Digital Image Processing: Comprehensive Study Guide

Part 1: Detailed Study Guide

This study guide covers fundamental concepts in digital image processing, from image representation to advanced filtering techniques in both spatial and frequency domains.

Section 1: Image Representation and Basic Operations

1. **Digital Image Fundamentals:**

- **Image Formation:** Understand the process of converting a continuous image signal into a digital image.
- **Sampling:**
  - Definition: Discretizing the spatial coordinates of an image.
  - Parameters: Δx and Δy (sampling periods).
  - Impact: Influences spatial resolution.
- **Quantization:**
  - Definition: Discretizing the amplitude (intensity) of an image.
  - Impact: Influences gray-level resolution.
- **Image Types:**
  - Digital Gray Level Images: Represented by a single intensity value per pixel.
  - Digital Color Images: Composed of multiple color channels (e.g., R, G, B).
  - Digital Color Video: Adds a temporal axis to color images, creating a sequence of frames.
- **Image Coordinate Systems:**
  - Conventions: (x, y) vs. (r, c) (row, column).
  - Starting Index: 0 vs. 1.
  - Vertical axis usually pointing down.
- **Resolution:**
  - **Spatial Resolution:** Number of pixels per unit distance; impacts the smallest detectable detail.
  - **Gray-level/Intensity Resolution:** Number of bits per pixel; impacts the smallest detectable change in gray level.
  - **Contrast:** Difference between the highest and lowest gray level in an image.

1. **Single-Pixel Operations (Intensity Transforms):**

- **Definition:** Operations where the output value of each pixel depends solely on its initial intensity value.
- **Input and Output:** $r = I(x, y)$ (input gray level), $s = T(r)$ (output gray level).
- **Types of Operations:**
  - **Negative:** $s = (L - 1) - r$ (switches dark and light).
  - **Logarithm Transformation:** $s = c \log(1 + r)$; highlights differences among pixels in low-intensity regions.
  - **Gamma Transformation:** $s = c\, r^{\gamma}$; tunable, used for gamma correction in displays (e.g., CRT monitors) to compensate for non-linear light intensity.
  - **Contrast Stretching:** Enhances image contrast by mapping a specific range of input intensities to a wider range of output intensities using a set of segments.
  - **Thresholding:** Converts a grayscale image into a binary image based on a threshold Th. Pixels above Th get LH, and those below/equal get LL.
    - Equation: $\mathrm{T(r)} = \mathrm{L_L}\ \text{if}\ \mathrm{r} \le \mathrm{T_h},\ \mathrm{L_H}\ \text{if}\ \mathrm{r} > \mathrm{T_h}$.

Section 2: Image Histograms and Enhancement

1. **Image Histograms:**

- **Definition:** A graphical representation of the distribution of intensity values in an image.
- **Evaluation:** $p(r_k) = h(r_k)/MN = n_k/MN$, where n_k is the number of pixels with intensity r_k, $M \times N$ is the total number of pixels. Can be treated as a Probability Density Function (PDF).
- **Cumulative Distribution Function (CDF):** $F_X(x) = P(X \leq x)$.
- **Applications:** Image statistics, compression, segmentation, image enhancement.

1. **Histogram Equalization:**

- **Definition:** A process that flattens the image histogram, distributing intensity values more uniformly across the full range.
- **Equalization Function:** The transformation function $T(r)$ is the CDF multiplied by $(L-1)$.
    - Discrete CDF: $\mathrm{s_k} = \mathrm{T(r_k)} = (\mathrm{L}-1) \sum_{\mathrm{j}=0}^{\mathrm{k}} p_r(r_j)$
- **Properties of T(r):** Monotonically non-decreasing, bounded ($0 \leq T(r) \leq L-1$), continuous and differentiable (for continuous signals).
- **Impact:** Increases the overall contrast of images, especially when the usable data is represented by a narrow range of intensities.

