Lecture 2 – Image Acquisition & Characteristics

This lecture will cover:

– **Image Acquisition** *(CH1.3, CH1.7)*

- Data acquisition
- Dynamic range and resolution
- Sampling frequency and bandwidth

– Image Characteristics *(CH1.4-1.5, CH1.8)*

- Spatial resolution
- Noise
- Image artifacts

Data Acquisition

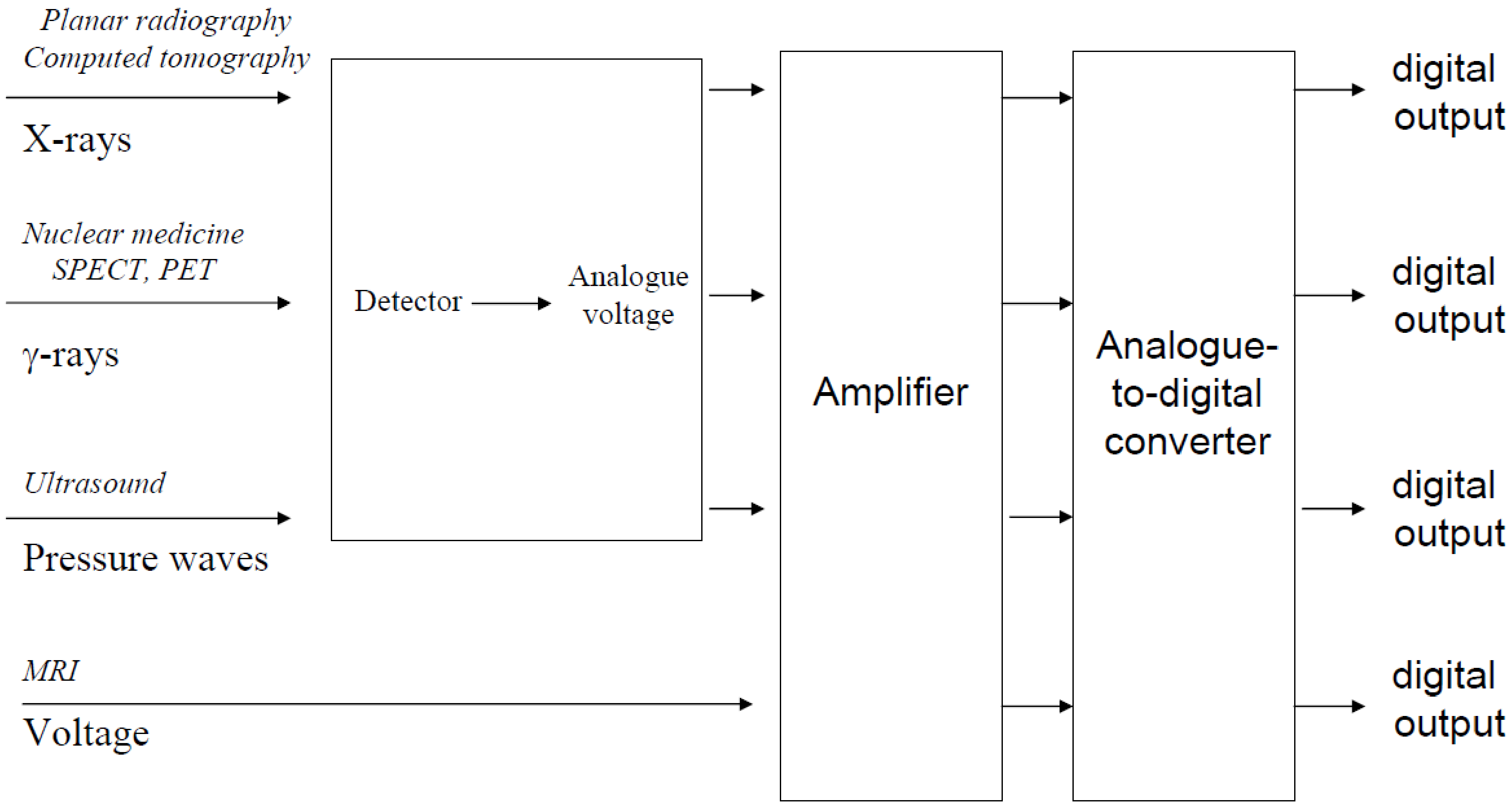


Figure. Data flow from different medical imaging modalities to produce a digital output.

Dynamic Range (动态范围)

- Color level or gray level
- Measured in bits : N bits ~ 2^N levels
- Resolution: difference between levels

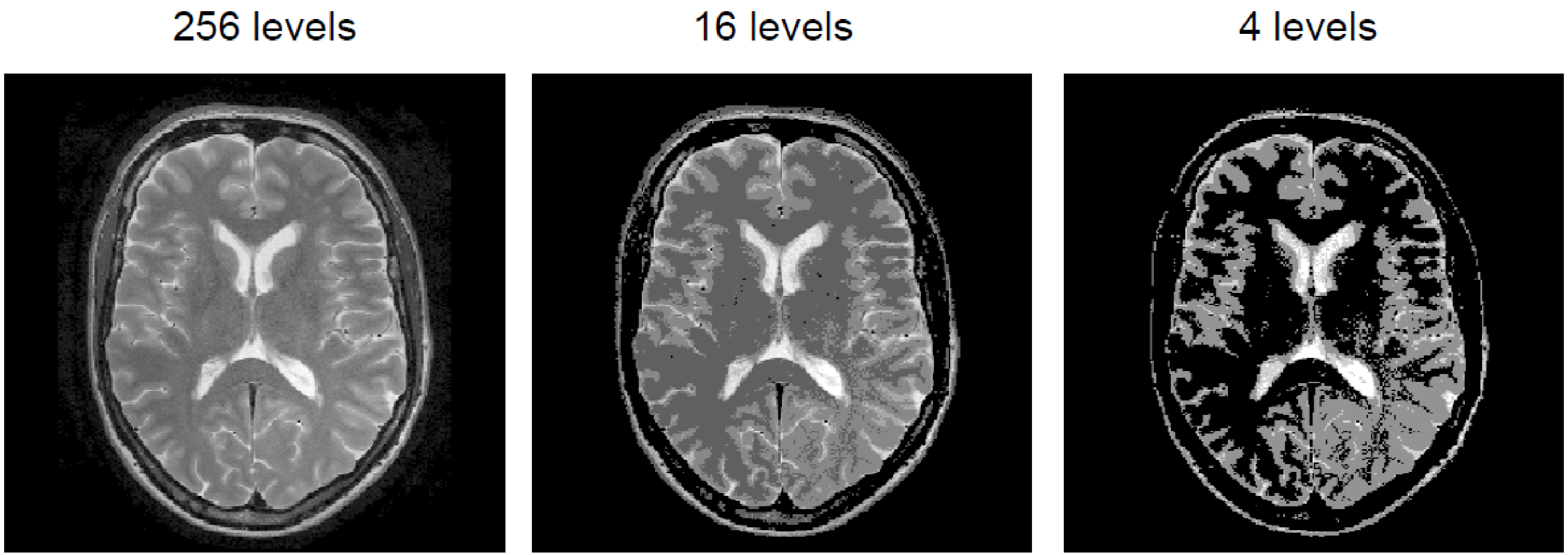


Figure. Representation of an MR image with a maximum of 256, 16 and 4 gray tone levels, corresponding to 8, 4 and 2-bit ADCs. The image quality is already significantly reduced at 16 levels.

