# Digital Image Processing

## Digital Imaging Fundamentals

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Images taken from:
R. Gonzalez and R. Woods. Digital Image Processing, Prentice Hall, 2008.
Digital Image Processing course by Brian Mac Namee, Dublin Institute of Technology.



## 2 Digital Image Fundamentals

*"Those who wish to succeed must ask the right preliminary questions"*

Aristotle



## 3 Contents

This lecture will cover:

- The human visual system
- Light and the electromagnetic spectrum
- Image representation
- Image sensing and acquisition
- Sampling, quantisation and resolution



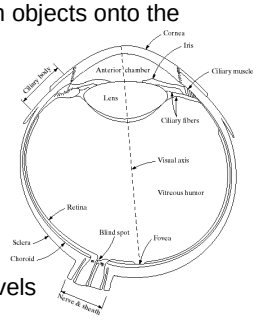
## 4 Human Visual System

- The best vision model we have!
- Knowledge of how images form in the eye can help us with processing digital images
- We will take just a whirlwind tour of the human visual system



## 5 Structure Of The Human Eye

- The lens focuses light from objects onto the retina
- The retina is covered with light receptors called cones (6-7 million) and rods (75-150 million)
- Cones are concentrated around the fovea and are very sensitive to colour
- Rods are more spread out and are sensitive to low levels of illumination

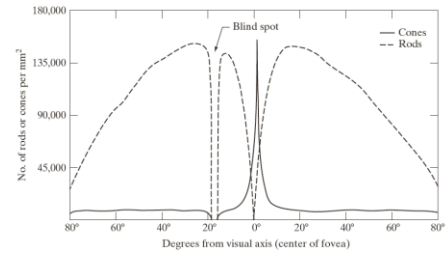



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 6 Structure Of The Human Eye (cont.)

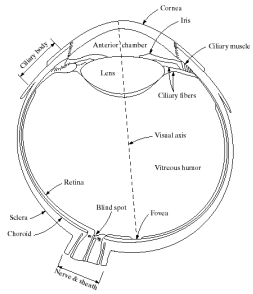
Density of cones and rods across a section of the right eye




Images taken from Gonzalez & Woods, Digital Image Processing (2002)

## 7 Structure Of The Human Eye (cont.)

- Each cone is connected to each own nerve end.
  - They can resolve fine details.
  - Sensitive to color (*photopic* vision)
- Many rods are connected to a single nerve end
  - Limited resolution with respect to cones
  - Not sensitive to color
  - Sensitive to low level illumination (*scotopic* vision)

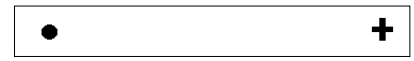



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 8 Blind-Spot Experiment

- Draw an image similar to that below on a piece of paper (the dot and cross are about 6 inches apart)

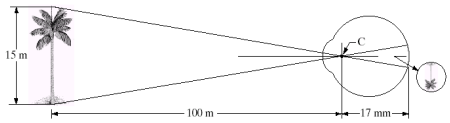


- Close your right eye and focus on the cross with your left eye
- Hold the image about 20 inches away from your face and move it slowly towards you
- The dot should disappear!



## 9 Image Formation In The Eye

- Muscles within the eye can be used to change the shape of the lens allowing us focus on objects that are near or far away (in contrast with a camera where the distance between the lens and the focal plane varies)
- An image is focused onto the retina causing rods and cones to become excited which ultimately send signals to the brain





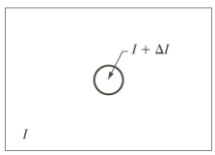

## 10 Brightness Adaptation & Discrimination

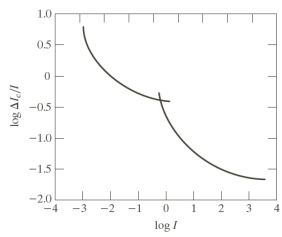
- The human visual system can perceive approximately $10^{10}$ different light intensity levels.
- At any time instance, we can only discriminate between a much smaller number – *brightness adaptation*.
- Similarly, the perceived intensity of a region is related to the light intensities of the regions surrounding it.



## 11 Brightness Adaptation & Discrimination (cont…)

Weber ratio

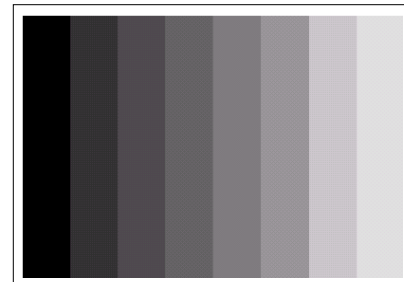



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



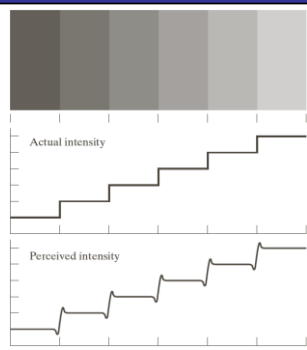
## 12 Brightness Adaptation & Discrimination (cont…)