1. **Histogram Specification (Matching):**

- **Definition:** A process to transform the histogram of an image to a *desired* specific shape, rather than just flattening it.

1. **Process:** Equalize the input image histogram to get $s_k = T(r_k)$.
2. Define the desired output Probability Mass Function (PMF) $p_z(z_i)$ and evaluate its corresponding CDF $s_q = G(z_q)$.
3. Obtain the inverse transformation $z_q = G^{-1}(s_q)$.
4. Apply the inverse mapping: $z = G^{-1}(s)$.

- **Use Cases:** When a specific distribution is desired for particular applications, or when equalization is unsuitable (e.g., too many pixels with low gray levels).

Section 3: Spatial Filtering

1. **Local Operations / Spatial Filtering:**

- **Definition:** Operations where the output value of a pixel depends on the initial values of the pixel *and* its neighbors.
- **Kernel/Spatial Filter:** Defines the neighborhood and the operation/weights applied to the pixels within that neighborhood.
- **Types:** Linear (convolution) and Non-linear (min, max, median).

1. **Convolution and Correlation:**

- **Convolution Formula (2D discrete):** $g(x,y) = \sum_{s=-a}^{a} \sum_{t=-b}^{b} w(s,t) I(x-s, y-t)$.
- **Correlation Formula (2D discrete):** $g(x,y) = \sum_{s=-a}^{a} \sum_{t=-b}^{b} w(s,t) I(x+s, y+t)$.
- **Distinction:** In computer vision, often used synonymously, especially for symmetric filters where they are equivalent. Filters obtained by convolution are called convolutional filters.
- **Application:** Filter superimposed on each pixel, weighted average calculated.
- **Brightness Preservation:** Brightness is unchanged if the sum of kernel weights $\sum w_i = 1$; otherwise, normalization is needed.

1. **Linear Filters:**

- **Averaging (Smoothing) Filters:** Calculate the average of pixel values in a neighborhood.
  - Masks typically have equal weights (e.g., a 3x3 kernel with all 1s, normalized by 1/9).
  - Larger filters result in stronger smoothing. Used for noise reduction.
- **Derivative (Sharpening) Filters:** Highlight intensity transitions (edges).
  - **First Order Derivative:**
    - Properties: Zero in flat segments, non-zero at step/ramp onsets, non-zero along ramps.
    - Discrete implementation: $f(x+1) - f(x)\ or\ \big(f(x+1) - f(x-1)\big)/2$.
    - Kernels: E.g., $[1, -1]\ or\ [-1, 1]$. Sensitive to noise.
    - **Gradient:** Highlights elements where the gradient is significant.
    - Sobel filters are common for noise rejection (larger kernels).
  - **Second Order Derivative:**
    - Properties: Zero in flat segments, non-zero at onset and end of step/ramp, zero along ramps of constant slope.
    - Discrete implementation: $f(x+1) + f(x-1) - 2f(x)$.
    - **Laplacian Filter:** Implements $\nabla^2 f(x, y) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}$.
    - Discrete mask: Typically [[0, 1, 0], [1, -4, 1], [0, 1, 0]] or similar with diagonals.
    - Used to enhance transitions and for image sharpening (often combined with the original image).

1. **Non-linear Filters:**

- **Definition:** Implement non-linear operations (e.g., min, max, median).
- **Advantages over Linear:** Can suppress "spikes" or impulse noise (e.g., salt-and-pepper noise) more effectively while preserving edges.
- **Types:**
  - **Min Filter:** Replaces pixel with the minimum value in its neighborhood. Removes salt noise, highlights pepper noise.
  - **Max Filter:** Replaces pixel with the maximum value in its neighborhood. Removes pepper noise, highlights salt noise.
  - **Median Filter:** Replaces pixel with the median value in its neighborhood. Highly effective at removing salt-and-pepper noise while preserving edge sharpness.