Quantization Error (量化误差)

- The difference between the true analogue input signal and the digitized output.
- Lie between 0 and ±1/2 of the ADC resolution

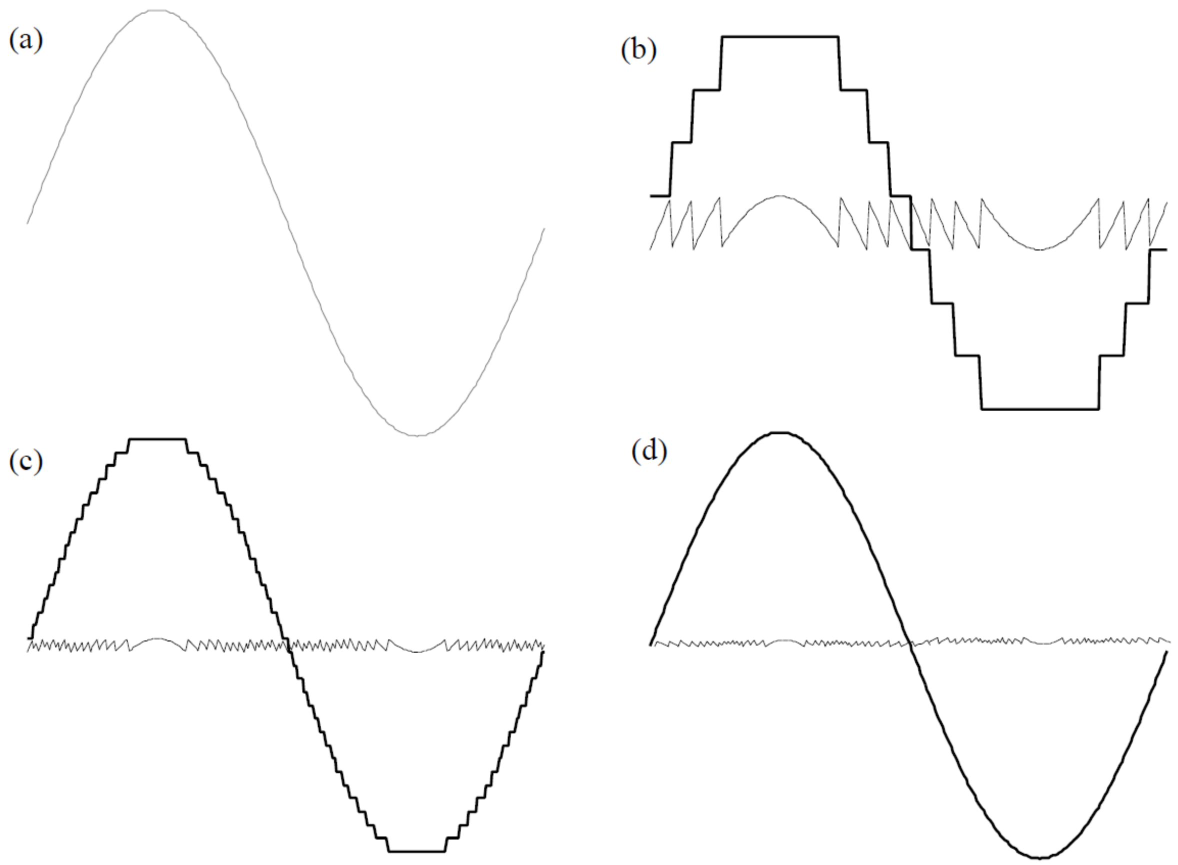


Figure. Dynamic range and quantization error. (a) The analogue sinusoidal signal which is to be digitized. (b) The signal recorded by a three-bit ADC (dark line) and the quantization error (dashed line). (c) Corresponding plot for a five-bit ADC, and (d) a six-bit ADC.

Sampling Frequency and Bandwidth

- Sampling - digitization in time domain or space domain
- The characteristics of ADC: 1) Bandwidth 2) sampling rate & resolution

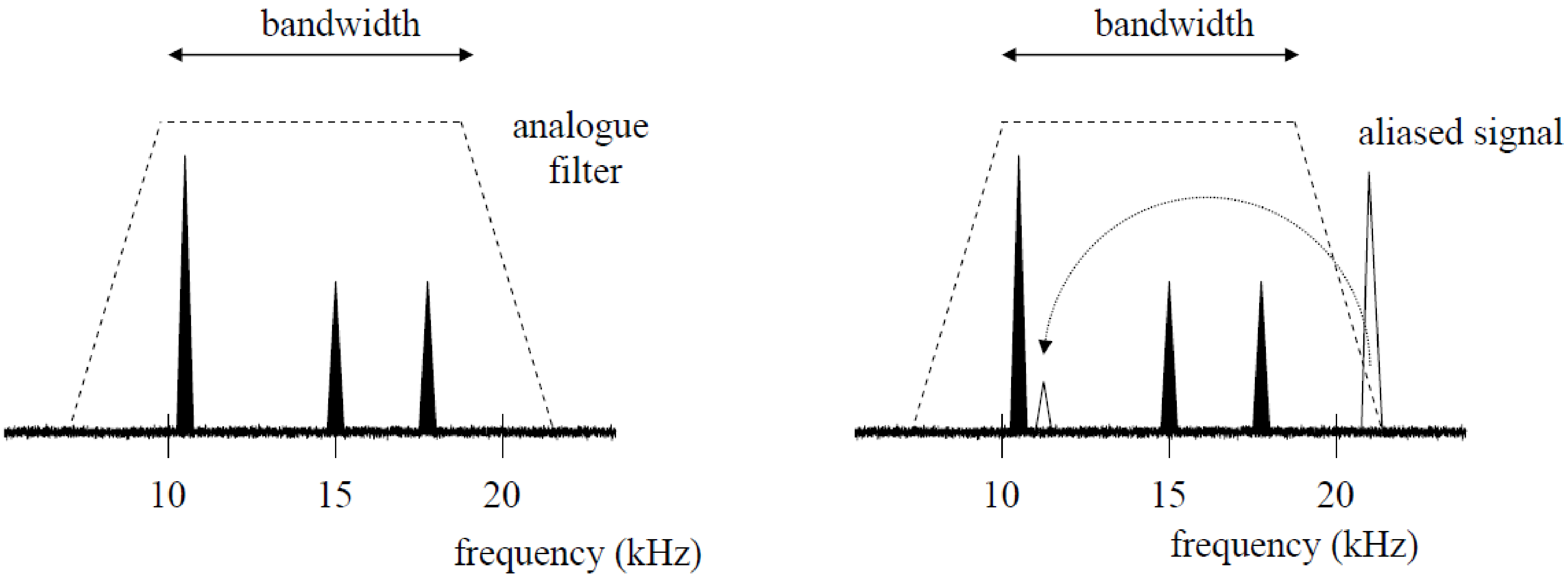


Figure. (left) A set of signals between 10 and 20 kHz is acquired by setting the central frequency of the ADC to 15 kHz with a 10 kHz bandwidth. (right) If an unexpected signal is present outside the bandwidth at 22 kHz, it is aliased back into the spectrum. Since the signal is partially filtered out by the analogue filter, the intensity of the aliased signal is reduced compared to its true intensity..

2D Sampling Theorem

- $f(t,z)$ is band-limited (带限函数) if $F(\mu,\nu)=0,\ |\mu|\geq\mu_{\max}$ and $|\nu|\geq\nu_{\max}$
- The sampling rate: $\frac{1}{\Delta T}>2\mu_{\max},\quad \frac{1}{\Delta Z}>2\nu_{\max}$

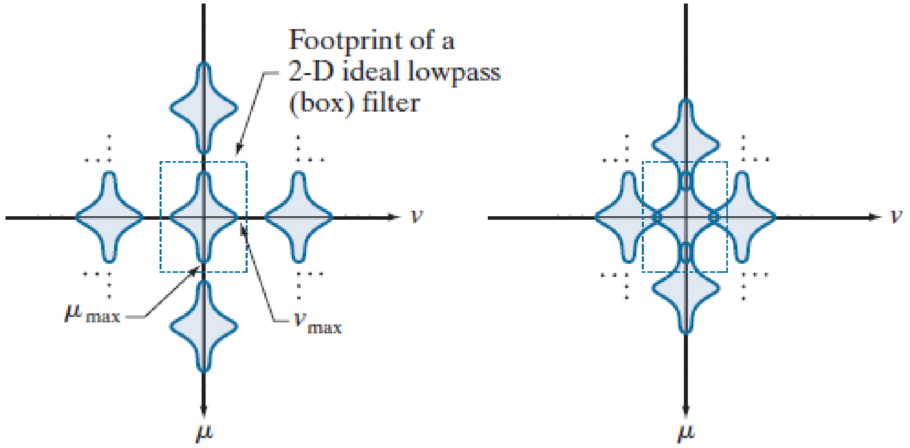


Figure. Two-dimensional Fourier transforms of (a) an over-sampled, and (b) an under-sampled, band-limited function.

