CS7.404: Digital Image Processing

Monsoon 2023: Image Restoration

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Image Restoration

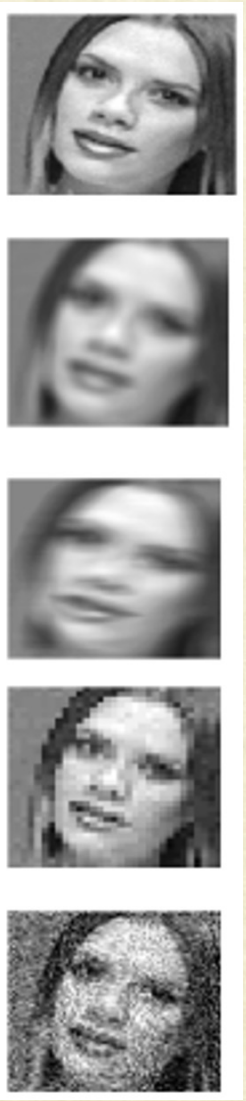
Original Image

Blurred Image

Can we undo these effects to "restore" the image to its original state?

- What caused the blurring?
  - Camera: Translation, shake, out-of-focus, Lens aberrations.
  - Environment: Light scattering, reflection
  - Device: Sensor noise; Quantization

Degradations



- Original
- Optical blur
- Motion blur
- Spatial quantization (discrete pixels)
- Additive intensity noise

Examples (Optical Blur)

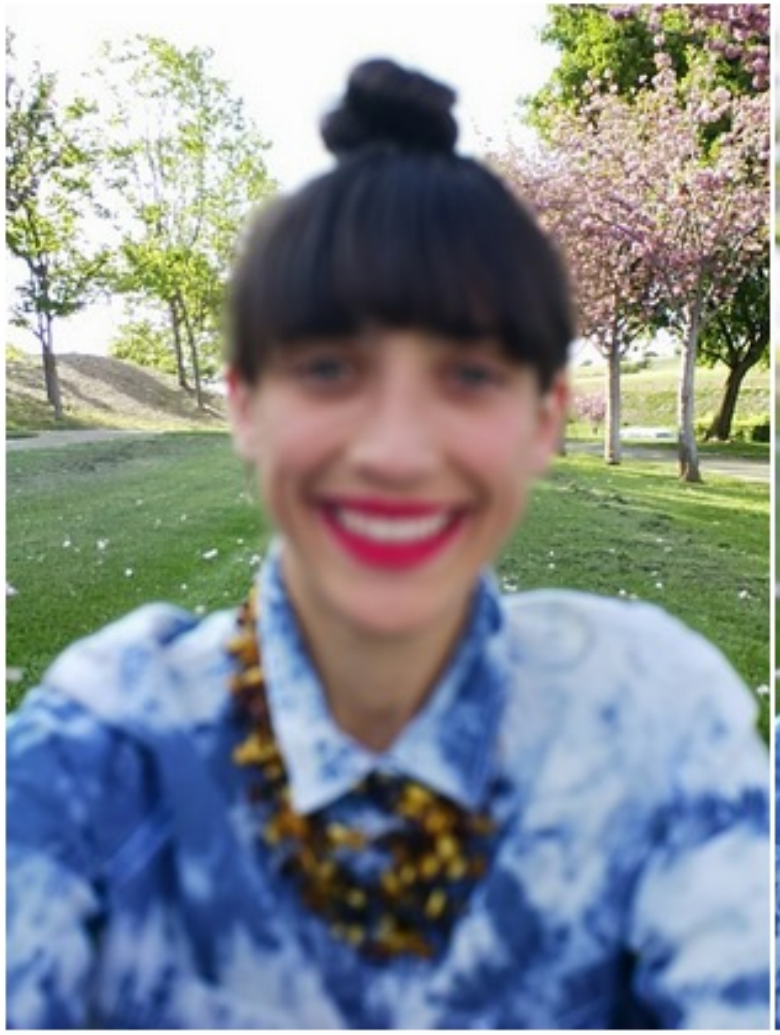
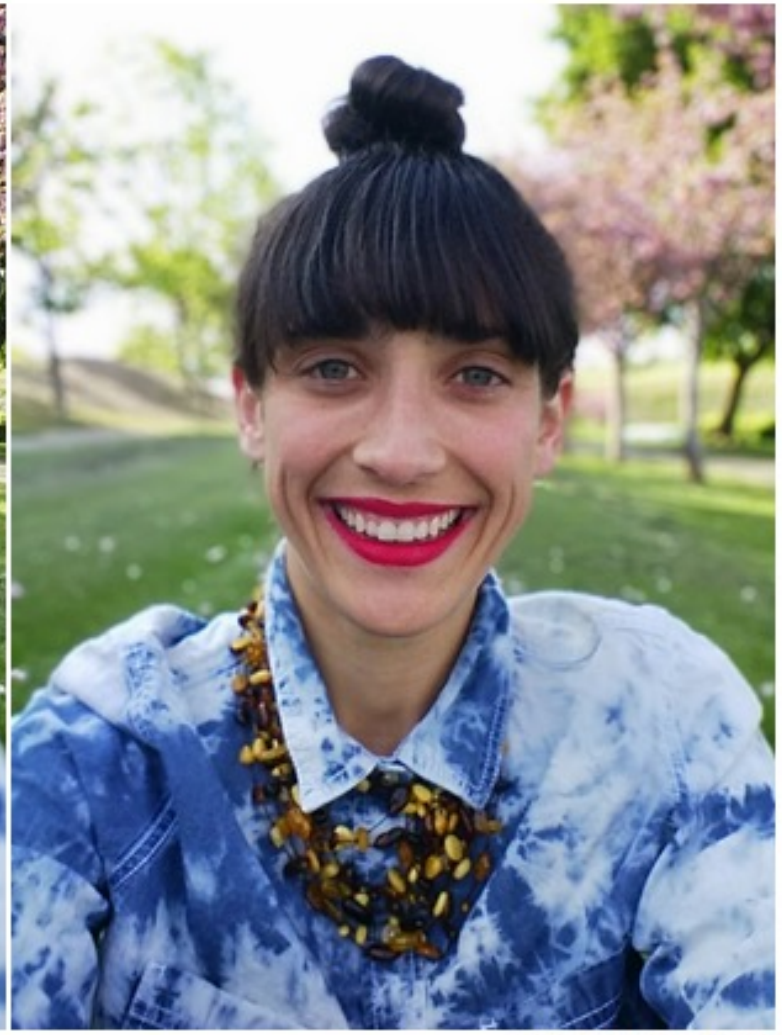


Photo by Rachel Been

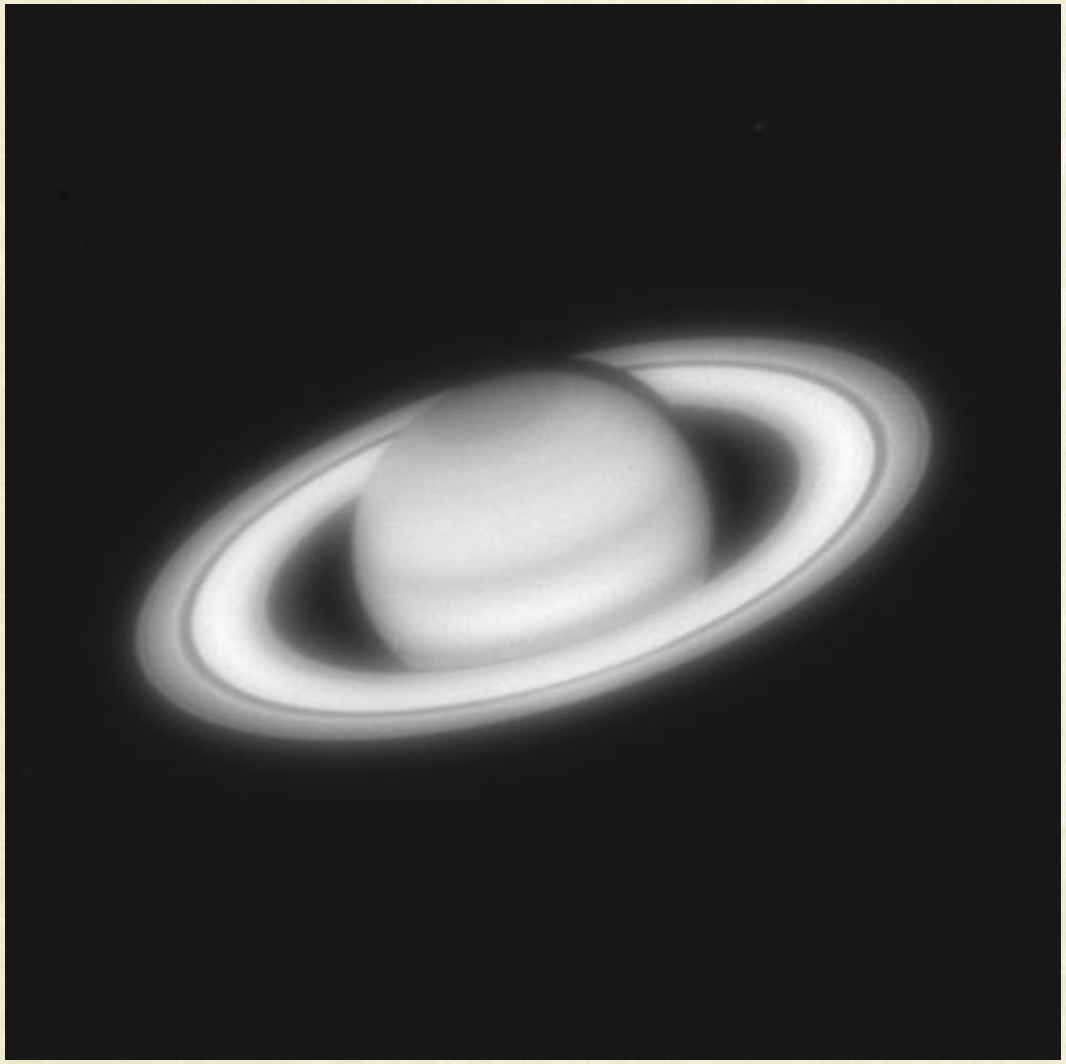
Lens Blur selfie, background focus



Lens Blur selfie, foreground focus

Interesting read:
Light Field Cameras

Examples (Optical Blur)



Courtesy: NASA

Examples (Restoration from camera shake)

Courtesy: Cho et al. ICCV 2007

Examples (Atmospheric conditions)

Single Image Haze Removal [He et al. CVPR 2009]

Image Restoration

- Started from 1950s
- Application Domains
  - Scientific explorations
  - Legal investigations
  - Film making and archival
  - Image and video de-coding
  - Consumer photography …
- Related Problem:
  - Image reconstruction in radio astronomy, radar imaging and tomography.

Image Enhancement

- “Improve” the appearance of an image; a subjective process.