1. **Image Restoration (Noise Removal):**

- **Noise Models:** Important to understand noise properties (e.g., Gaussian, salt-and-pepper).
- **Restoration Techniques:**
  - **Smoothing Filters:** Averaging, Gaussian filter (effective for Gaussian noise).
  - **Non-linear Filters:** Median, Min, Max filters (effective for salt-and-pepper noise).
  - **Types of Averaging Filters:** Arithmetic mean, Geometric mean, Harmonic mean, Contraharmonic mean, Alpha-trimmed mean.
    - Harmonic < Geometric < Arithmetic mean in general.
    - Alpha-trimmed mean is a hybrid between mean and median, removing a specified number of lowest and highest values before averaging.
  - **Adaptive Filters:** Tune their effect based on local image variance (σ_L^2) and noise variance (σ_η^2).
    - Weak when $\sigma_\eta^2 \ll \sigma_L^2$ (e.g., near edges) to preserve detail.
    - Strong when $\sigma_\eta^2 \approx \sigma_L^2$ (e.g., in uniform regions) to effectively remove noise. Examples: Adaptive mean, Adaptive median.

Section 4: The Bilateral Filter

1. **Overview:**

- A commonly used, relatively recent spatial filter.
- **Edge-preserving filter:** Unlike Gaussian filters, it smooths images while preserving sharp edges.
- Based on Gaussian filter principles.

1. **Mechanism:**

- Calculates a weighted average of pixels.
- **Two weighting factors:**
    - **Space Gaussian (G_{σ_s}):** Depends on geometrical distance; *decreases the influence of distant pixels* (standard Gaussian blur component).
    - **Range Gaussian (G_{σ_r}):** Depends on gray-level distance; *decreases the influence of pixels with significantly different intensity values from the center pixel*.
- **Combined Effect:** Pixels are weighted less if they are far away *or* if their intensity is very different from the central pixel, allowing edges to remain sharp.
- **Kernel Shape:** The kernel shape (weights) depends on the image content (pixel intensities).

Section 5: Geometric Transformations

1. **Definition:**

- Modification of the spatial relationship among pixels.
- Involves two steps:

1. **Coordinate Transform:** $(x', y') = T(x, y)$.
2. **Image Resampling:** Determining pixel values for the new coordinates.

1. **Homogeneous Coordinates:**

- A "mathematical trick" to express planar transformations as matrix multiplications.
- A 2D point (x, y) is represented as (wx, wy, w) or commonly $(x, y, 1)$.
- Enables combining multiple transformations (e.g., translation, rotation, scaling) into a single matrix.

1. **Basic Planar Transformations in Homogeneous Coordinates:**

- **Translation:** Shifts an image.
    - Matrix: $1 \& 0 \& b\_1 \;\; 0 \& 1 \& b\_2 \;\; 0 \& 0 \& 1$ (where b_1, b_2 are translation amounts).
- **Affine Transform:** A more generic transformation, combining a linear transform and a translation.
    - Preserves point collinearity and distance ratios along a line.
    - Matrix: $t\_\{11\} \& t\_\{12\} \& t\_\{13\} \;\; t\_\{21\} \& t\_\{22\} \& t\_\{23\} \;\; 0 \& 0 \& 1$.

Section 6: Images in the Frequency Domain

1. **Fourier Transform:**

- **Purpose:** A mathematical tool for analyzing signals in the frequency domain. Transforms a signal from its original domain (e.g., time, space) to a frequency domain.
- **Image Fourier Transform:** Transforms spatial coordinates (x, y) to spatial frequencies $\left(f_x, f_y\right)$ or (u, v).
- **FFT (Fast Fourier Transform):** An efficient algorithm for computing the Discrete Fourier Transform.
- **Effect of Sampling:** In the frequency domain, sampling causes the original signal's spectrum to be replicated.
- **Image Reconstruction:** Involves isolating one replica of the spectrum in the frequency domain (e.g., using a rect function) and then applying the inverse Fourier transform.
- **Rect Function & Sinc Function:** The Fourier transform of a rectangular function (rect) is a sinc function.