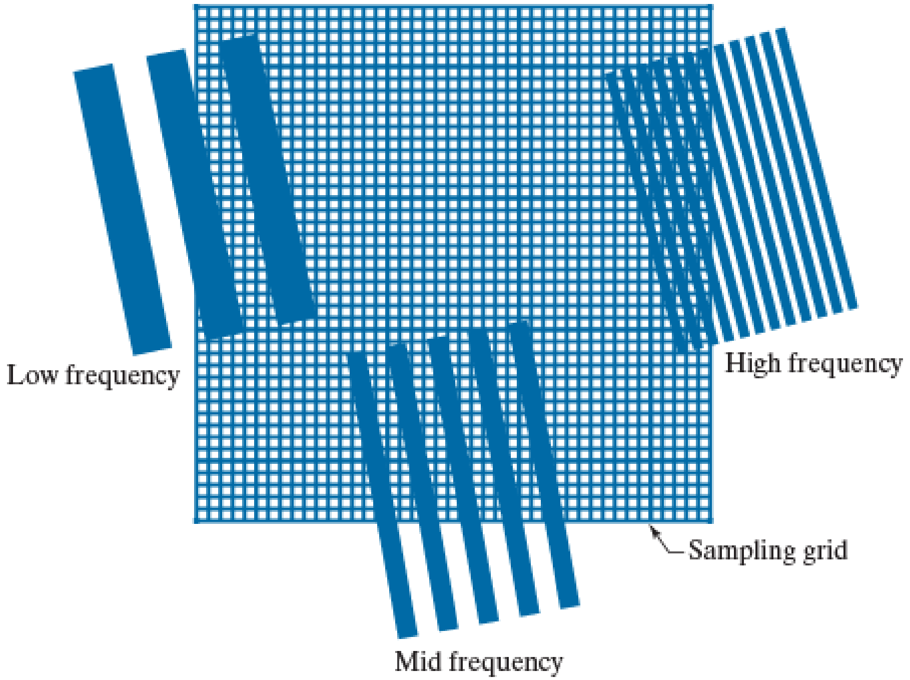


Figure. Various aliasing effects resulting from the interaction between the frequency of 2-D signals and the sampling rate used to digitize them. The regions outside the sampling grid are continuous and free of aliasing.

Digital Oversampling

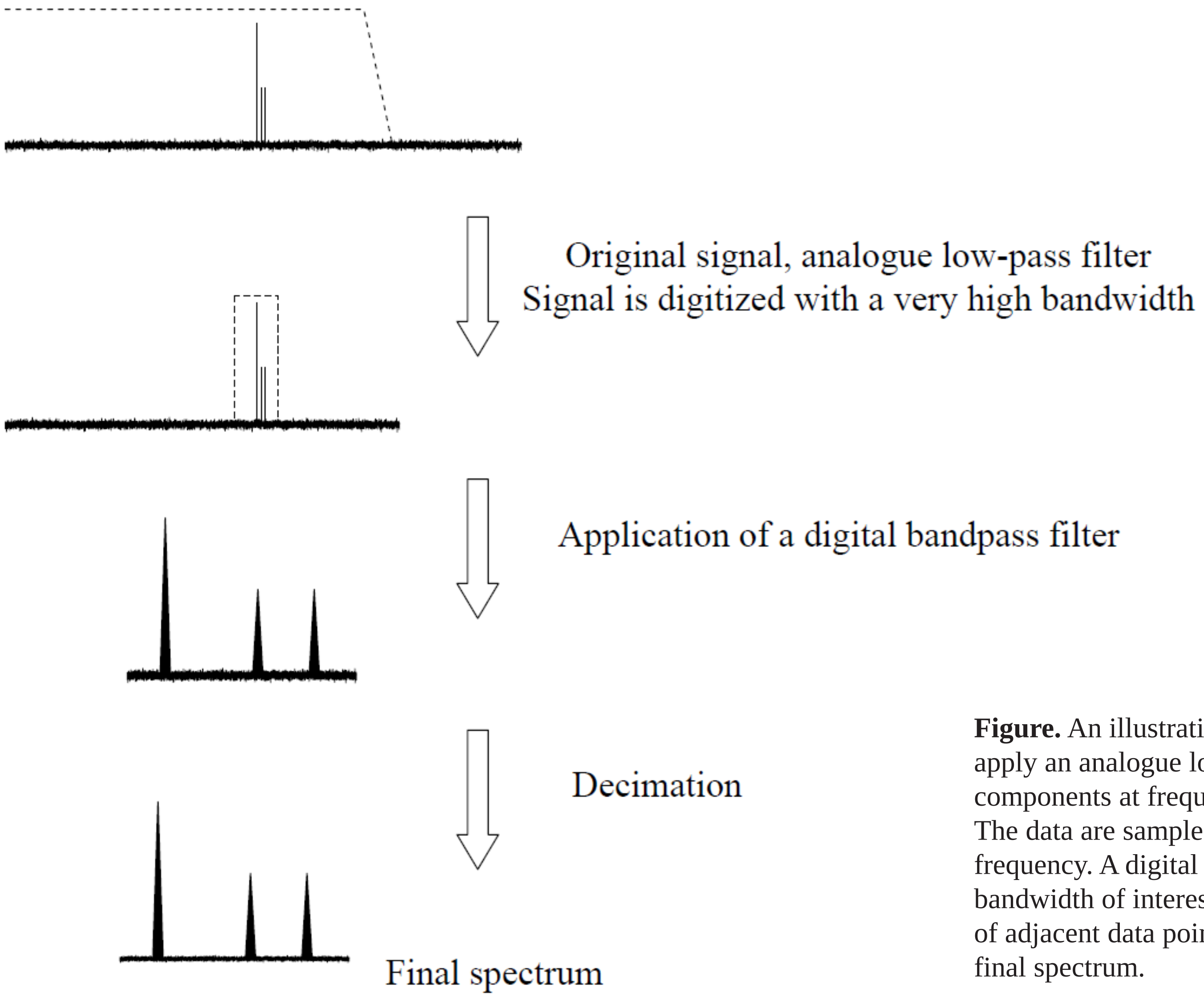


Figure. An illustration of digital oversampling. The first step is to apply an analogue low-pass filter to remove spectral and noise components at frequencies much higher than the signal bandwidth. The data are sampled at a frequency much greater than the Nyquist frequency. A digital bandpass filter is used to select only the bandwidth of interest. Finally, the process of decimation (averaging of adjacent data points) is used to reduce the quantization noise of the final spectrum.

Lecture 2 – Image Acquisition & Characteristics

This lecture will cover:

– Image Acquisition

- Data acquisition
- Dynamic range and resolution
- Sampling frequency and bandwidth

– Image Characteristics

- Spatial resolution
- Noise
- Image artifacts

Spatial Resolution

- The spatial resolution of an imaging system is related to
  - the smallest feature that can be visualized
  - the smallest distance between two features such that the features can be individually resolved
- Spatial frequency: $\boldsymbol{\omega} = \frac{\mathbf{1}}{\boldsymbol{\lambda}}$
- The common measures of spatial resolution
  - The line spread function (线扩散函数)
  - The point spread function (点扩散函数)
  - The modulation transfer function (调制传递函数)