An example of Mach bands

Images taken from Gonzalez & Woods, Digital Image Processing (2002)

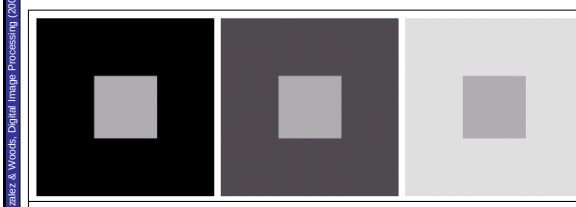
## 13 Brightness Adaptation & Discrimination (cont…)




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 14 Brightness Adaptation & Discrimination (cont…)



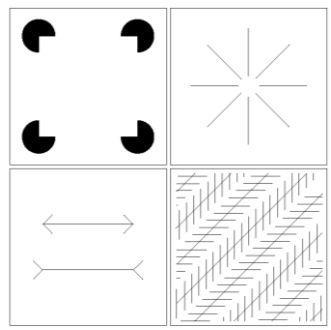
An example of *simultaneous contrast*

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



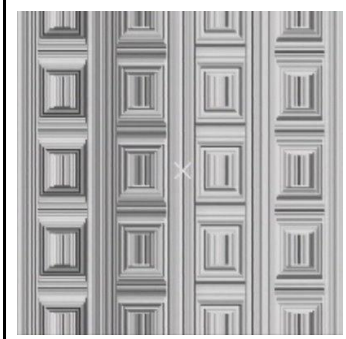
## 15 Optical Illusions

- Our visual system plays many interesting tricks on us





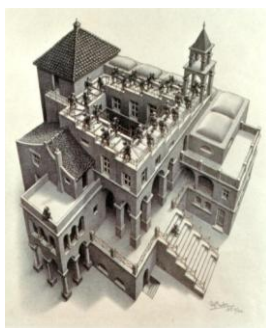
## 16 Optical Illusions (cont…)



Stare at the cross in the middle of the image and think circles



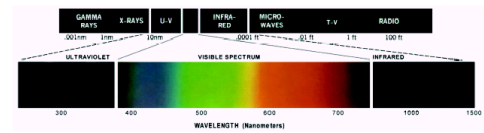
## 17 Optical Illusions (cont…)





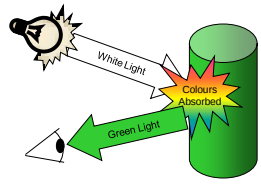
## 18 Light And The Electromagnetic Spectrum

- Light is just a particular part of the electromagnetic spectrum that can be sensed by the human eye
- The electromagnetic spectrum is split up according to the wavelengths of different forms of energy



## 19 Reflected Light

- The colours that we perceive are determined by the nature of the light reflected from an object
- For example, if white light is shone onto a green object most wavelengths are absorbed, while green light is reflected from the object

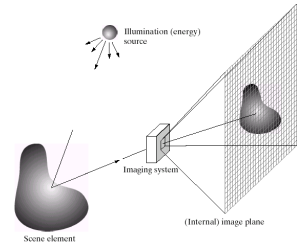





## 20 Image Acquisition

Images are typically generated by *illuminating* a *scene* and absorbing the energy reflected by the objects in that scene

- Typical notions of illumination and scene can be way off:
  - X-rays of a skeleton
  - Ultrasound of an unborn baby
  - Electro-microscopic images of molecules

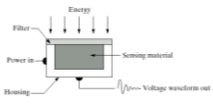



Images taken from Gonzalez & Woods, Digital Image Processing (2002)

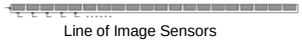


## 21 Image Sensing and Acquisition

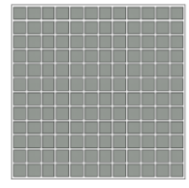
- Sensors transform the incoming energy into voltage and the output of the sensor is digitized.