1. **Aliasing and Moiré Effect:**

- **Aliasing:** Occurs when the sampling rate is too low (undersampling), causing replicas of the spectrum to overlap in the frequency domain. This results in misrepresentation of high-frequency components as lower frequencies in the reconstructed signal.
- **Moiré Effect:** Caused by the beating of similar patterns (e.g., gratings with similar spacing). It is not directly related to aliasing (no undersampling involved) but can produce visually similar patterns.

1. **Filtering in the Frequency Domain:**

- **Advantages:** Allows for direct manipulation of frequency components. Convolution in the spatial domain becomes multiplication in the frequency domain (simplifies computation).
- **Process:**

1. Compute the Fourier Transform of the image.
2. Multiply the transformed image by a filter function in the frequency domain.
3. Compute the Inverse Fourier Transform to get the filtered image in the spatial domain.

- **Zero-frequency:** Located at the center of the frequency domain representation.
- **Spatial Mask Derivation:** The spatial filter (kernel) corresponding to a frequency domain filter can be obtained by applying the inverse Fourier transform to the frequency filter.

1. **Types of Frequency Filters:**

- **Low-Pass Filters (Smoothing):** Allow low frequencies to pass, block high frequencies.
    - Result: Smoothes images, reduces noise, blurs edges.
    - **Ideal Low-Pass Filter (ILPF):** Sharp cutoff. Causes "ringing artifacts" (oscillations around edges) due to its discontinuities in the frequency domain.
    - **Butterworth Low-Pass Filter:** Smoother transition than ILPF; reduces ringing artifacts. Tunable by parameter 'n' (order).
    - **Gaussian Low-Pass Filter:** Very smooth transition; causes no ringing artifacts. Best for smoothing and noise reduction without severe artifacts.
- **High-Pass Filters (Sharpening):** Allow high frequencies to pass, block low frequencies.
    - Obtained by: $H_{HP}(u, v) = 1 - H_{LP}(u, v)$.
    - Result: Sharpen images, enhance edges, highlight details.
    - **Ideal, Butterworth, Gaussian High-Pass Filters:** Exhibit similar characteristics (e.g., ringing) as their low-pass counterparts.

- **Selective Filters:**
  - **Band-Reject Filter:** Blocks a specific range of frequencies (e.g., to remove periodic noise).
  - **Band-Pass Filter:** Allows a specific range of frequencies to pass.
  - **Notch Filter:** Blocks frequencies at specific locations (often used to remove specific noise frequencies).

Part 2: Quiz

Instructions: Answer each question in 2-3 sentences.

1. Explain the fundamental difference between sampling and quantization in digital image formation.
2. How does spatial resolution differ from gray-level resolution, and what visual impact does each have on an image?
3. Describe what a single-pixel operation is. Give one example and explain its effect on image intensity.
4. What is the purpose of histogram equalization, and what mathematical function is primarily used to achieve it?
5. Distinguish between image contrast stretching and thresholding as single-pixel operations.
6. Define a local operation in image processing. What is the role of a "kernel" in such operations?
7. What is the main advantage of using non-linear filters (like the median filter) over linear filters (like the averaging filter) for image restoration?
8. Explain the concept of an edge-preserving filter, and how the bilateral filter achieves this property.
9. In the context of image processing, what are homogeneous coordinates, and why are they useful for geometric transformations?
10. Describe the phenomenon of "aliasing" in images, referencing its cause in the frequency domain.