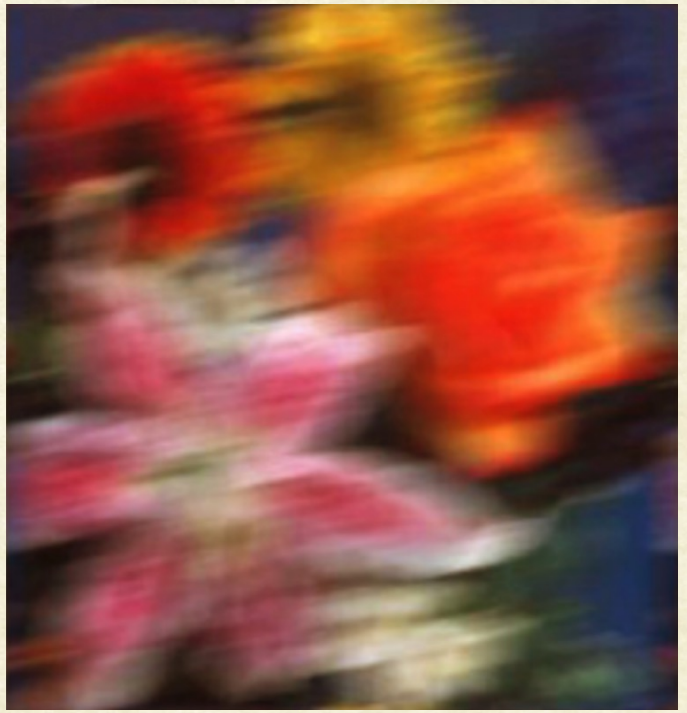
Original Image

Blurred Image

Image Restoration

- Remove distortions from an image to go back to the “original” image; an objective process.

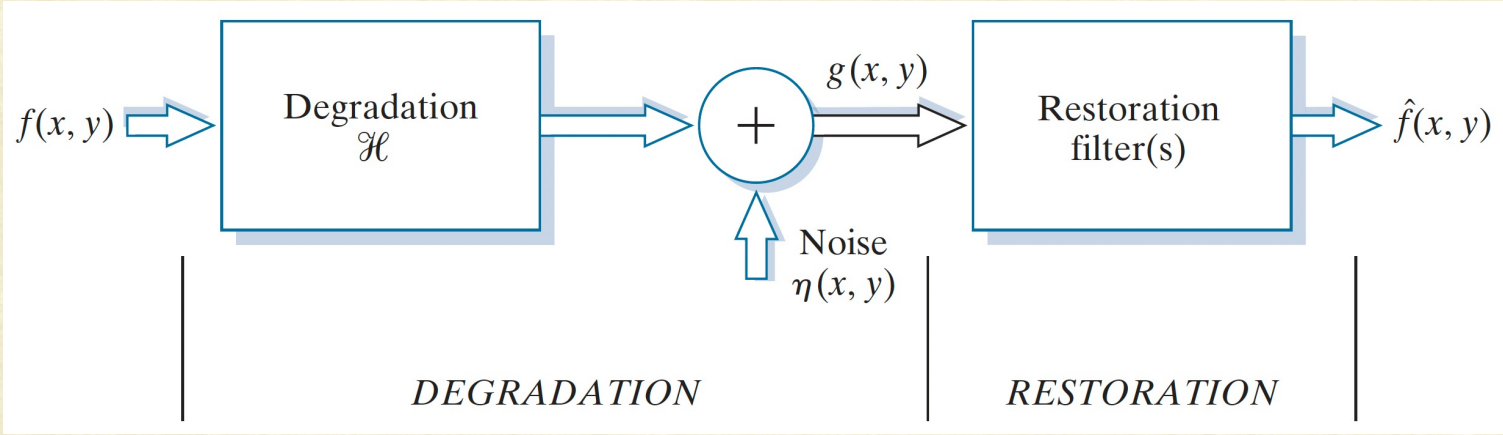
Original Image



Degraded Image

A Model for Image Degradation and Restoration

- Image Restoration
  - Use a priori knowledge of the degradation
  - Modeling the degradation and apply the inverse process
  - Formulate and evaluate objective criteria of goodness

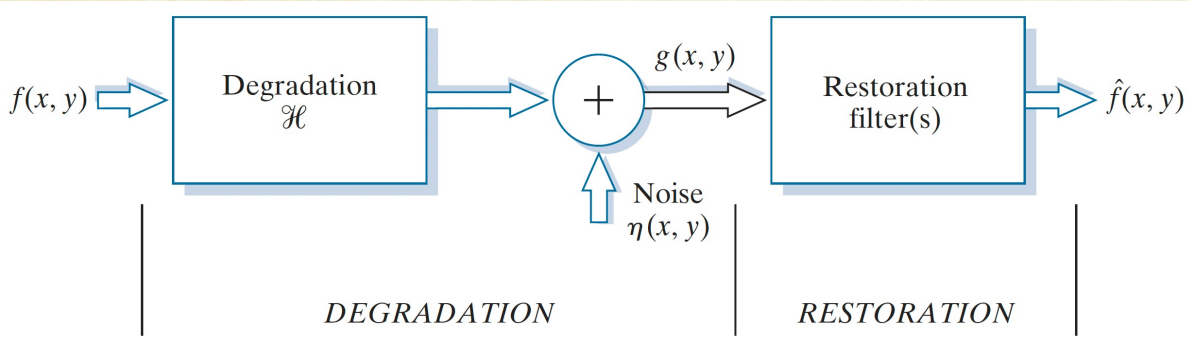


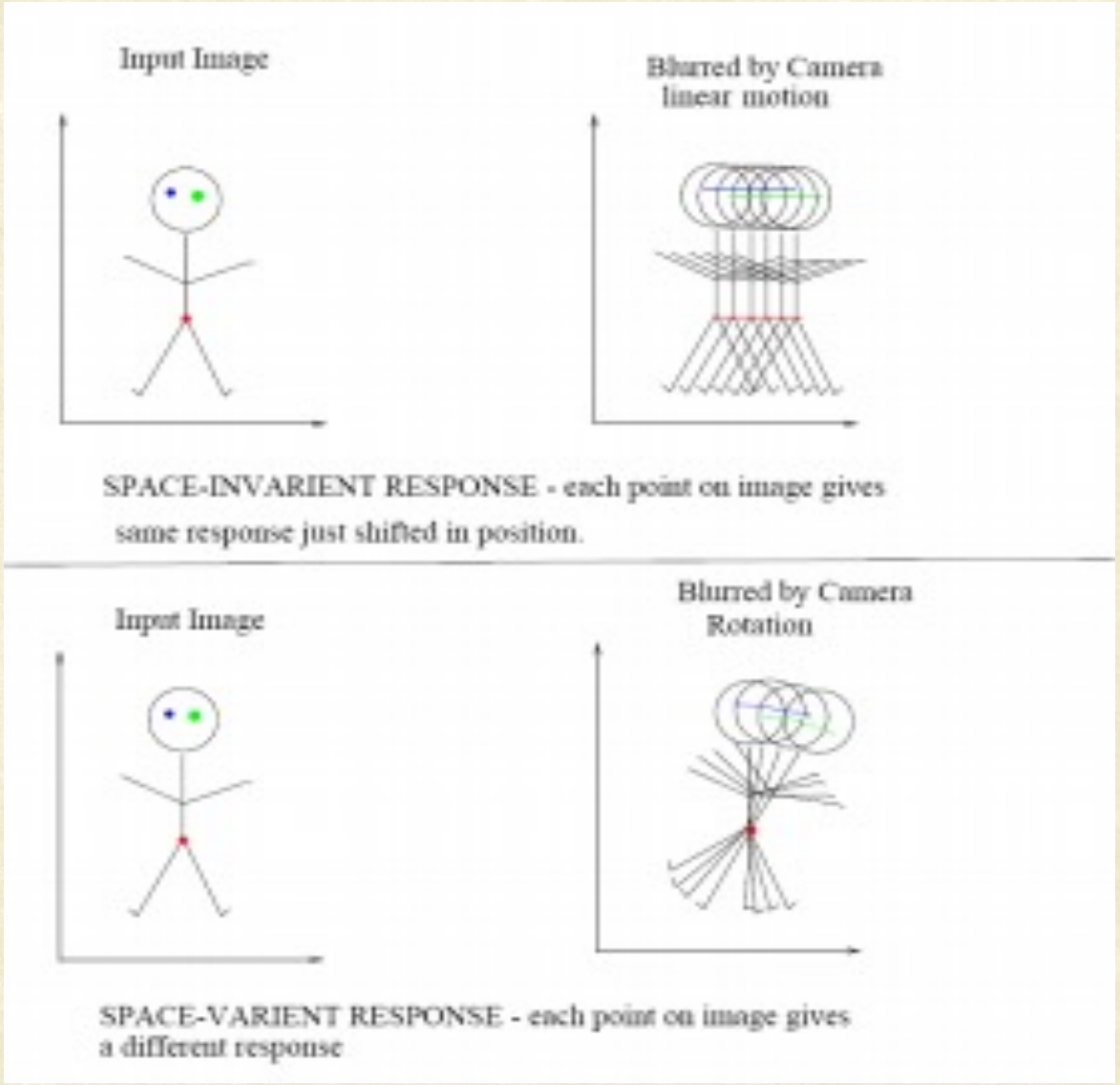
$$g(x,y) = H[f(x,y)] + \eta(x,y)$$

  - Design the restoration filters such that $\hat{f}(x,y)$ is as close to $f(x,y)$ as possible.

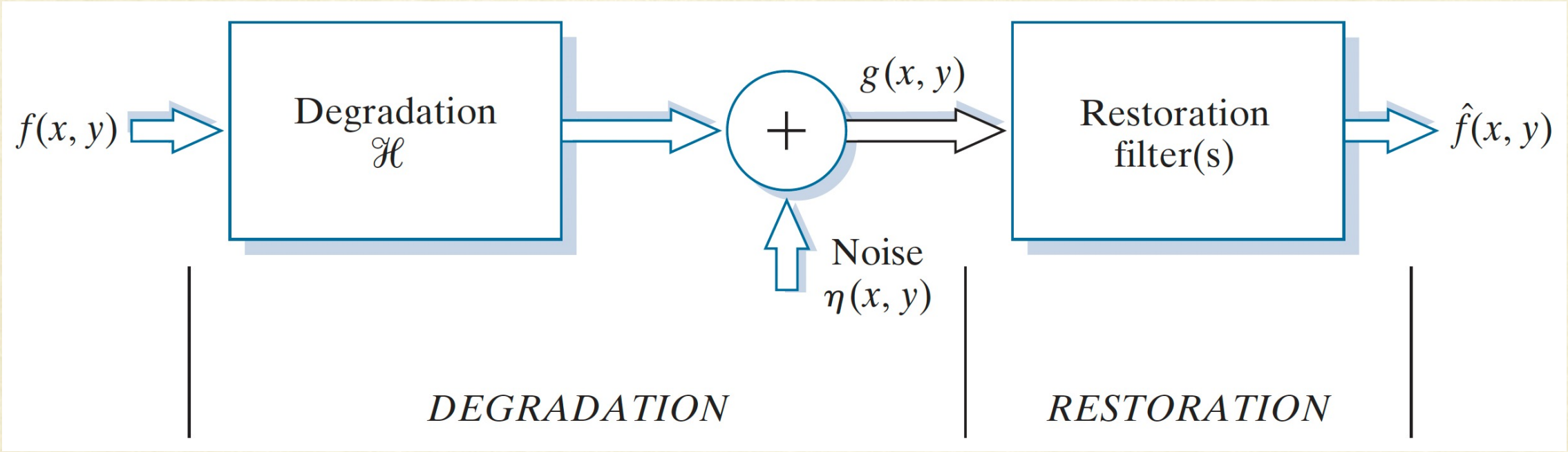
Assumptions for the Distortion Model

- Noise
  - Independent of spatial location
    - except for periodic noise
  - Uncorrelated with the image
- Degradation function, H
  - Linear
  - Position-invariant