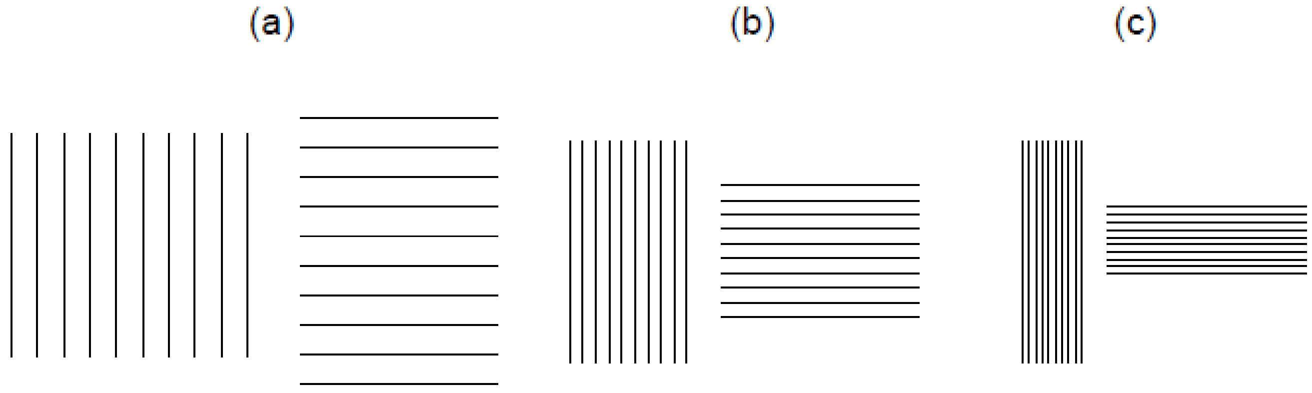


Figure. Grid patterns with increasing spatial frequencies going from (a) to (c)..

The Line Spread Function (LSF)

- The degree of blurring for a line in the image (2D)

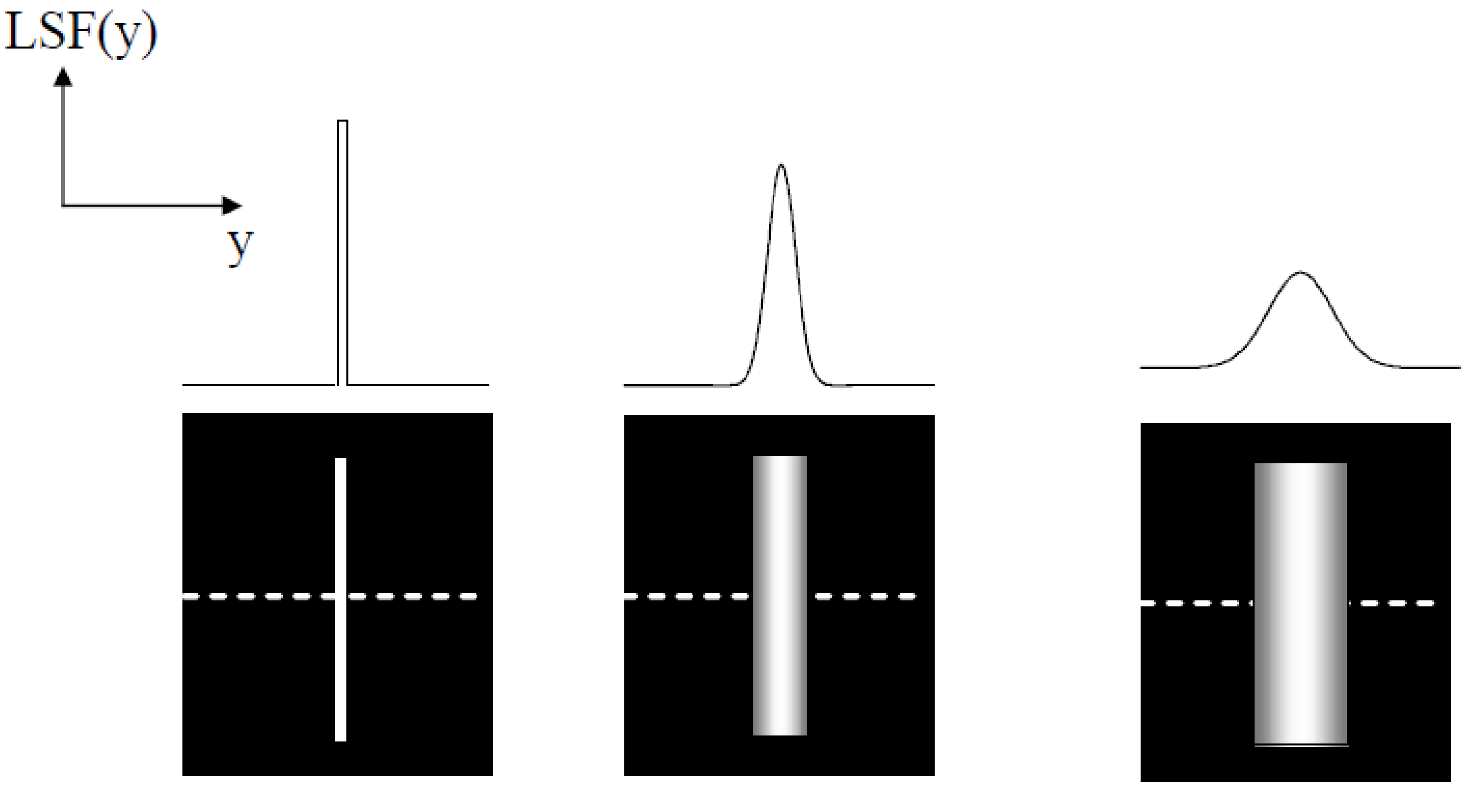


Figure. The concept of the line-spread function. A thin object is imaged using three different imaging systems. The system on the left has the sharpest LSF, as defined by the one-dimensional projection measured along the dotted line and shown above each image. The system in the middle produces a more blurred image, and has a broader LSF, with the system on the right producing the most blurred image with the broadest LSF.

The Line Spread Function (LSF)

$$\mathrm{LSF}(y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(y - y_0)^2}{2\sigma^2}\right)$$

$$\mathrm{FWHM} = \left(2\sqrt{2\ln 2}\right)\sigma \cong 2.36\sigma$$

where,

LSF : a Gaussian function

y_0 : center of the function

σ : the standard deviation of the distribution

FWHM: full width half maximum (半高宽)

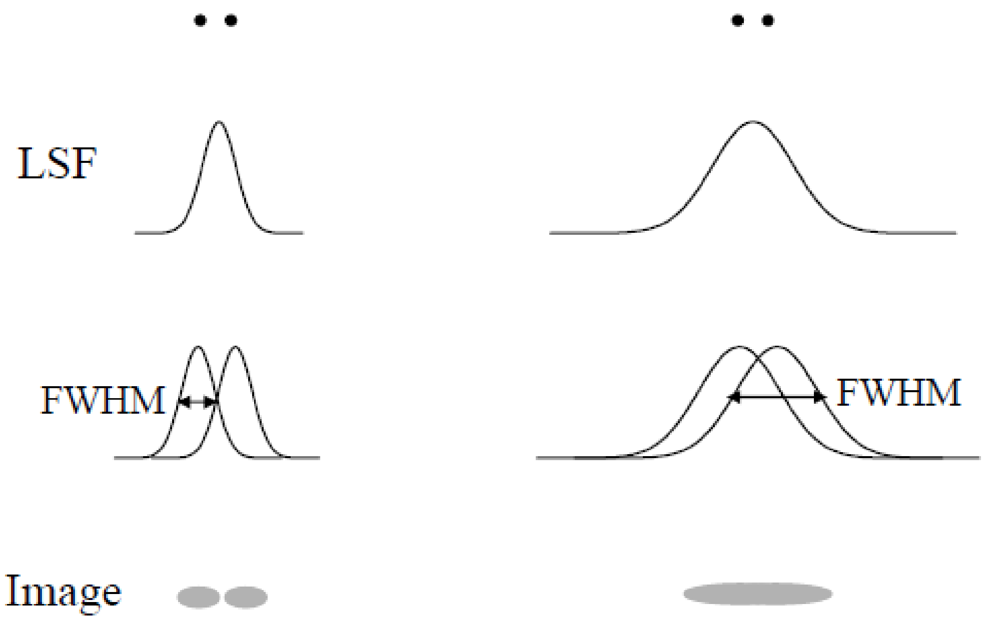


Figure. Imaging results produced by two different systems with a relatively narrow (left) and broad (right) LSF. In the case on the left, two small structures within the body (top) have a separation which is slightly greater than the FWHM of the LSF, and so the resulting image shows the two different structures. In the case on the right, the FWHM of the LSF is greater than the separation of the structures, and so the image appears as one large structure.