Part 3: Quiz Answer Key

1. **Sampling** discretizes the spatial coordinates of a continuous image, determining its spatial resolution (pixels per unit distance). **Quantization**, on the other hand, discretizes the amplitude or intensity values, affecting the gray-level resolution (bits per pixel). Sampling determines *where* pixels are, while quantization determines *what value* each pixel can have.
2. **Spatial resolution** refers to the number of pixels per unit distance and influences the smallest detectable detail in an image, affecting image sharpness and clarity. **Gray-level resolution** is the number of bits used per pixel to represent intensity, determining the smallest detectable change in gray level and impacting the image's ability to represent smooth tonal variations without banding.
3. A **single-pixel operation** is an image transformation where the output value of each pixel depends solely on its initial intensity value. For example, a **negative image** transform ($s = L - 1 - r$) inverts the intensity values, making light areas dark and dark areas light, similar to a photographic negative.
4. The purpose of **histogram equalization** is to enhance the contrast of an image by redistributing its intensity values to span the full range more uniformly. It is primarily achieved using the **Cumulative Distribution Function (CDF)** of the image's intensity values, scaled by (L-1), as the transformation function.
5. **Contrast stretching** is a single-pixel operation used to enhance the overall contrast of an image by mapping a narrow range of input intensities to a wider range of output intensities. **Thresholding**, conversely, converts a grayscale image into a binary (black and white) image by setting all pixels below a certain intensity threshold to one value (e.g., black) and all pixels above it to another (e.g., white).

6. A **local operation** in image processing computes the output value of a pixel based on the initial values of that pixel and its neighboring pixels. A **kernel** (or spatial filter) defines this neighborhood and the specific weights or operations to be performed on the pixel values within that neighborhood.
7. The main advantage of **non-linear filters** (like the median filter) over **linear filters** (like the averaging filter) for image restoration is their superior ability to suppress impulse noise (e.g., salt-and-pepper noise) while preserving edge sharpness. Linear filters tend to blur edges along with noise, whereas non-linear filters can selectively remove extreme values without smearing fine details.
8. An **edge-preserving filter** is designed to smooth regions of an image while maintaining the sharpness of edges. The **bilateral filter** achieves this by using two Gaussian weighting factors: one based on spatial distance (standard Gaussian blur) and another based on intensity difference. This means pixels are only averaged if they are both spatially close *and* have similar intensity values, preventing blurring across intensity boundaries (edges).
9. **Homogeneous coordinates** are a mathematical construct that represents a 2D point (x, y) as a 3D vector (wx, wy, w), commonly $(x, y, 1)$. They are useful for geometric transformations because they allow complex operations like translation, rotation, and scaling to be expressed as a single matrix multiplication, simplifying the composition of multiple transformations.
10. **Aliasing** in images is a visual artifact that occurs when a continuous image is sampled at too low a rate (undersampling), causing high-frequency components (fine details or rapid intensity changes) to be misrepresented as lower frequencies. In the frequency domain, this happens when the replicated spectra of the sampled signal overlap, leading to a loss of information and visible distortions.

Part 5: Glossary of Key Terms

- **Adaptive Filters:** Image filters that automatically adjust their behavior (e.g., filter strength) based on local image characteristics, such as local variance compared to noise variance.
- **Affine Transform:** A geometric transformation that preserves point collinearity (points on a line remain on a line) and distance ratios along a line. It combines linear transformations (scaling, rotation, shear) with translation.
- **Aliasing:** A distortion or artifact introduced when a continuous signal is sampled at a rate too low to capture all its high-frequency components, causing high frequencies to appear as lower frequencies in the reconstructed signal.
- **Alpha-trimmed Mean Filter:** A non-linear averaging filter that removes a specified number of the lowest and highest intensity values within a neighborhood before calculating the mean, making it robust against certain types of noise while still performing smoothing.
- **Averaging Filter:** A linear spatial filter that smooths an image by replacing each pixel's value with the average of its neighbors, effective for reducing Gaussian noise but can blur edges.
- **Band-Reject Filter:** A frequency domain filter designed to block (attenuate) a specific range of frequencies while allowing others to pass, useful for removing periodic noise.
- **Bilateral Filter:** An edge-preserving spatial filter that smooths an image by computing a weighted average of pixel values, where weights depend on both spatial distance and intensity difference.
- **Butterworth Filter:** A frequency domain filter (can be low-pass or high-pass) characterized by a smooth transition between passed and blocked frequencies, which helps to reduce ringing artifacts compared to ideal filters.
- **Contrast:** The difference between the highest and lowest intensity (gray level) values in an image, influencing the discernible range of tones.
- **Contrast Stretching:** A single-pixel operation that enhances the contrast of an image by mapping a narrow range of input intensity values to a wider range of output intensity values.
- **Convolution:** A mathematical operation used in linear spatial filtering, where a kernel (filter mask) is systematically applied across an image to produce a new pixel value based on a weighted sum of its neighbors.
- **Correlation:** A mathematical operation similar to convolution, where a kernel is applied across an image, but without the kernel being flipped. Often used synonymously with convolution in image processing for symmetric filters.