Mathematical model of Image Degradation/Restoration



$$g(x,y) = H[f(x,y)] + \eta(x,y)$$

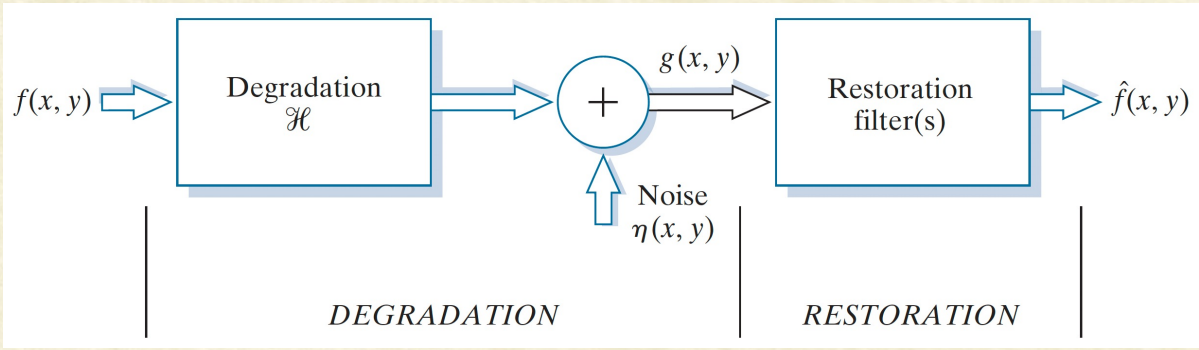
If H is a linear, position-invariant process,

$$g(x,y) = h(x,y) \star f(x,y) + \eta(x,y), \text{ or}$$

$$G(u,v) = H(u,v)\, F(u,v) + N(u,v)$$

Divide and Conquer: Step #1

- Image degraded only by noise



- Assuming 'H' is identity, the model reduces to:

$$g(x,y) = f(x,y) + \eta(x,y)$$

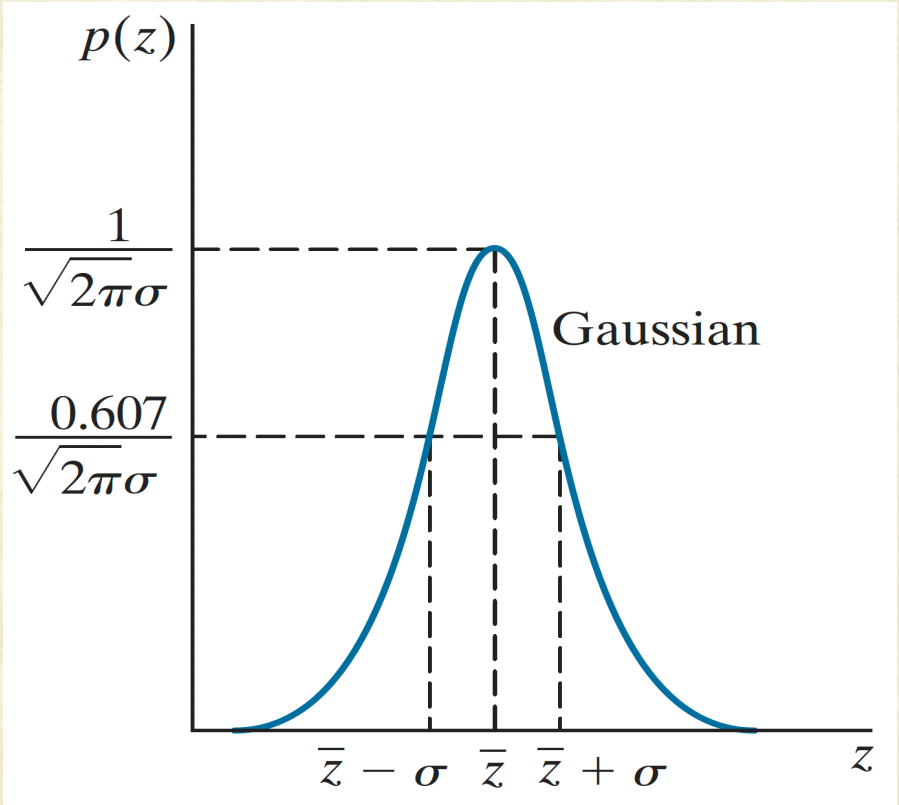
or

$$G(u,v) = F(u,v) + N(u,v)$$

Noise Models: Gaussian

- Gaussian (normal) Noise.
- Widely used due to
  - mathematical convenience
  - Robustness to model error

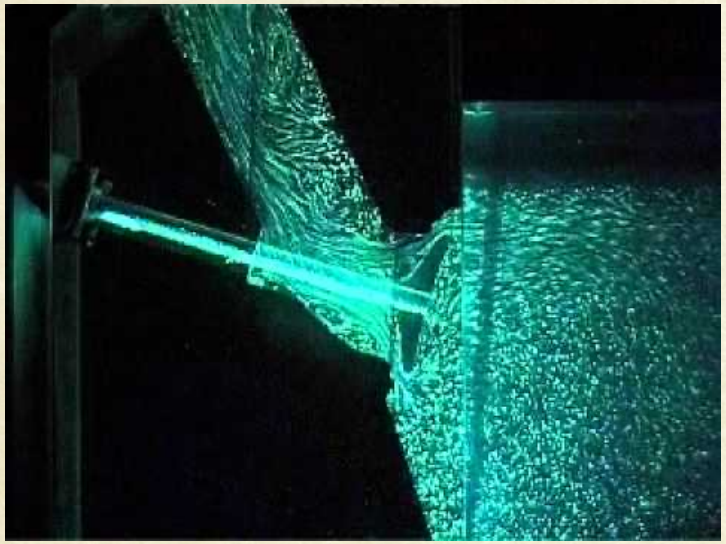
$$p(z) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(z-\bar{z})^2}{2\sigma^2}}$$

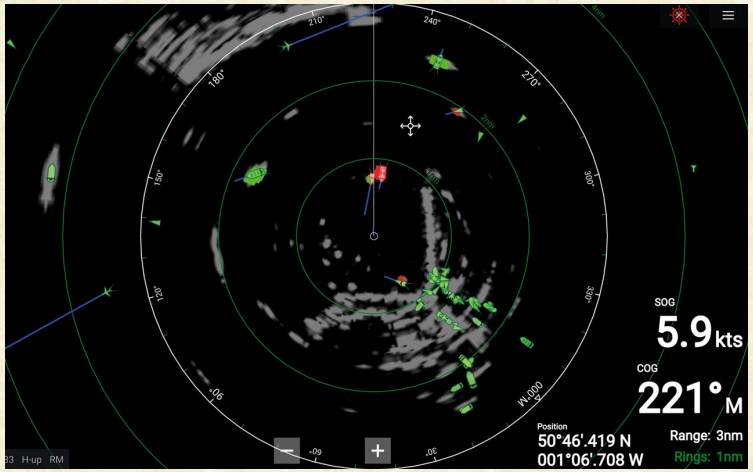


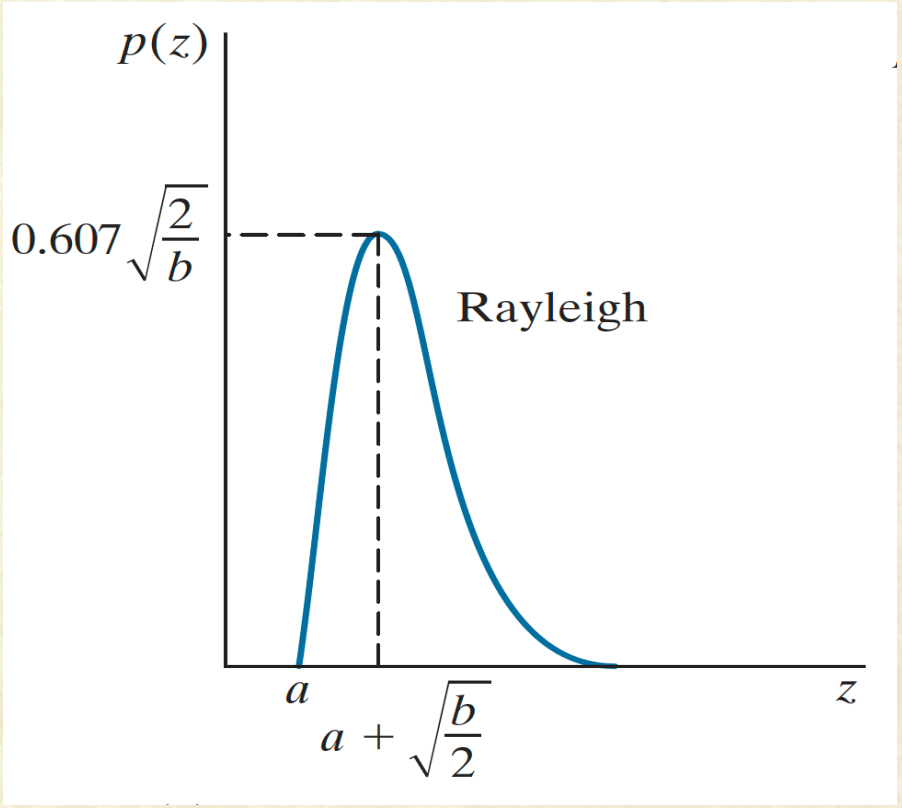
Noise Models: Rayleigh

$$p(z) = \begin{cases} \frac{2}{b}(z-a)e^{-\frac{(z-a)^2}{b}} & z \geq a \\ 0 & z < a \end{cases}$$