The Point Spread Function (PSF)

- A full description of the spatial resolution of an imaging system (3D):

$$\mathbf{I}(x,y,z) = \mathbf{O}(x,y,z) * \mathbf{h}(x,y,z)$$

where,

$\mathbf{h}(x,y,z)$: PSF

$\mathbf{O}$: object

$\mathbf{I}$: image

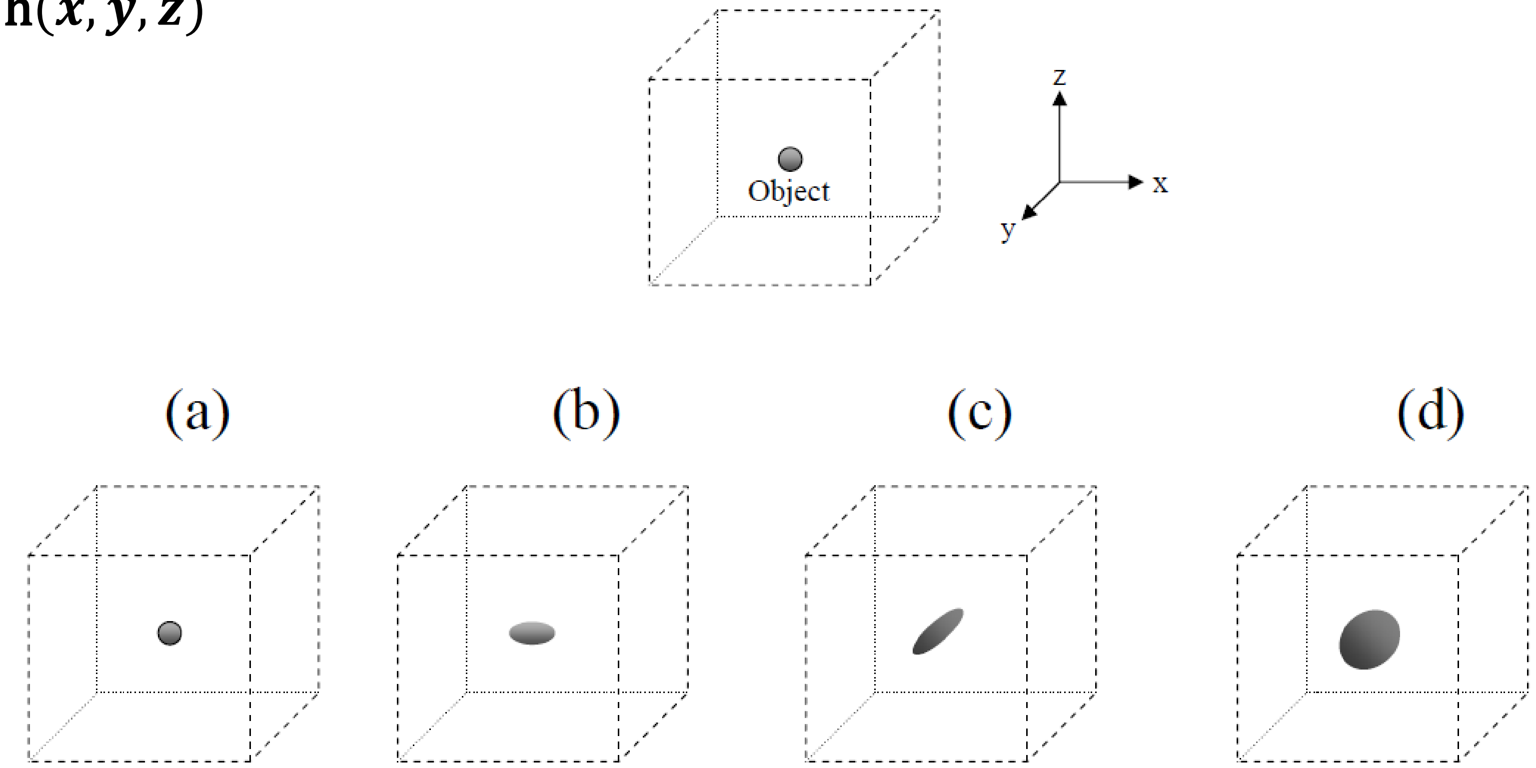


Figure. (top) Small point object being imaged. (a)-(d) Images produced with different point spread functions. (a) A sharp PSF in all three dimensions. (b) A PSF which is significantly broader in x than in y or z. (c) A PSF which is broadest in the y-dimension. (d) A PSF which is broad in all three dimensions.

The Modulation Transfer Function (MTF)

The Fourier transform of PSF

$$\mathbf{MTF}\left(\boldsymbol{k_x}, \boldsymbol{k_y}, \boldsymbol{k_z}\right) = \mathbf{F}\{\mathbf{PSF}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})\}$$