- **Cumulative Distribution Function (CDF):** In the context of image histograms, the CDF at a given intensity level represents the probability that a pixel's intensity value is less than or equal to that level. It's crucial for histogram equalization.
- **Derivative Filters:** Spatial filters (linear) designed to highlight regions of rapid intensity change (edges) by approximating image derivatives. Examples include gradient and Laplacian filters.
- **Digital Color Image:** An image composed of multiple channels (e.g., Red, Green, Blue) to represent color, where each channel is a digital gray-level image.
- **Digital Gray Level Image:** An image where each pixel is represented by a single numerical value indicating its intensity or brightness, typically ranging from black to white.
- **Dirac Delta Function:** A mathematical construct used in sampling theory, representing an infinitely narrow impulse with an area of one, typically zero everywhere except at a single point.
- **Edge-Preserving Filter:** A type of image filter that aims to reduce noise and smooth image regions while maintaining sharp transitions (edges) between different objects or areas.
- **Fast Fourier Transform (FFT):** An efficient algorithm for computing the Discrete Fourier Transform (DFT), which transforms a signal from its spatial or temporal domain to its frequency domain representation.
- **Fourier Transform:** A mathematical transform that decomposes a signal (e.g., an image) into its constituent frequencies, revealing the frequency content and distribution within the signal.
- **Gamma Correction:** The process of adjusting image intensity values to compensate for the non-linear response of display devices (e.g., CRT monitors), ensuring that perceived brightness is accurate.
- **Gamma Transformation:** A single-pixel intensity transformation ($s = cr^\gamma$) used for image enhancement, particularly to adjust overall brightness and contrast, and for gamma correction.
- **Gaussian Filter:** A linear spatial or frequency domain filter that uses a Gaussian function for its weights. It is highly effective for smoothing and noise reduction and causes no ringing artifacts in the frequency domain due to its smooth transition.
- **Geometric Transformations:** Operations that modify the spatial relationship between pixels in an image, such as scaling, rotation, translation, and affine transforms.
- **Gray-level Resolution:** The number of bits used to represent the intensity (gray level) of each pixel in a digital image, determining the number of discrete intensity levels available.
- **High-Pass Filter:** A frequency domain filter that allows high frequencies to pass and attenuates low frequencies, used for image sharpening and edge enhancement.
- **Histogram Equalization:** A single-pixel image enhancement technique that aims to improve contrast by redistributing the intensity values of an image such that its histogram is flattened (more uniformly distributed).
- **Histogram Specification (Matching):** An image enhancement technique that transforms an image's histogram to match a desired, predefined shape, offering more control over the final intensity distribution than equalization.
- **Homogeneous Coordinates:** A system of coordinates that allows geometric transformations (like translation, rotation, scaling) to be represented as matrix multiplications, simplifying their combination and application.
- **Ideal Filter:** A theoretical frequency domain filter (low-pass or high-pass) characterized by a sharp, abrupt transition between frequencies that are passed and those that are blocked. It typically causes ringing artifacts in the spatial domain.
- **Image Restoration:** The process of attempting to recover an ideal image from a degraded version, often involving the removal of noise or the correction of distortions.
- **Intensity Transform:** Another term for single-pixel operations, where the output pixel value depends only on the input pixel's intensity.
- **Kernel (Filter Mask):** A small matrix of coefficients used in spatial filtering operations. It defines the neighborhood and the weights applied to pixels within that neighborhood to calculate the new pixel value.
- **Laplacian Filter:** A second-order derivative spatial filter used for image sharpening and edge detection. It highlights regions of rapid intensity change and can be combined with the original image for enhanced sharpness.
- **Linear Filter:** A spatial filter whose output is a linear combination of its input pixel values, typically involving convolution (e.g., averaging filter, derivative filters).