- Rayleigh Noise
  - Radar images
  - Velocity images







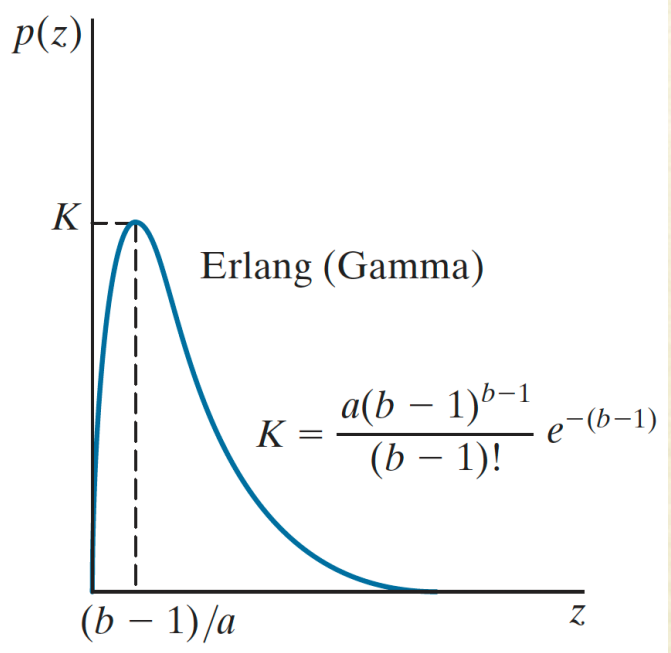
$$\bar{z} = a + \sqrt{\pi b/4}$$

$$\sigma^2 = \frac{b(4-\pi)}{4}$$

Other Noise Models

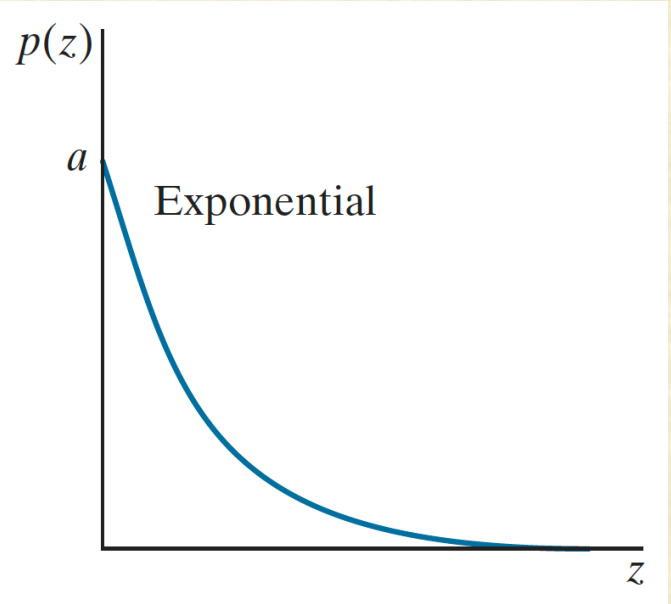
- Erlang (Gamma) Noise [Laser images]

$$p(z) = \begin{cases} \dfrac{a^b z^{b-1}}{(b-1)!} e^{-az} & z \geq 0 \\ 0 & z < 0 \end{cases}$$



- Exponential Noise

$$p(z) = \begin{cases} ae^{-az} & z \geq 0 \\ 0 & z < 0 \end{cases}$$



Noise Models

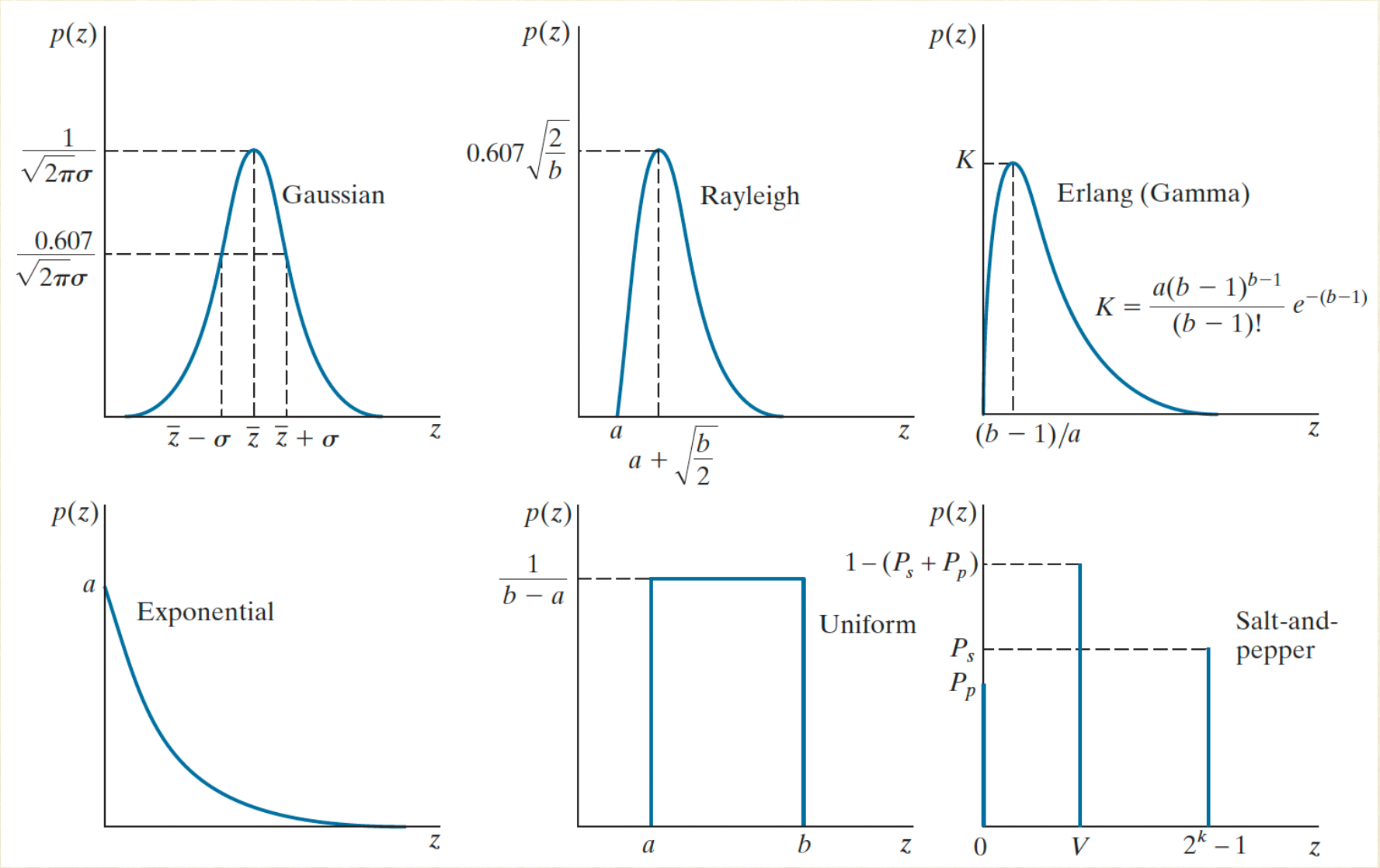


Illustration of Noise Models

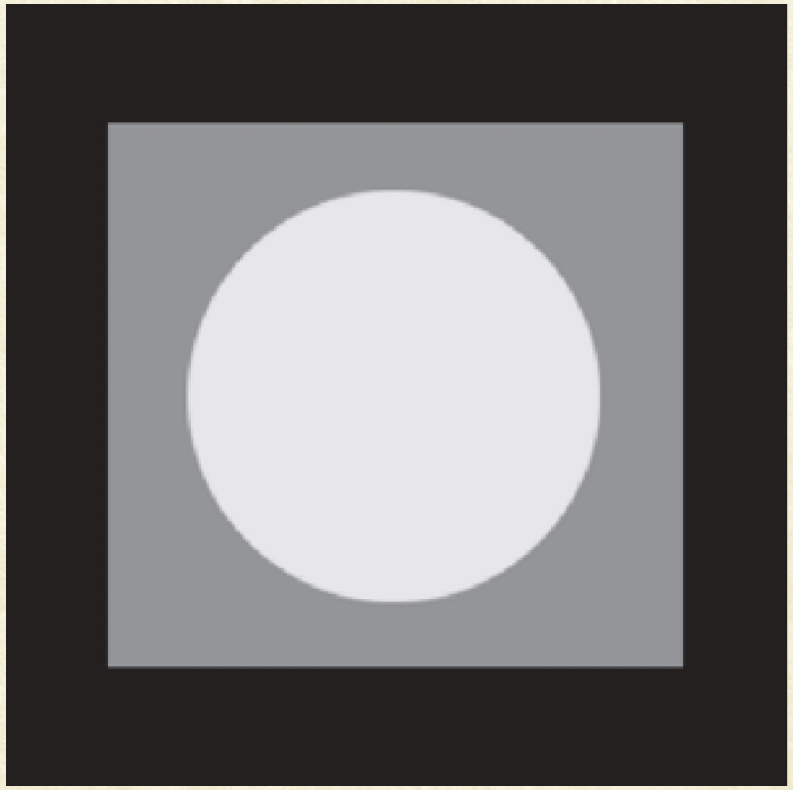
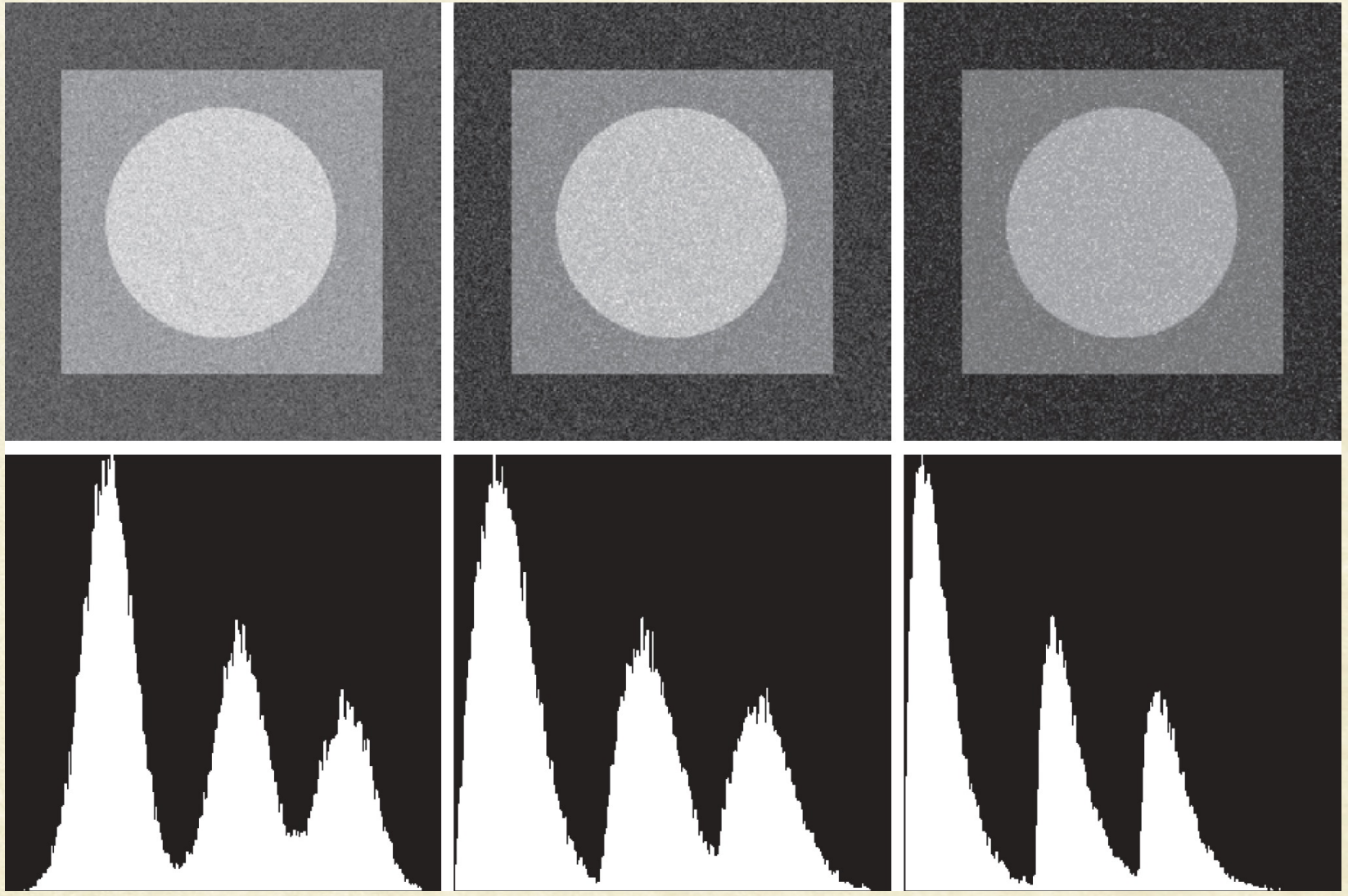


FIGURE 5.3 Test pattern used to illustrate the characteristics of the noise PDFs shown in Fig. 5.2.