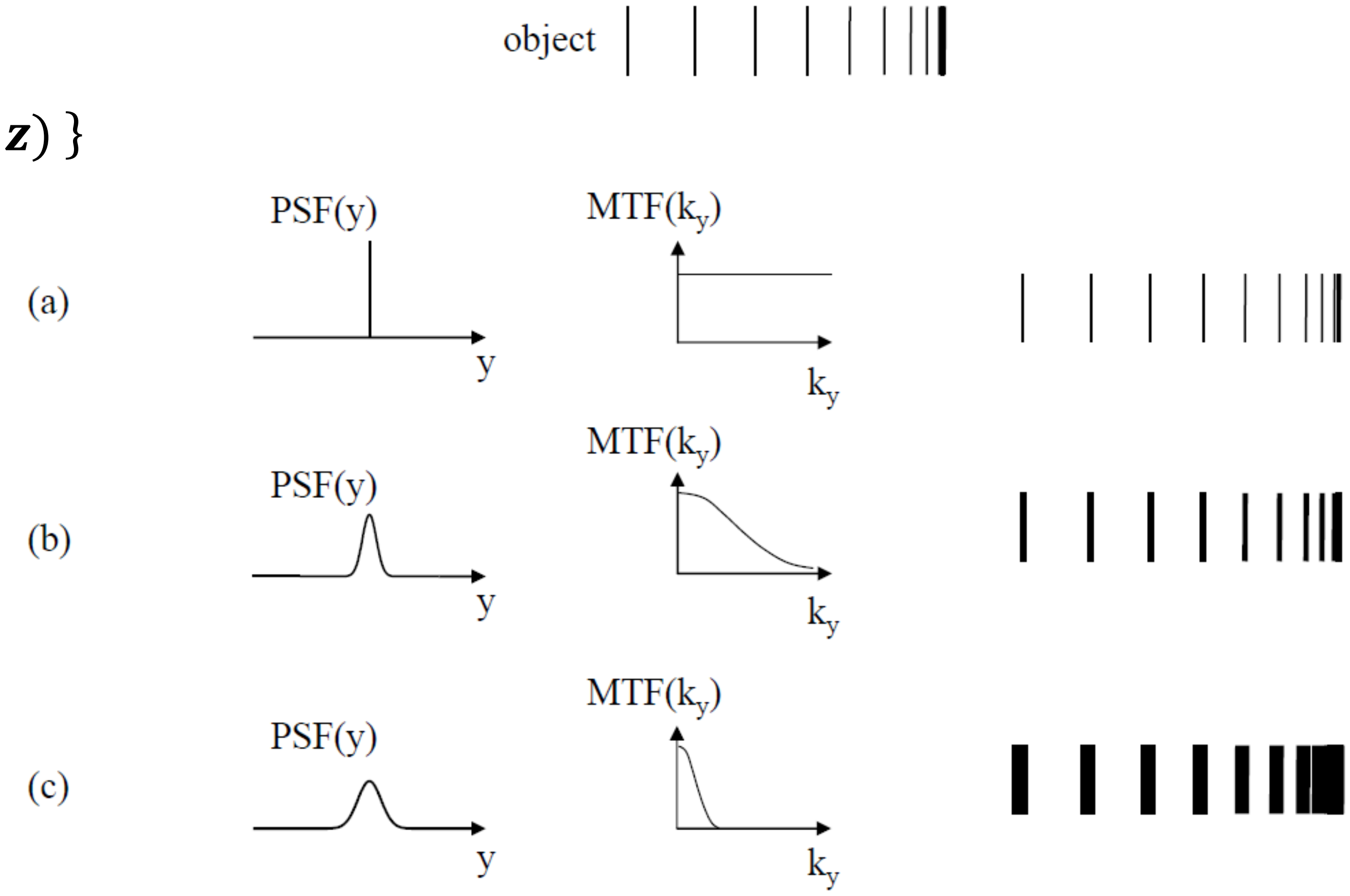


Figure. (top) The object being imaged corresponds to a set of lines with increasing spatial frequency from left-to-right. (a) An ideal PSF and the corresponding MTF produce an image which is a perfect representation of the object. (b) A slightly broader PSF produces an MTF which loses the very high spatial frequency information, and the resulting image is blurred. (c) The broadest PSF corresponds to the narrowest MTF, and the greatest loss of high spatial frequency information.

Resolution of Medical Imaging

TABLE 1-1 THE LIMITING SPATIAL RESOLUTIONS OF VARIOUS MEDICAL IMAGING MODALITIES. THE RESOLUTION LEVELS ACHIEVED IN *TYPICAL* CLINICAL USAGE OF THE MODALITY ARE LISTED

MODALITY	SPATIAL RESOLUTION (mm)	COMMENTS
Screen film radiography	0.08	Limited by focal spot size and detector resolution
Digital radiography	0.17	Limited by size of detector elements and focal spot size
Fluoroscopy	0.125	Limited by detector resolution and focal spot size
Screen film mammography	0.03	Highest resolution modality in radiology, limited by same factors as in screen film radiography
Digital mammography	0.05–0.10	Limited by same factors as digital radiography
Computed tomography	0.3	About ½ mm pixels
Nuclear medicine planar imaging	2.5 (detector face), 5 (10 cm from detector)	Spatial resolution degrades substantially with distance from detector
Single photon emission computed tomography	7	Spatial resolution worst towards the center of cross-sectional image slice
Positron emission tomography	5	Better spatial resolution than the other nuclear imaging modalities
Magnetic resonance imaging	1.0	Resolution can improve at higher magnetic fields
Ultrasound imaging (5 MHz)	0.3	Limited by wavelength of sound

Noise

- Definition: any recorded signal not related to the actual signal that one is trying to measure.
- Properties
  - Mostly random
  - Mean is zero
  - Quantitative measure of noise is conventionally the standard deviation.

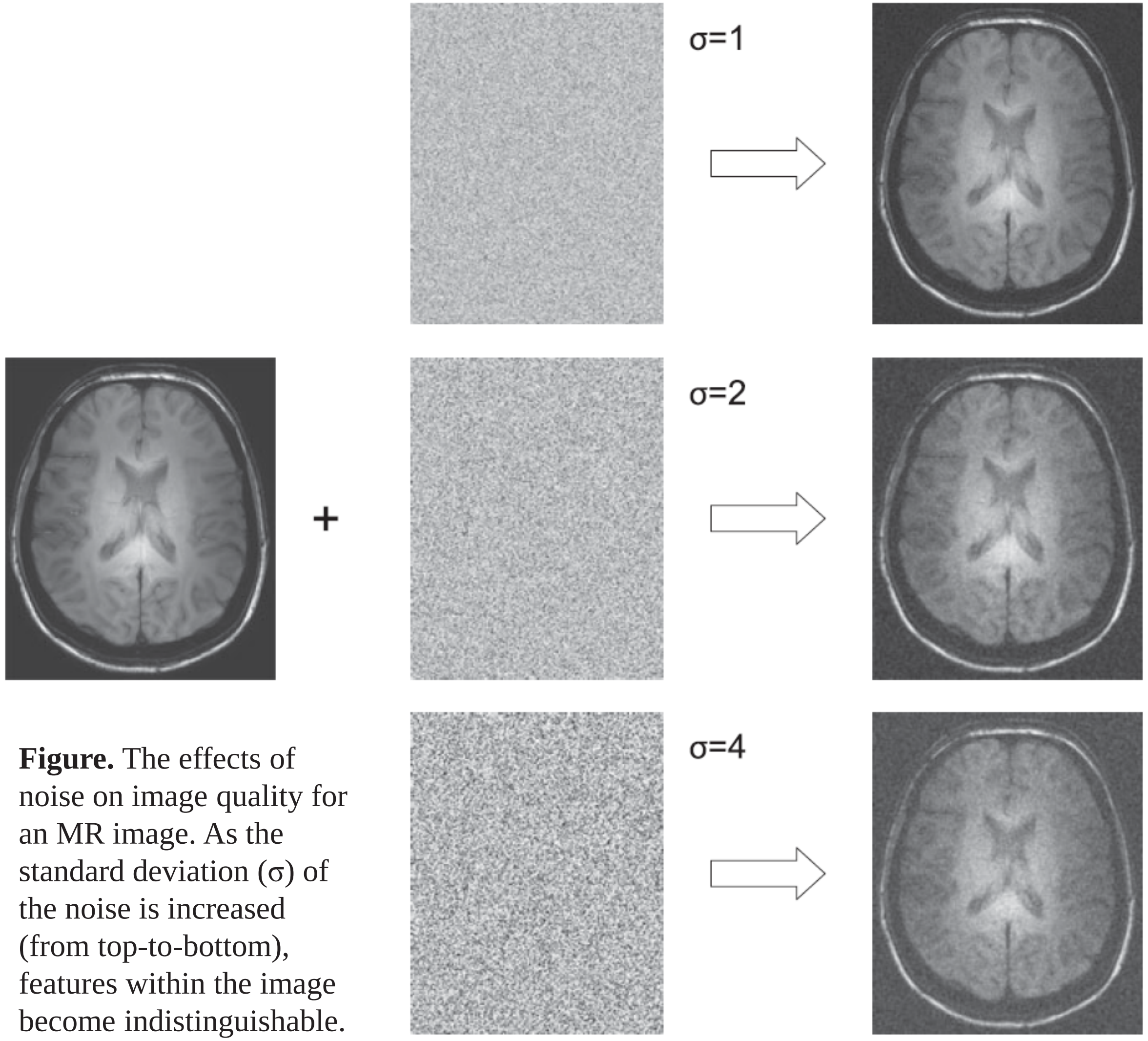
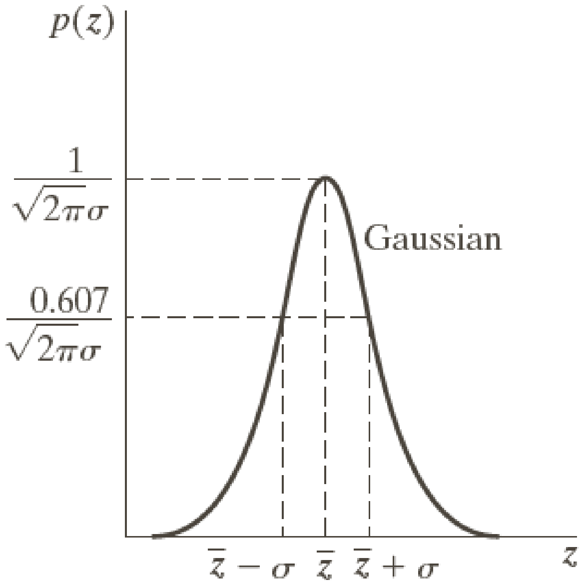


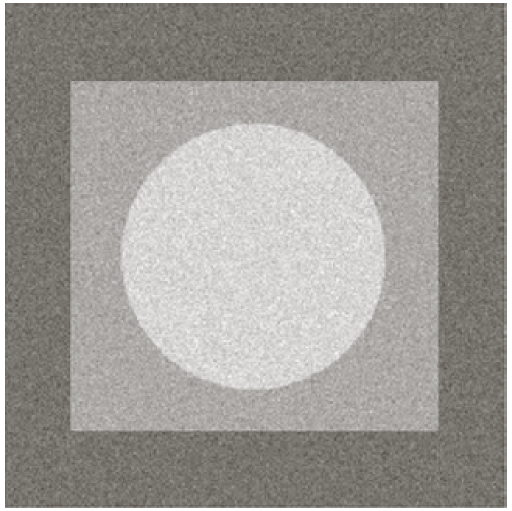
Figure. The effects of noise on image quality for an MR image. As the standard deviation (σ) of the noise is increased (from top-to-bottom), features within the image become indistinguishable.