- **Local Operations:** Image processing operations where the output value of a pixel is determined by the values of the input pixel and its surrounding neighbors, defined by a kernel.
- **Logarithm Transformation:** A single-pixel intensity transformation that compresses the dynamic range of an image, highlighting details in darker regions.
- **Low-Pass Filter:** A frequency domain filter that allows low frequencies to pass and attenuates high frequencies, resulting in image smoothing and noise reduction.
- **Max Filter:** A non-linear spatial filter that replaces each pixel's value with the maximum value in its neighborhood, effective at removing pepper noise and highlighting salt noise.
- **Median Filter:** A non-linear spatial filter that replaces each pixel's value with the median value of its neighbors. It is highly effective at removing salt-and-pepper noise while preserving edges.
- **Min Filter:** A non-linear spatial filter that replaces each pixel's value with the minimum value in its neighborhood, effective at removing salt noise and highlighting pepper noise.
- **Moiré Effect:** Visual patterns created when two or more regular patterns (e.g., gratings) are superimposed with slightly different orientations or spacings, causing visible interference patterns. It is distinct from aliasing.
- **Negative Image:** A single-pixel transformation where the intensity of each pixel is inverted, creating an image similar to a photographic negative (e.g., white becomes black, black becomes white).
- **Noise Models:** Mathematical descriptions of the characteristics and distribution of noise in an image (e.g., Gaussian noise, salt-and-pepper noise), used to inform restoration techniques.
- **Non-linear Filter:** A spatial filter where the output is not a linear combination of its input pixel values (e.g., min, max, median filters). These are often more effective at handling impulse noise while preserving edges.
- **Notch Filter:** A specialized band-reject filter in the frequency domain that blocks frequencies at specific, narrow locations, typically used to remove very specific, localized noise components.
- **Quantization:** The process of discretizing the continuous amplitude (intensity) values of an image into a finite number of levels, determining the gray-level resolution.
- **Ringing Artifacts:** Oscillations or "ghosting" effects that appear around sharp edges in an image, often caused by the use of ideal filters in the frequency domain due to their abrupt transitions.
- **Salt Noise and Pepper Noise:** Types of impulse noise where pixels are randomly set to maximum (salt) or minimum (pepper) intensity values.
- **Sampling:** The process of discretizing the continuous spatial coordinates of an image into a finite grid of pixels, determining the spatial resolution.
- **Sinc Function:** A mathematical function that is the Fourier transform of a rectangular (rect) function. It has a central lobe and decaying oscillations.
- **Single-Pixel Operations:** Image transformations where the output value of each pixel depends solely on its own input intensity value, independent of its neighbors.
- **Spatial Filtering:** The application of a kernel (spatial filter) to an image in the image's spatial domain, where the output pixel value depends on the input pixel and its neighborhood.
- **Spatial Resolution:** The number of pixels per unit distance in an image, influencing the level of detail that can be captured and displayed.
- **Thresholding:** A single-pixel operation that converts a grayscale image into a binary (black and white) image by comparing each pixel's intensity to a predefined threshold.