Illustration of Noise Models

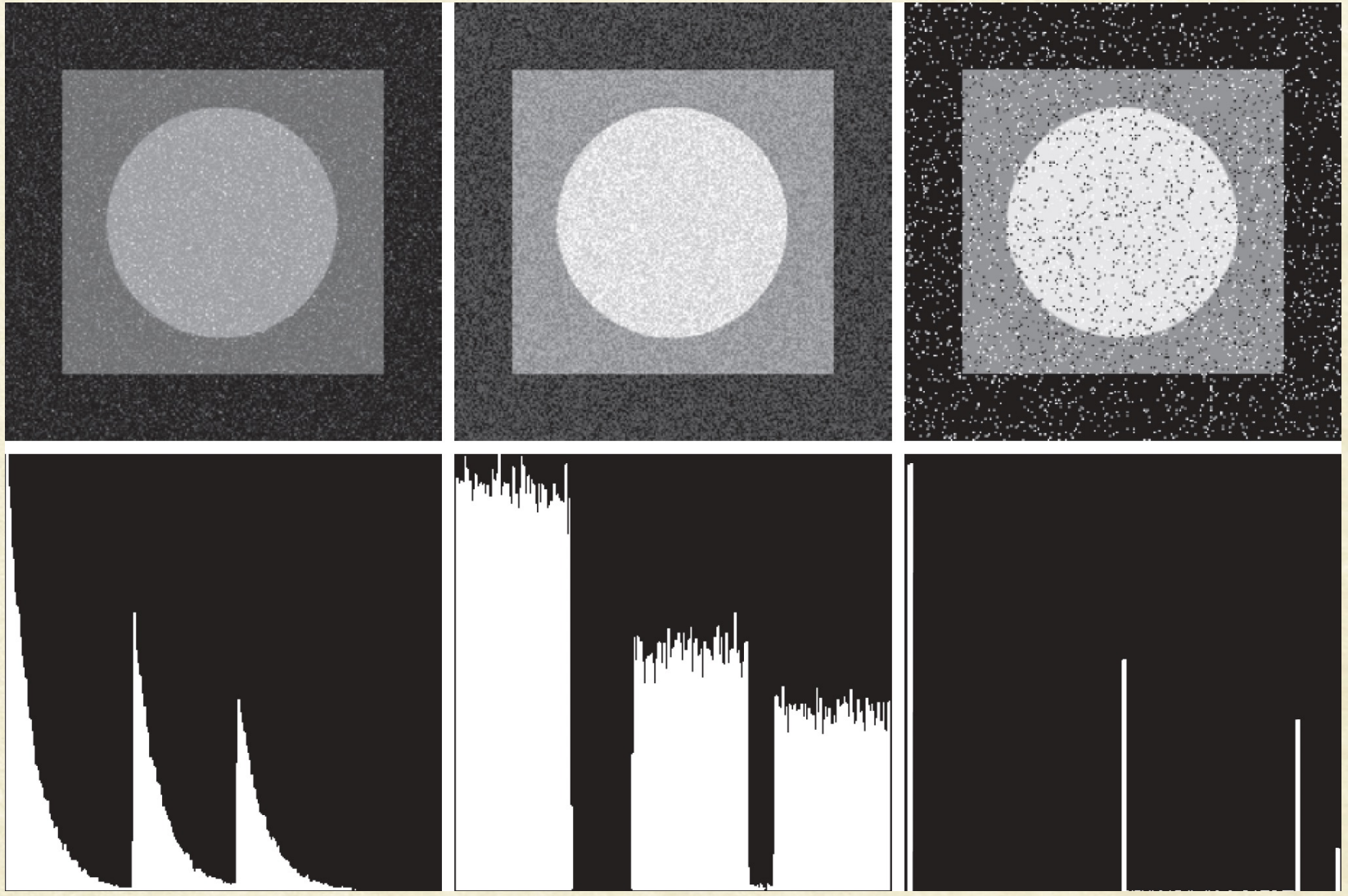
- Visually similar.
- Not easy to determine noise model from appearance



Gaussian Rayleigh Erlang

Illustration of Noise Models

- Visually similar.
- Not easy to determine noise model from appearance



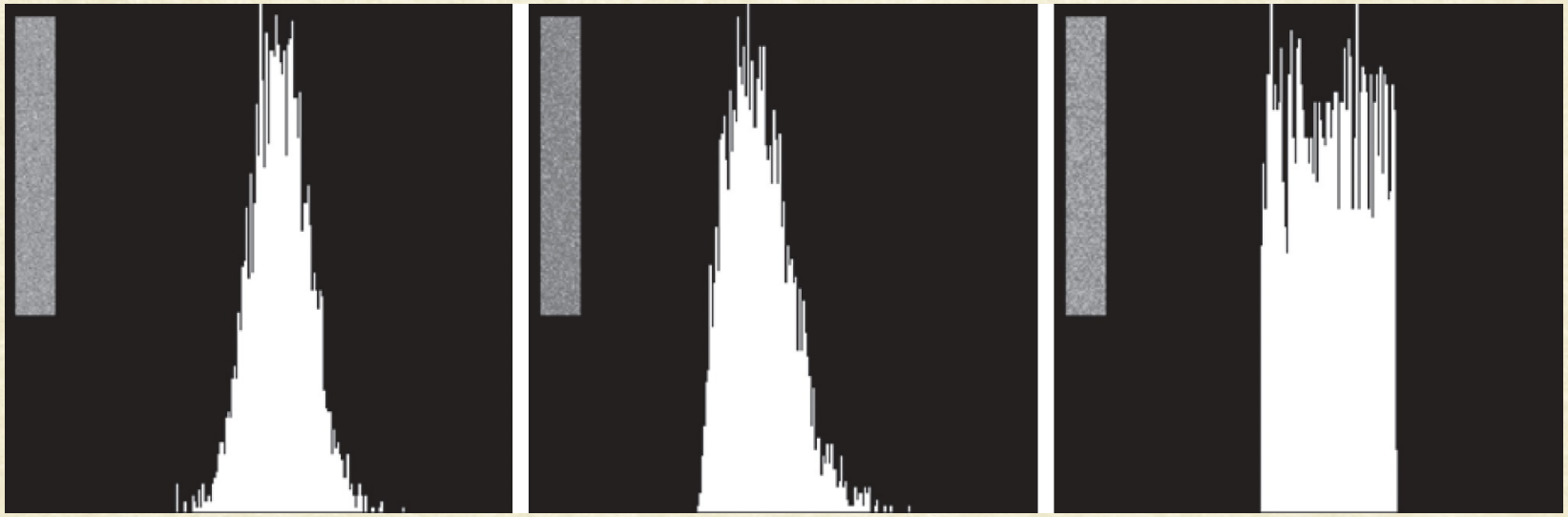
Exponential Uniform Salt & Pepper

Understanding System Noise

- Case 1: Imaging system available
  - Noise Calibration: Capture a set of ‘flat environments’ (e.g. solid gray board, object at fixed location)
  - Select the model with better statistical test scores (Akaike Information Criteria (AIC) or Likelihood Ratio Test (LRT))
  - Compute model parameters (mean, variance, etc.) from the statistics of pixel values.

Understanding System Noise

- Case 2: Only images available
  - Estimate from patches of constant intensity
  - For impulse noise, use a mid-gray patch/area



Gaussian Rayleigh Uniform

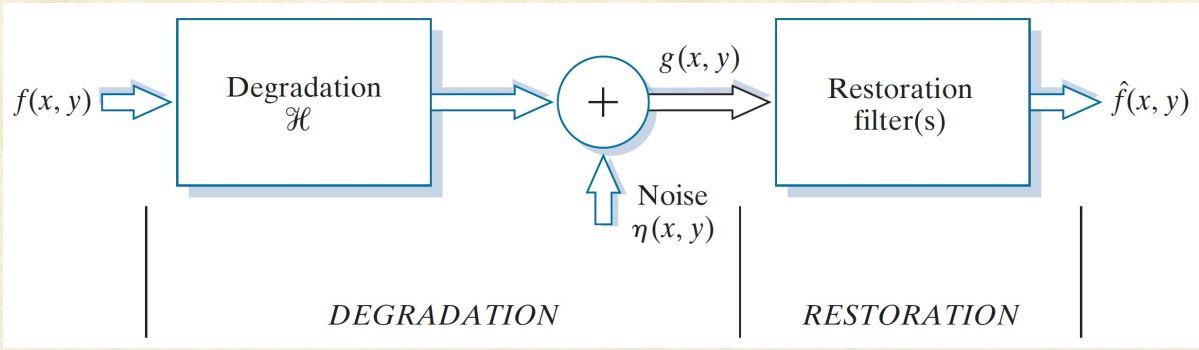
Restoration (in presence of noise only)

- Assuming ‘H’ is identity, the model reduces to:

$$g(x,y) = f(x,y) + \eta(x,y)$$

or

$$G(u,v) = F(u,v) + N(u,v)$$



Restoration (in presence of noise only)