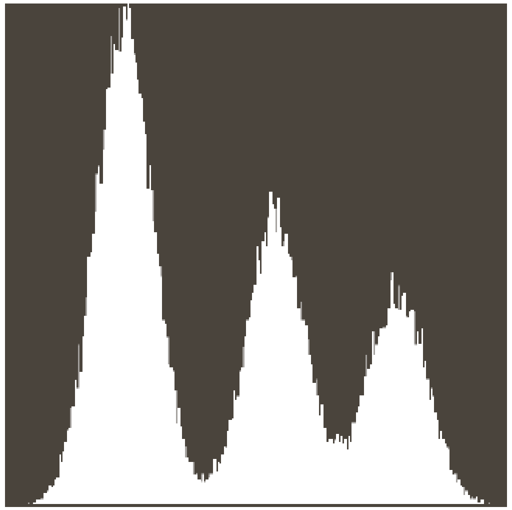
Gaussian Noise (高斯噪声)

Gaussian Noise(高斯噪声): $p(z) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(z-\bar{z})^2}{2\sigma^2}}$

$\bar{z}$: mean (average) σ: standard deviation σ^2: variance



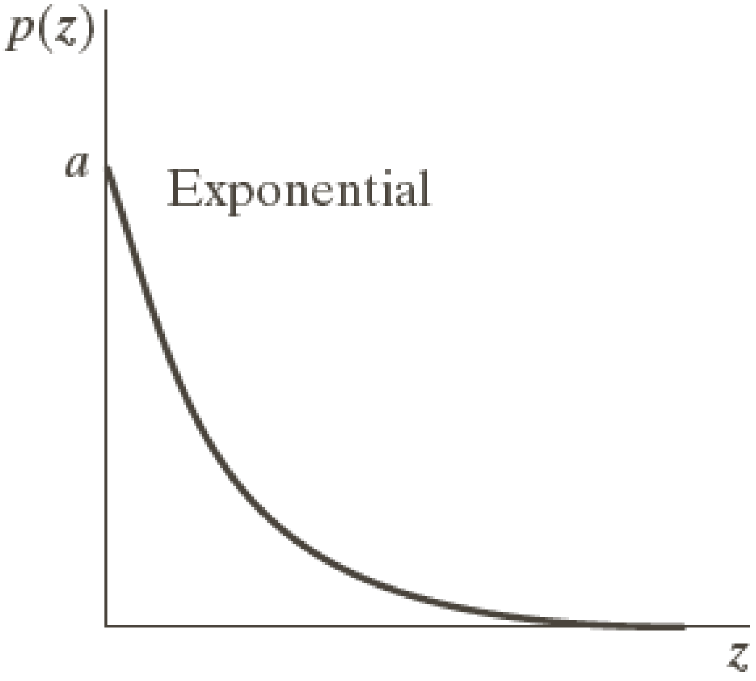


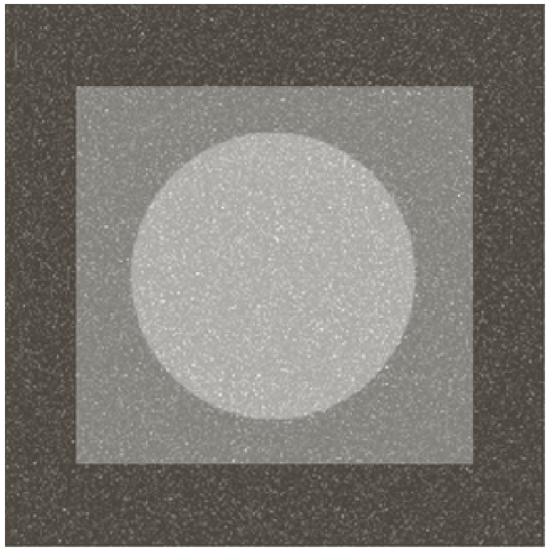


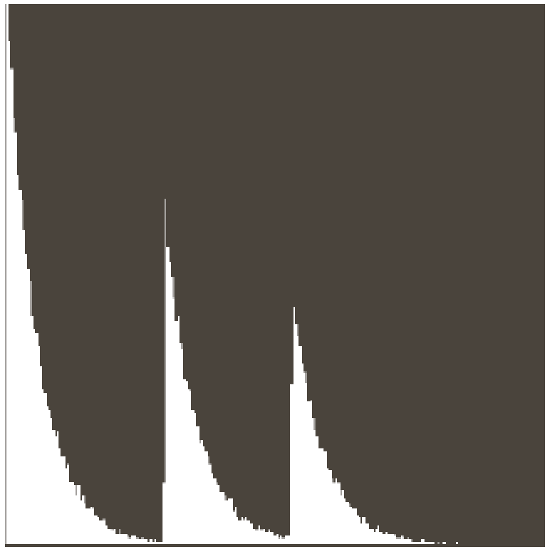
Exponential Noise（指数噪声）

Exponential Noise（指数噪声）: $p(z) = \begin{cases} ae^{-az}, & \text{for } z \geq 0 \\ 0, & \text{for } z < 0 \end{cases}$

$\bar{z} = \frac{1}{a}$ $\sigma^2 = \frac{1}{a^2}$







Signal-to-noise ratio (SNR)

- **Signal-to-noise ratio (SNR，信噪比)**

$$\mathrm{SNR} = \sqrt{\frac{P_S}{P_n}} = \sqrt{\frac{E(S^2)}{\sigma^2}} = \frac{\sqrt{E(S^2)}}{\sigma}$$

- **Increase SNR by factor of $\sqrt{N}$**
    - Repeating scan numbers (Averaging)
    - Increasing scan time (Higher energy)

