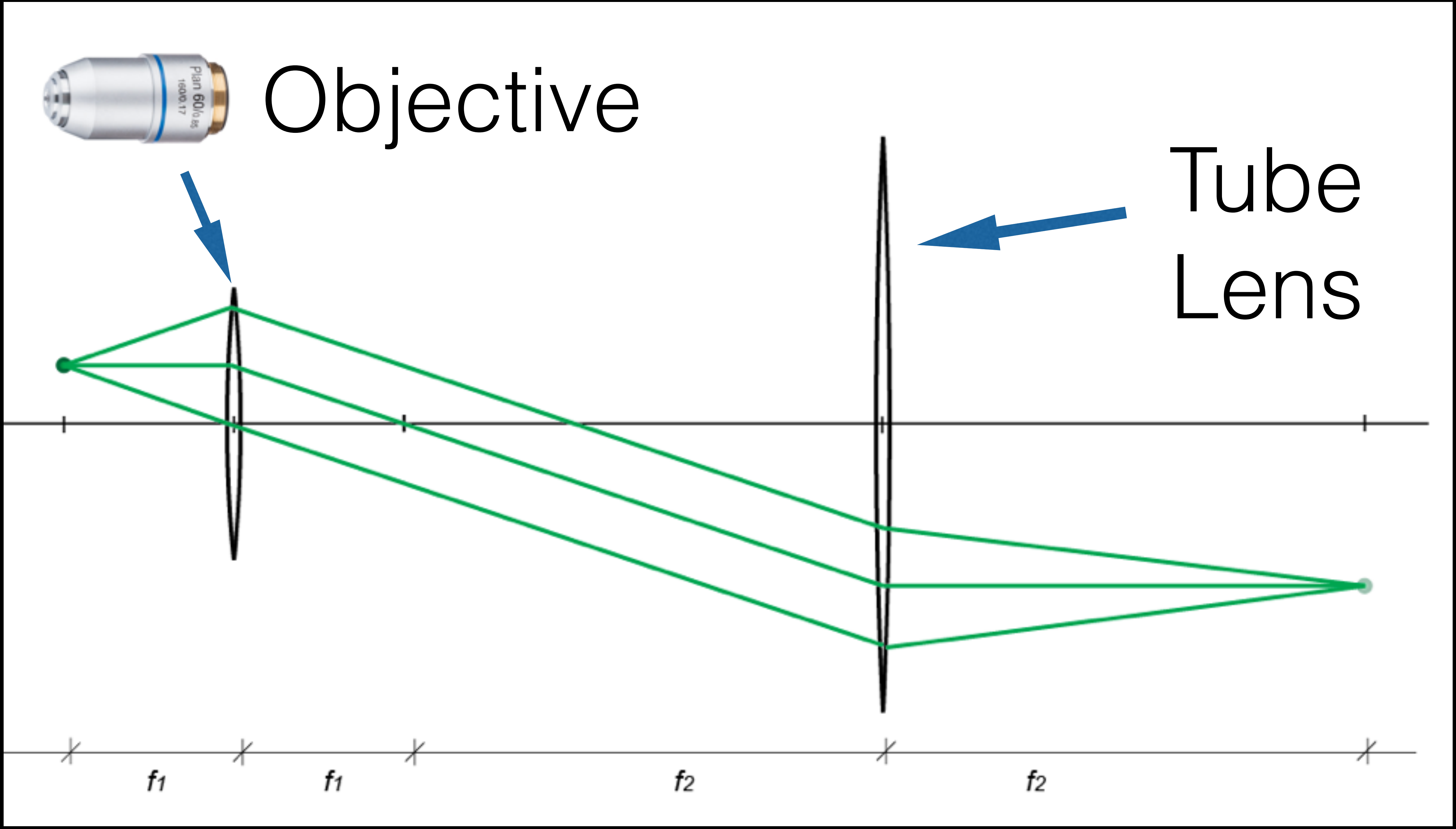
Sampling density 1 corresponds to "many" sample points per period of the sine wave. Density 2 corresponds to exactly two sample points per period, and density 3 to less than two sample points per period. Let us make simple image reconstructions (linear interpolation) from the sampled values for the three sampling densities:



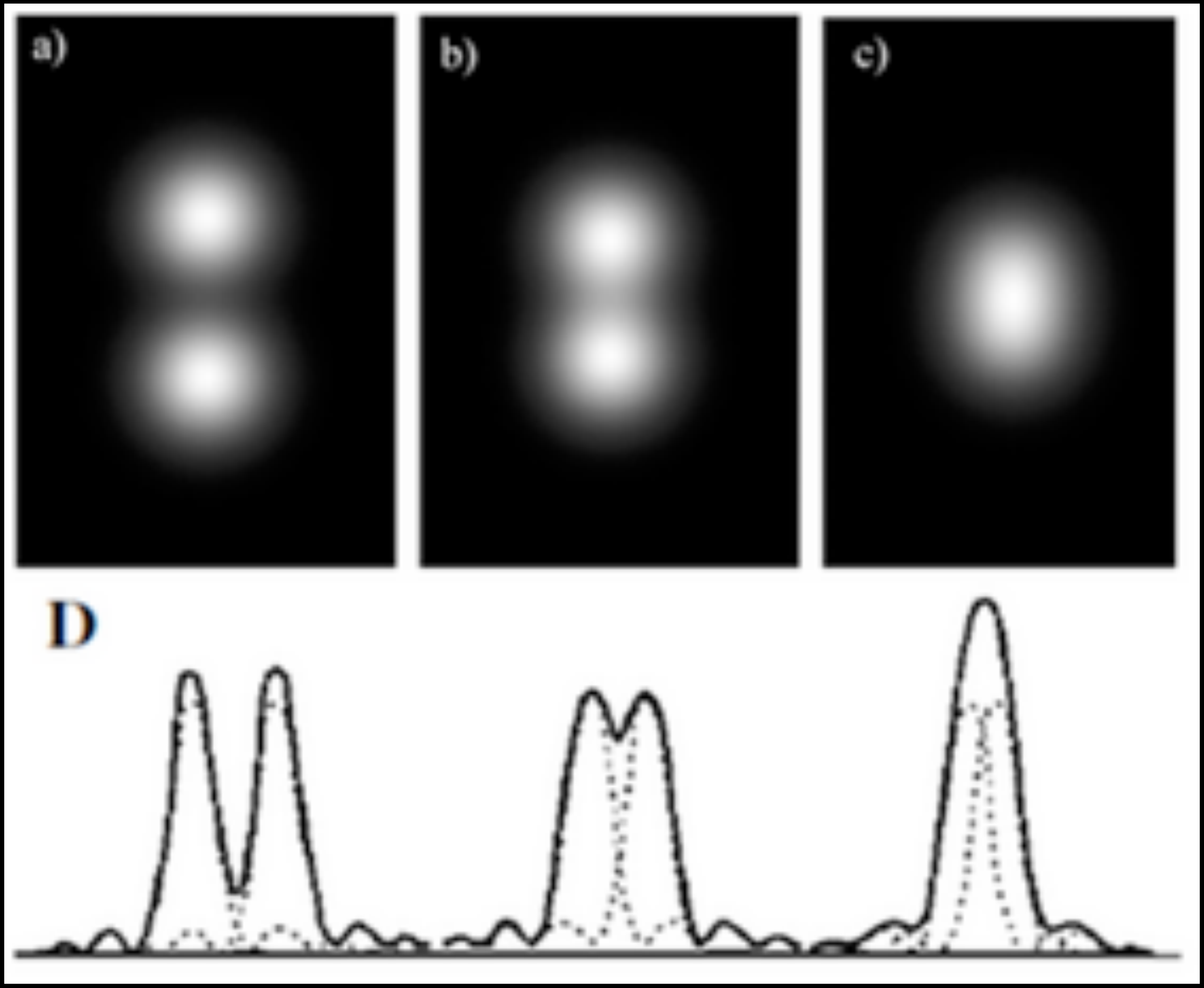




Recap from last week
The Microscope:



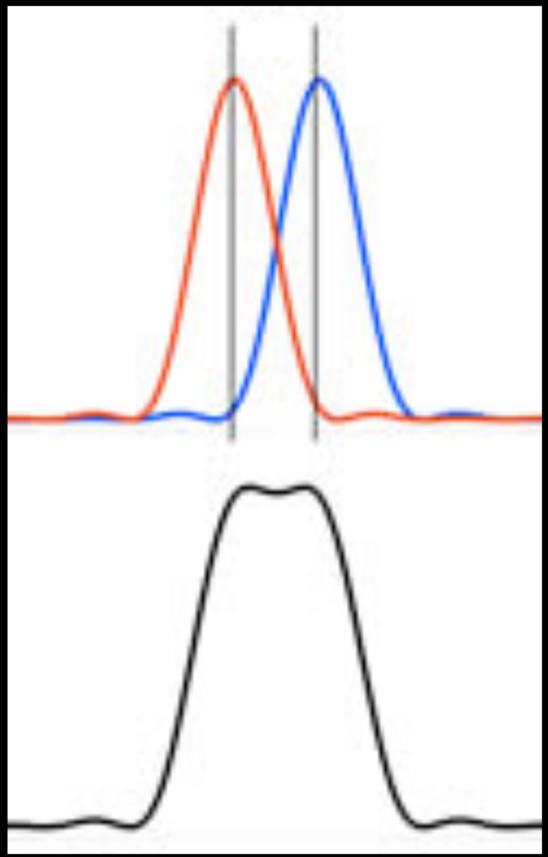
Resolution



Abbe Limit of Resolution

$$d = \lambda / (2 \times NA)$$

Lateral resolution is classically limited by diffraction to ~200nm (determined by Numerical Aperture NA and wavelength)



Example for green light with high NA objective: $d = (550\text{ nm}) / (2 \times 1.4) \approx 200\text{ nm}$

Resolution and Magnification

- Example:
  - We have a CCD camera with 512x512 pixels of 16x16 microns size
  - We have a 100x objective with NA =1.5
    - Resolution: (0.5)/(2*1.5) ≈ 166 nm
    - 100X mag => ≈ 16.6 microns in image space
    - => We need to sample at twice this ≈ 8 microns
    - => This camera will not work well for us