- Mean filters
  - Arithmetic mean filter

$$\hat{f}(x,y) = \frac{1}{mn} \sum_{(r,c)\in S_{xy}} g(r,c)$$

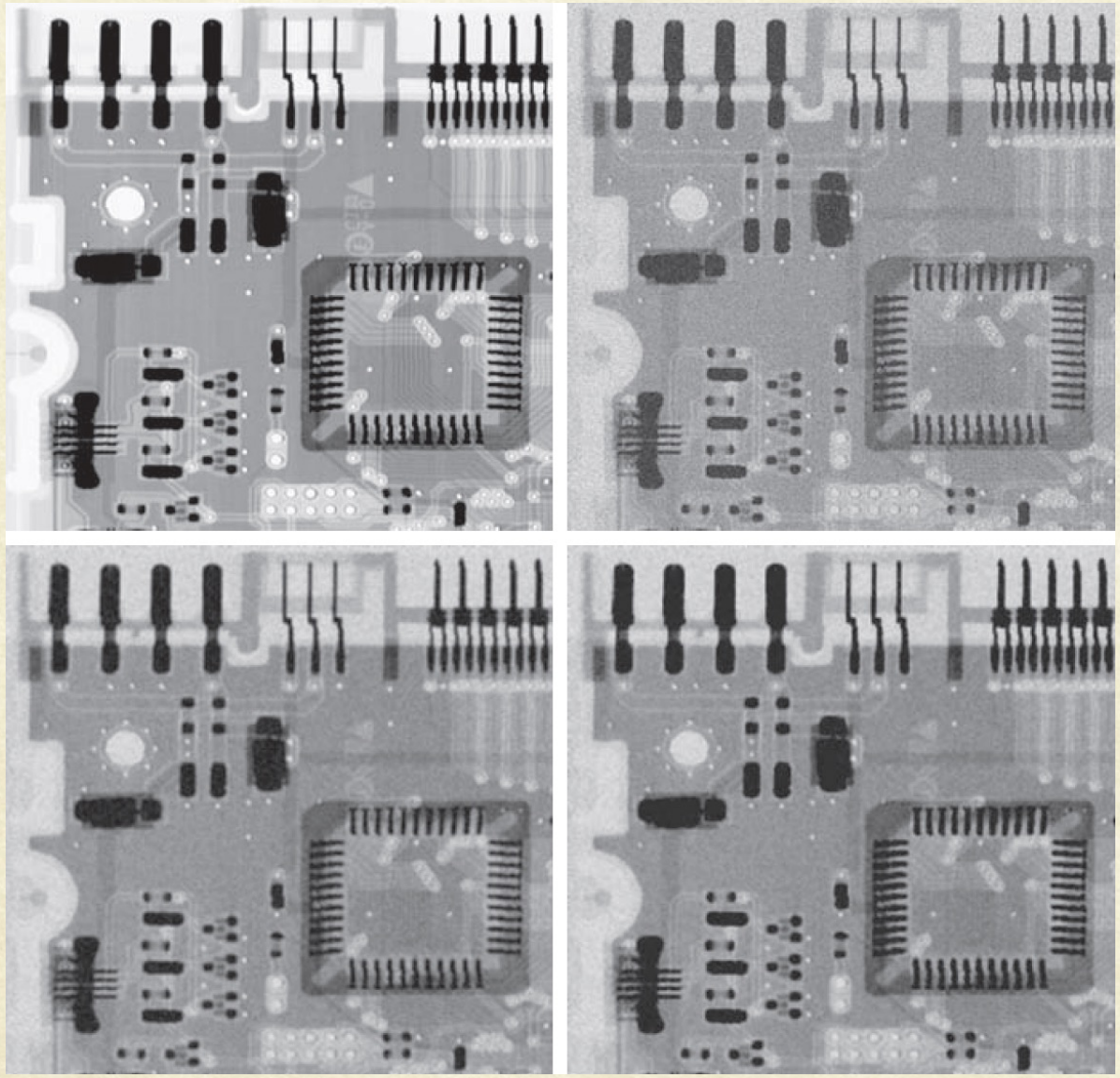
  - Geometric mean filter

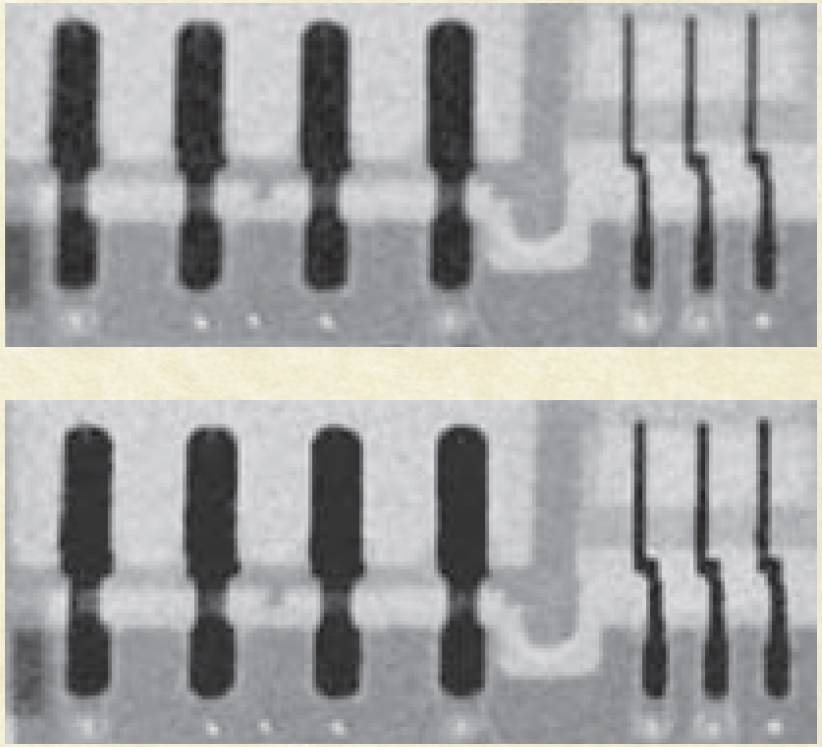
$$\hat{f}(x,y) = \left[\prod_{(r,c)\in S_{xy}} g(r,c) \right]^{\frac{1}{mn}}$$

Restoration (in presence of noise only)

a b
c d

FIGURE 5.7
(a) X-ray image of circuit board. (b) Image corrupted by additive Gaussian noise. (c) Result of filtering with an arithmetic mean filter of size 3×3. (d) Result of filtering with a geometric mean filter of the same size. (Original image courtesy of Mr. Joseph E. Pascente, Lixi, Inc.)





Restoration (in presence of noise only)

- Mean filters
  - Harmonic mean filter (Gaussian, Salt)

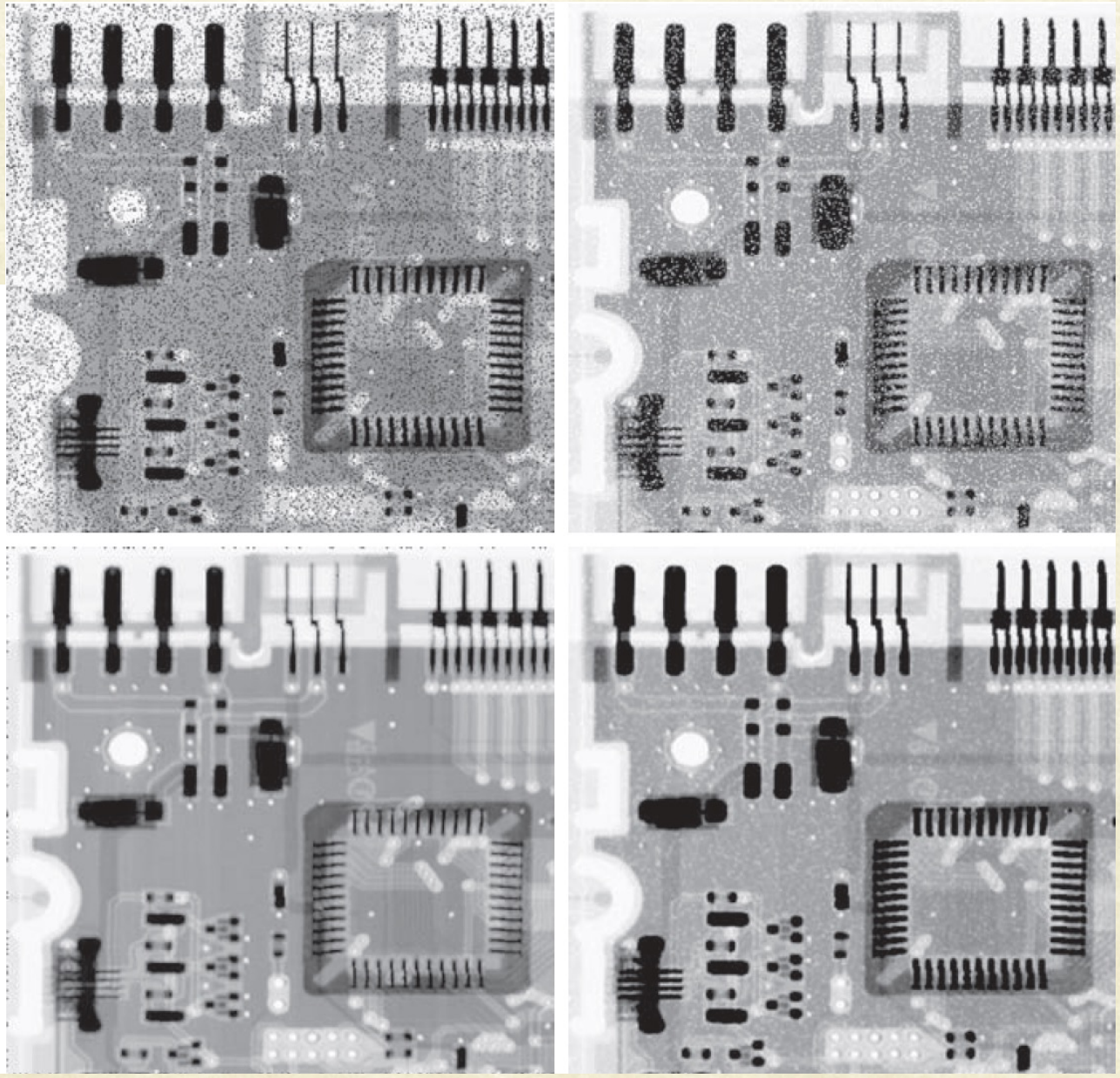
$$\hat{f}(x,y) = \frac{mn}{\sum_{(r,c)\in S_{xy}} \frac{1}{g(r,c)}}$$

  - Contraharmonic mean filter (Salt & Pepper)

$$\hat{f}(x,y) = \frac{\sum_{(r,c)\in S_{xy}} g(r,c)^{Q+1}}{\sum_{(r,c)\in S_{xy}} g(r,c)^{Q}}$$

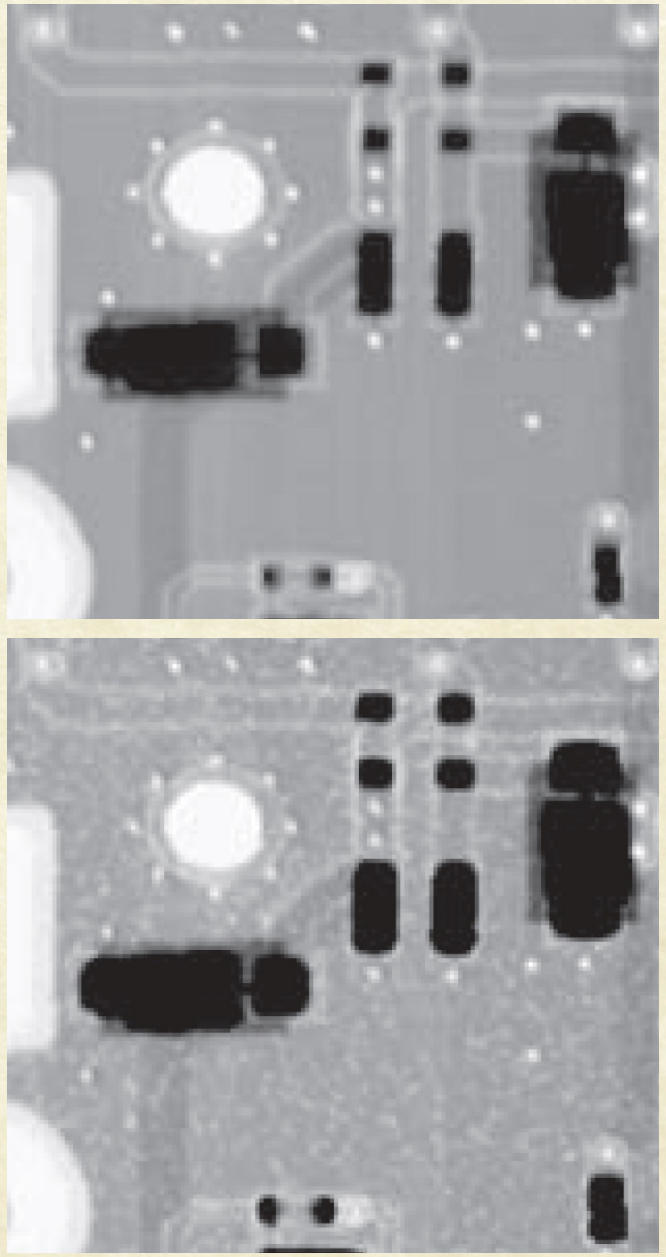
Q = *order* of the filter
Good for salt-and-pepper noise.
Eliminates pepper noise for $Q > 0$ and salt noise for $Q < 0$
NB: cf. arithmetic filter if $Q = 0$, harmonic mean filter if $Q = -1$