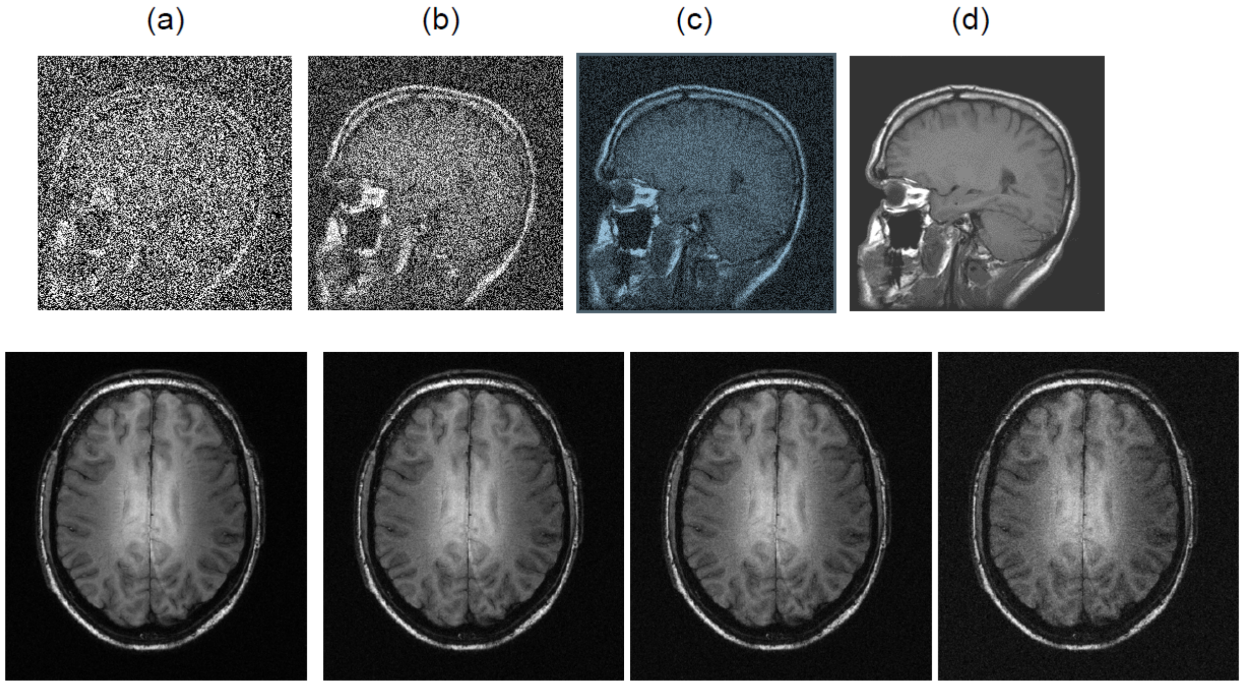


Figure. Signal averaging to improve the image SNR. (a) MR image acquired in a single scan, (b) two identical scans averaged together, (c) four scans, and (d) sixteen scans.

Contrast-to-noise ratio (CNR)

- **Contrast-to-noise ratio (CNR，对比噪声比)**

$$\mathbf{CNR}_{AB} = \frac{\mathbf{C}_{AB}}{\sigma_n} = \frac{|\mathbf{S}_A - \mathbf{S}_B|}{\sigma_n} = |\mathbf{SNR}_A - \mathbf{SNR}_B|$$

Where

$\mathbf{CNR}_{AB}$: the contrast between tissue A and tissue B

$\mathbf{S}_A, \mathbf{S}_B$: the signals from tissue A and B

$\boldsymbol{\sigma_n}$: the standard deviation of noise

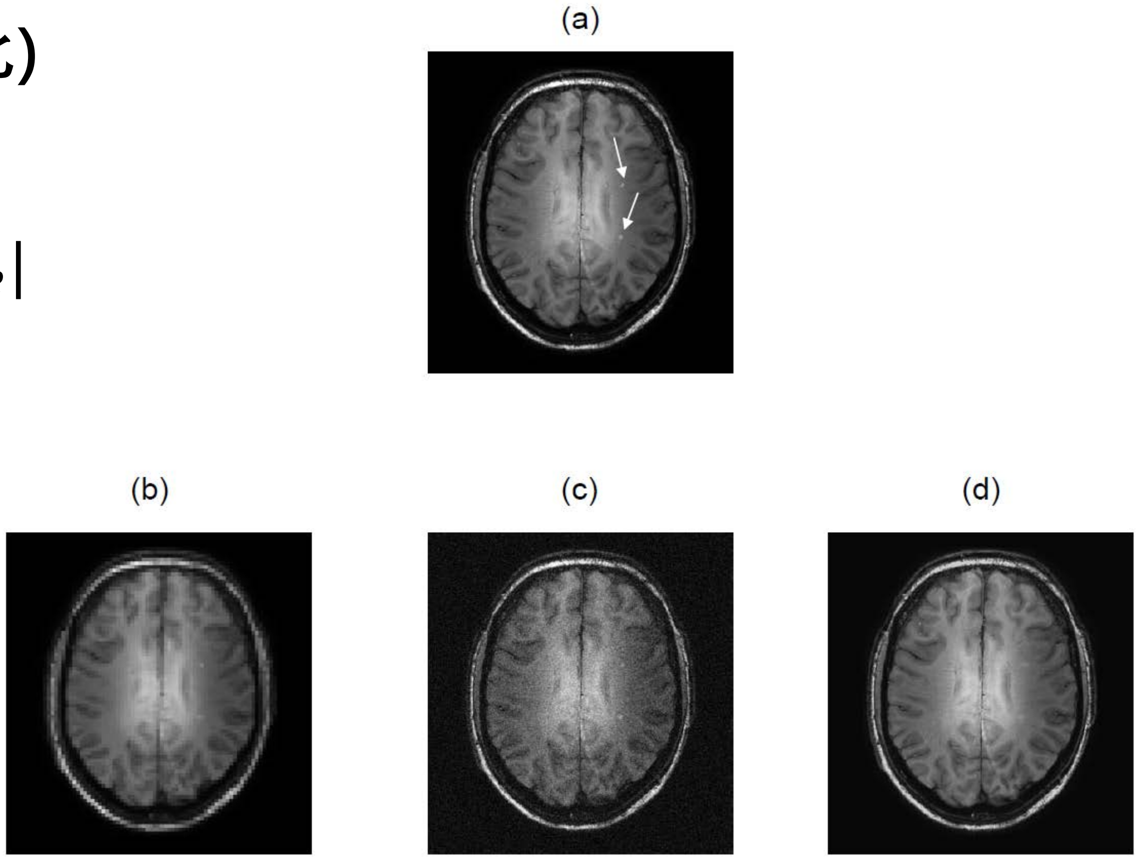
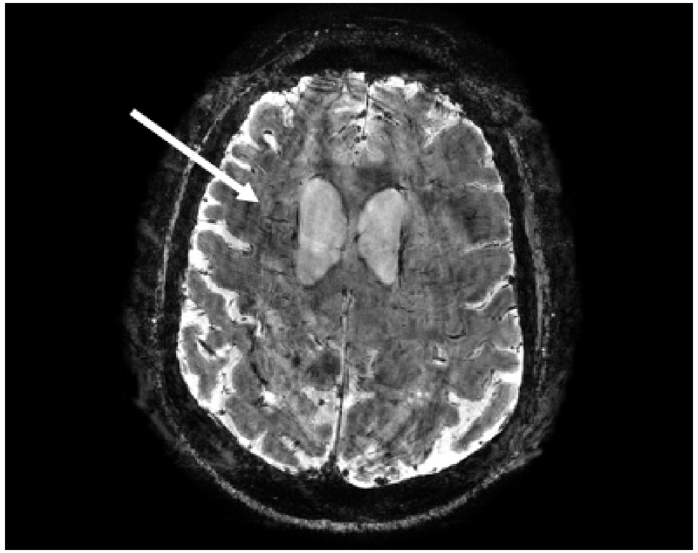


Figure. (a) MR image showing two small white-matter lesions indicated by the arrows. Corresponding images acquired with (b) four times poorer spatial resolution, (c) four times lower SNR, and (d) a reduced CNR between the lesions and the surrounding healthy tissue. The arrows point to lesions that can be detected.

Image Artifacts (伪影)

Signals in an image

① caused by a phenomenon related to the imaging process
② distorting the image or introduces an apparent features without physical counterpart



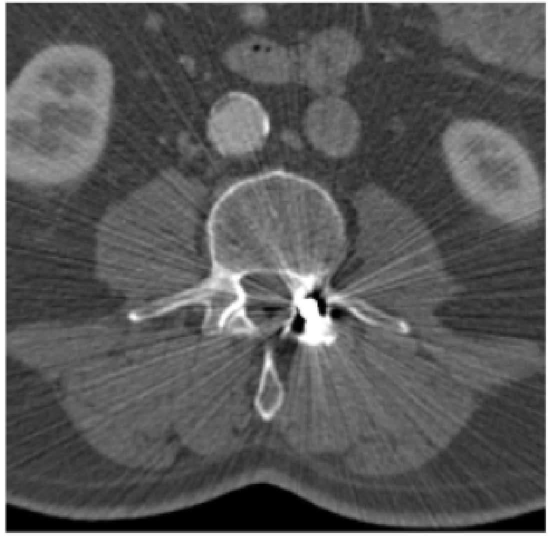


Figure. Examples of image artifacts. (a) Motion in MRI causes extra lines to appear in the image (arrowed), (b) acoustic shadowing in ultrasound produces a black hole in the image (arrowed), and (c) a metal implant causes 'streaking artifacts' in a CT image.