Restoration (in presence of noise only)



a b
c d

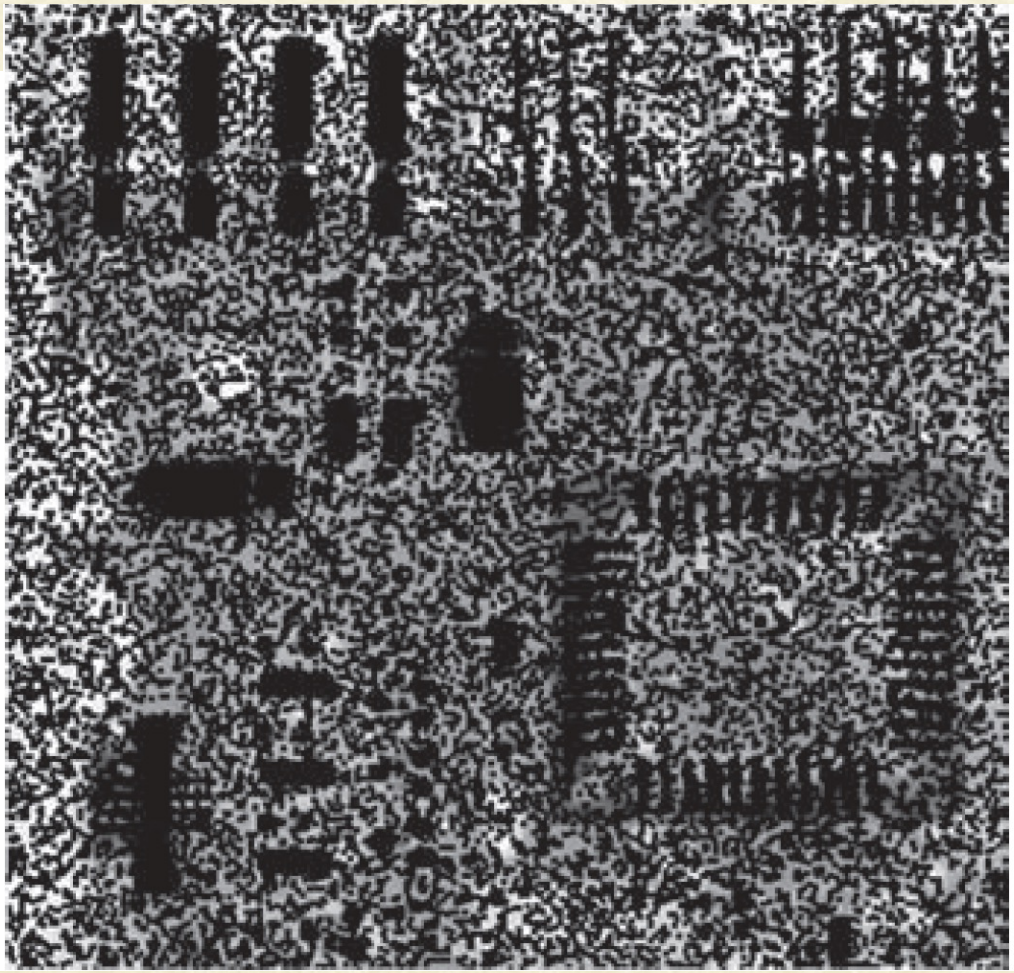
FIGURE 5.8
(a) Image corrupted by pepper noise with a probability of 0.1. (b) Image corrupted by salt noise with the same probability. (c) Result of filtering (a) with a 3×3 contra-harmonic filter $Q = 1.5$. (d) Result of filtering (b) with $Q = -1.5$.

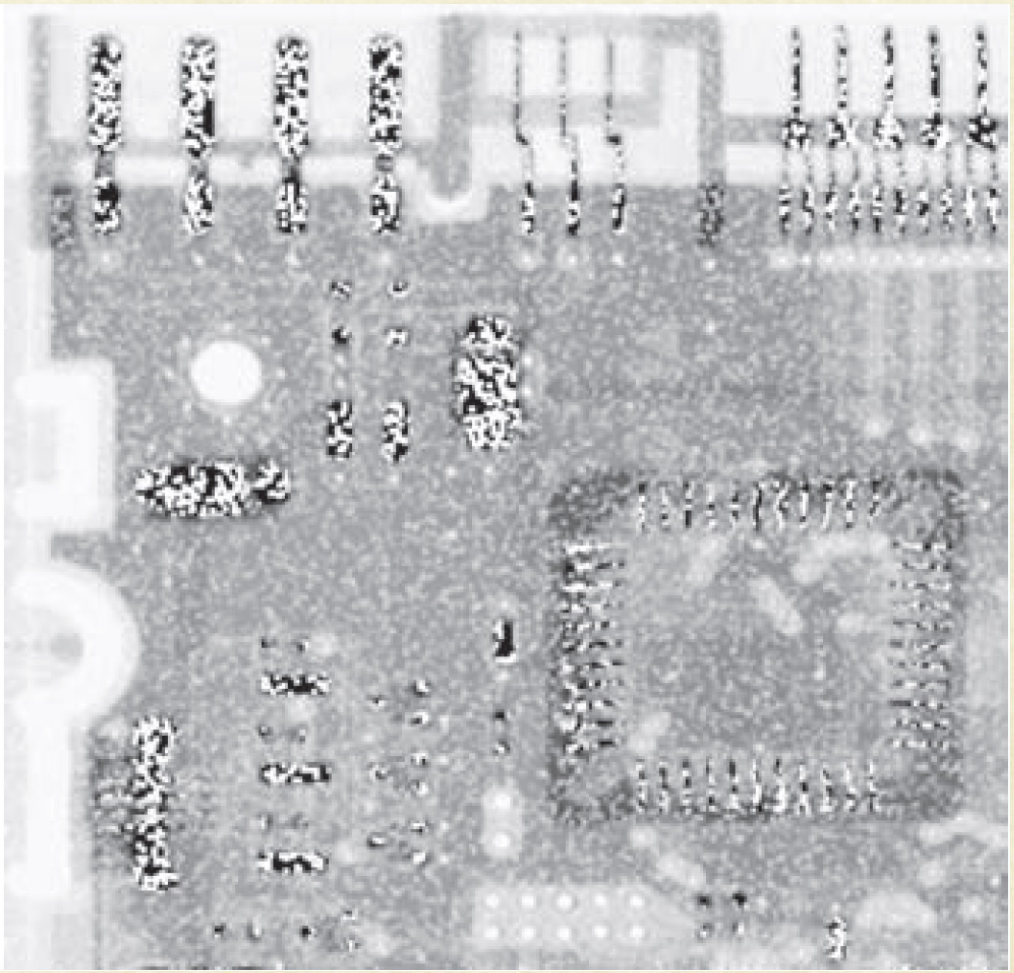


Restoration (in presence of noise only)

a b

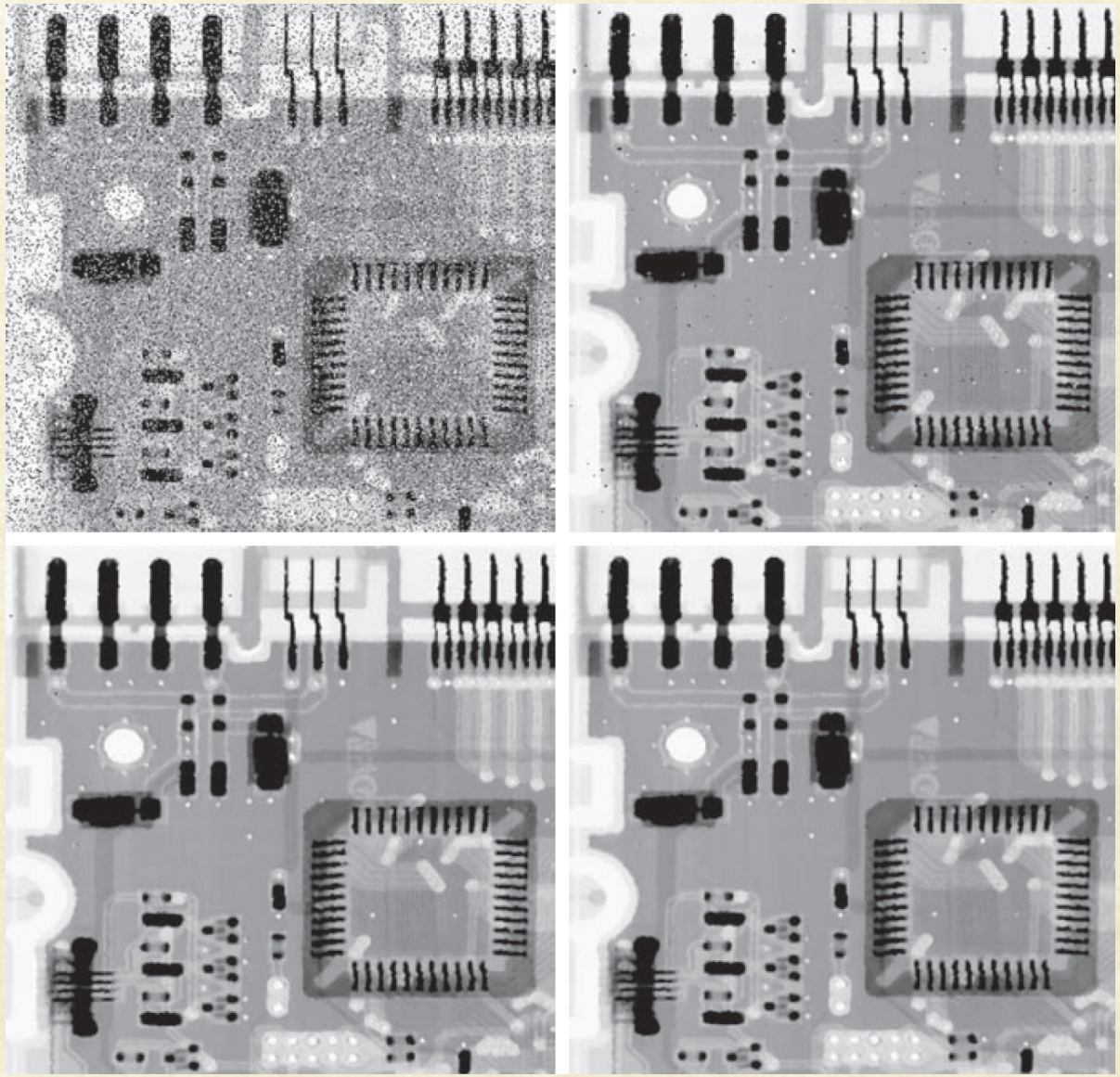
FIGURE 5.9
Results of selecting the wrong sign in contraharmonic filtering.
(a) Result of filtering Fig. 5.8(a) with a contraharmonic filter of size 3×3 and $Q = -1.5$.
(b) Result of filtering Fig. 5.8(b) using $Q = 1.5$.





Restoration (in presence of noise only)

- Median filter

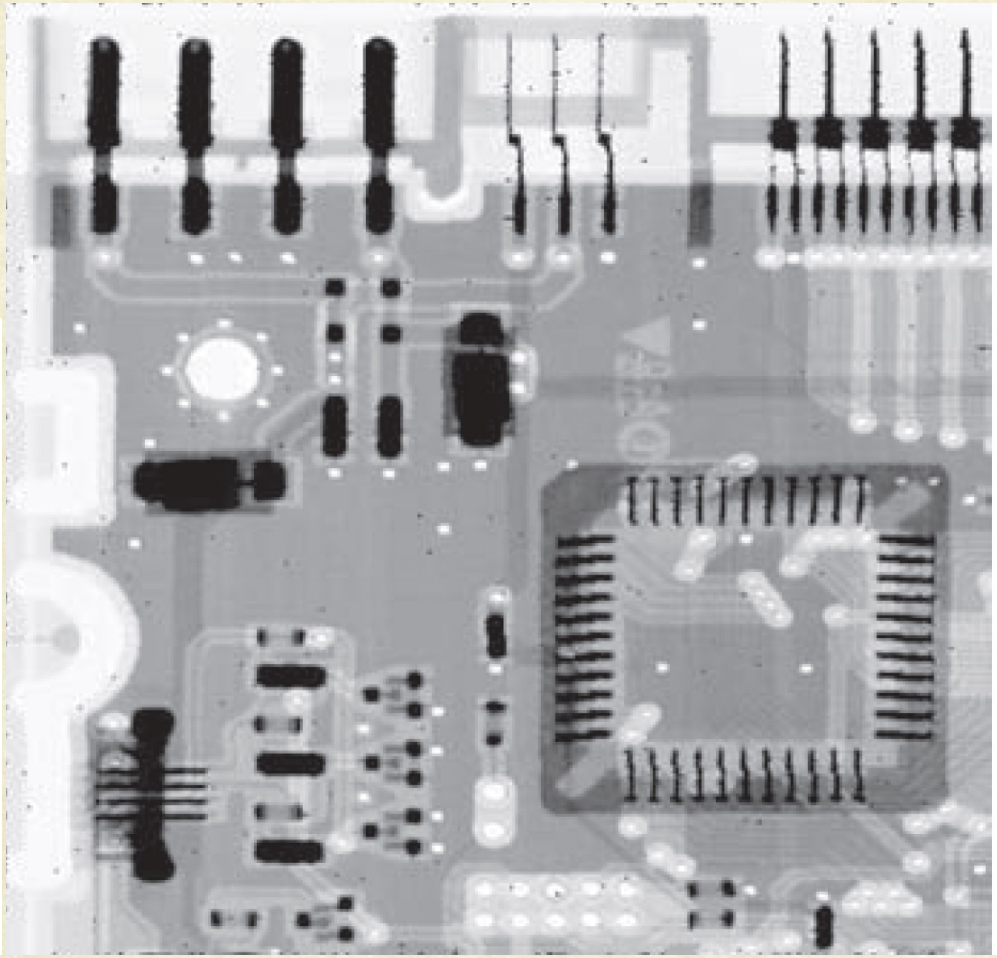


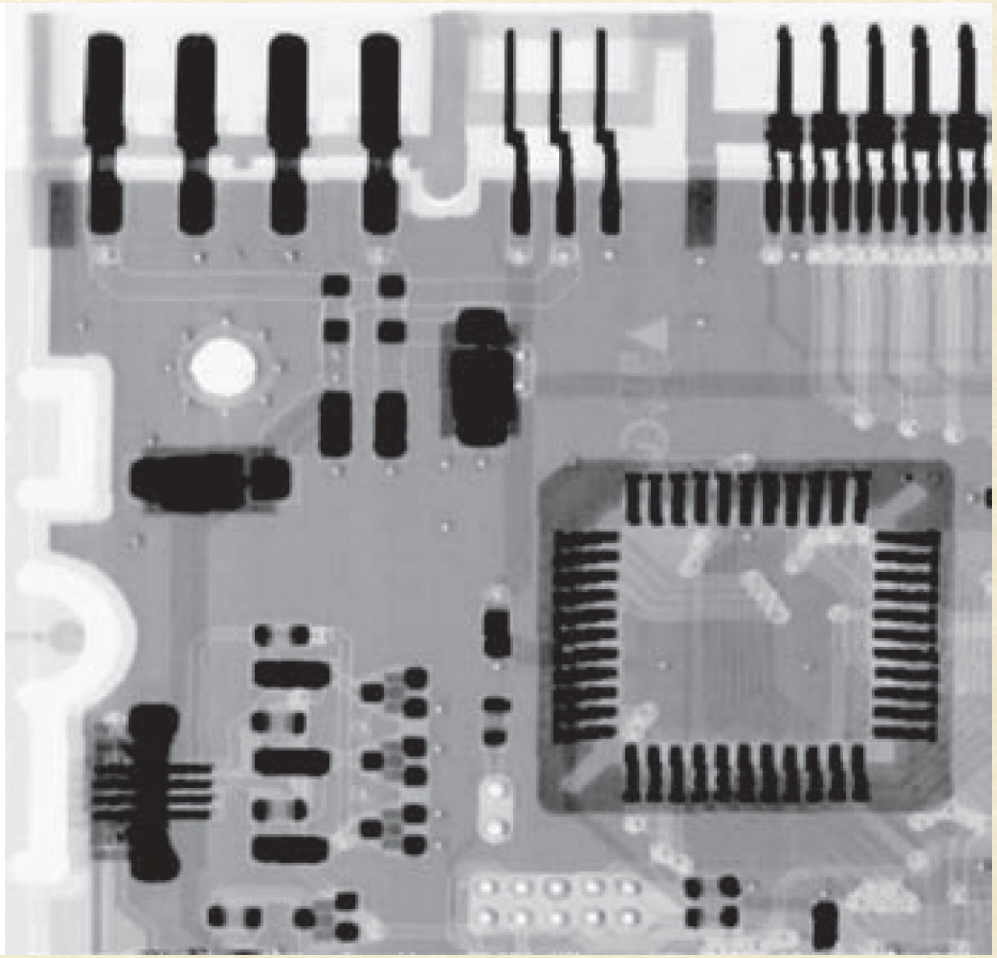
a b
c d

FIGURE 5.10
(a) Image corrupted by salt-and- pepper noise with probabilities $P_s = P_p = 0.1$. (b) Result of one pass with a median filter of size 3×3. (c) Result of processing (b) with this filter. (d) Result of processing (c) with the same filter.

Restoration (in presence of noise only)

- Max, Min filters





a b

FIGURE 5.11
(a) Result of filtering Fig. 5.8(a) with a max filter of size 3×3.
(b) Result of filtering Fig. 5.8(b) with a min filter of the same size.

Restoration (in presence of noise only)

- Midpoint filter

$$\hat{f}(x,y) = \frac{1}{2}\left[\max\{g(s,t)\}_{(s,t)\in S_{xy}} + \min\{g(s,t)\}_{(s,t)\in S_{xy}}\right]$$

Best for Uniform or Gaussian noise

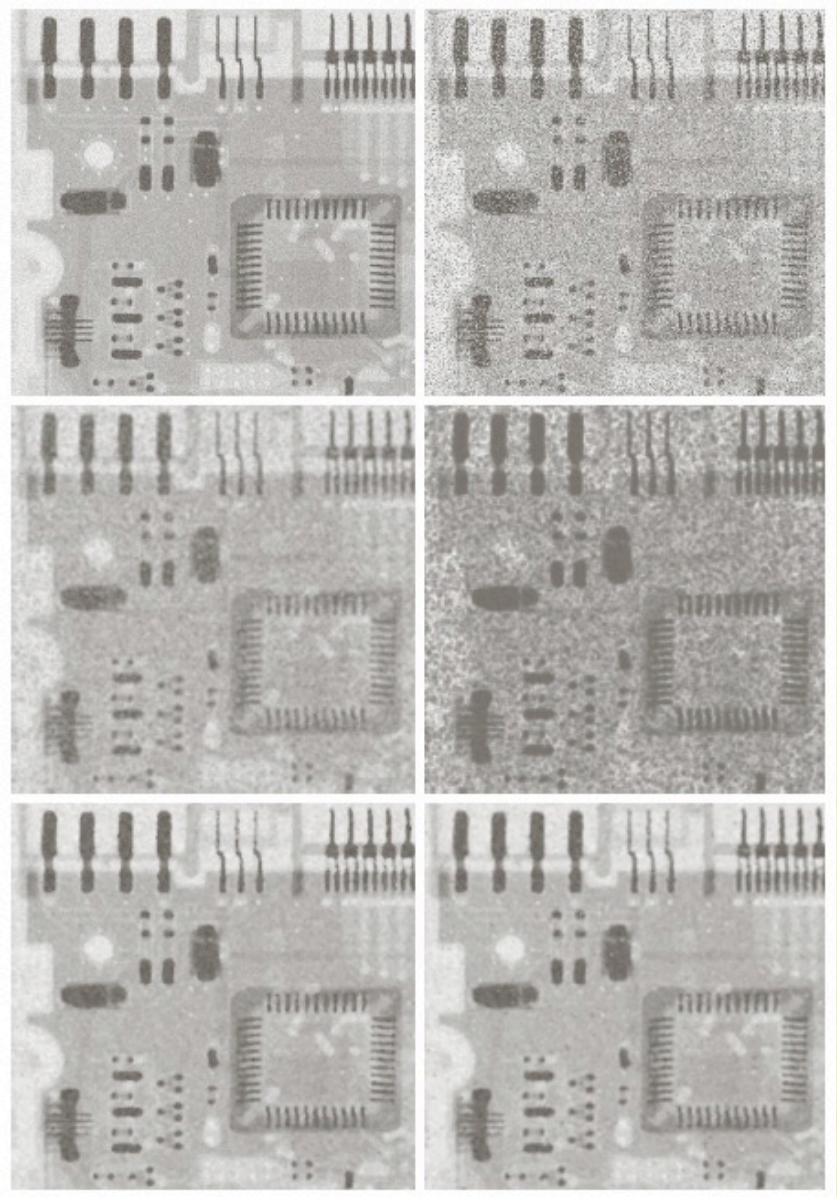
- Alpha trimmed filter

$$\hat{f}(x,y) = \frac{1}{mn-d}\sum_{(s,t)\in S_{xy}} g_r(s,t)$$

Where g_r represents the image *g* in which the *d/2* lowest and *d/2* highest intensity values in the neighbourhood S_{xy} were deleted

Restoration (in presence of noise only)

original



Original + salt and pepper noise

Arithmetic mean filter

Geometric mean filter

Median filter

Alpha Trimmed filter

Questions?