Imaging Sensor



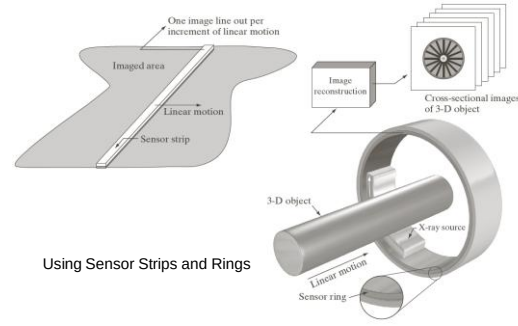
Line of Image Sensors



Array of Image Sensors



## 22 Image Sensing



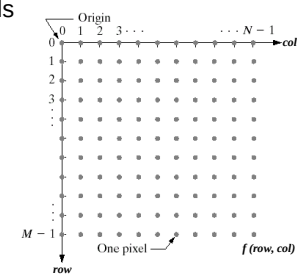

Using Sensor Strips and Rings

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 23 Image Representation

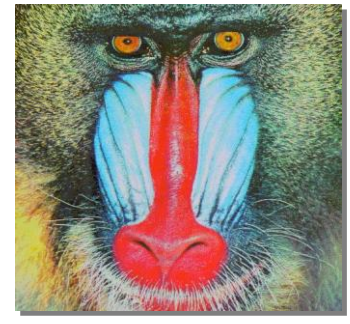
- A digital image is composed of $M$ rows and $N$ columns of pixels each storing a value
- Pixel values are in the range 0-255 (black-white)
- Images can easily be represented as matrices




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 24 Colour images



Images taken from Gonzalez & Woods, Digital Image Processing (2002)

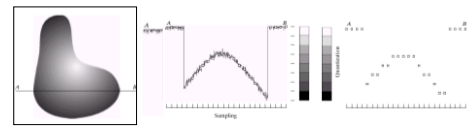
## 25 Colour images

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 26 Image Sampling And Quantisation

- A digital sensor can only measure a limited number of **samples** at a **discrete** set of energy levels
- Quantisation is the process of converting a continuous **analogue** signal into a digital representation of this signal

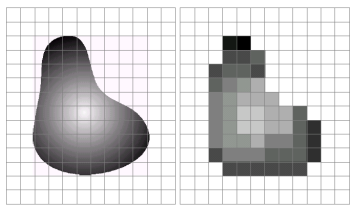


Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 27 Image Sampling And Quantisation (cont…)

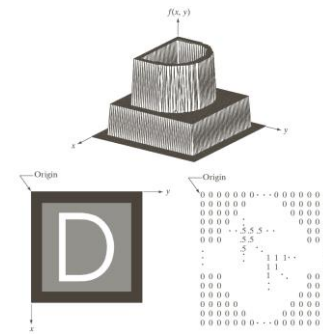
- Remember that a digital image is always only an **approximation** of a real world scene



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 28 Image Representation

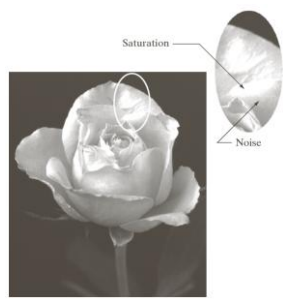



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 29 Saturation & Noise

- **Dynamic range**: The ratio of the maximum (*saturation*) to the minimum (*noise*) detectable intensity of the imaging system.
- Noise generally appear as a grainy texture pattern in the darker regions and masks the lowest detectable true intensity level




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 30 Spatial Resolution

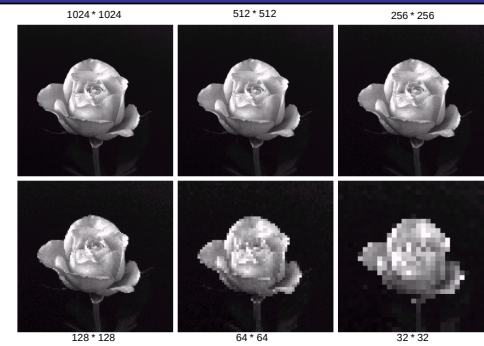
- The spatial resolution of an image is determined by how sampling was carried out
- Spatial resolution simply refers to the smallest discernable detail in an image
  - Vision specialists will often talk about pixel size
  - Graphic designers will talk about dots per inch (DPI)

## 31 Spatial Resolution (cont…)


Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 32 Spatial Resolution (cont…)




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 33 Spatial Resolution (cont…)

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



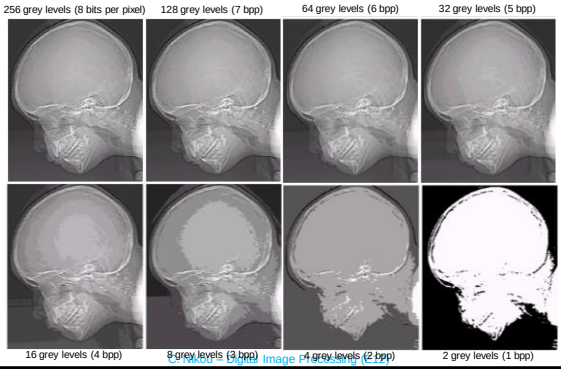
## 34 Intensity Level Resolution

- Intensity level resolution refers to the number of intensity levels used to represent the image
  - The more intensity levels used, the finer the level of detail discernable in an image
  - Intensity level resolution is usually given in terms of the number of bits used to store each intensity level

| Number of Bits | Number of Intensity Levels | Examples |
|---|---|---|
| 1 | 2 | 0, 1 |
| 2 | 4 | 00, 01, 10, 11 |
| 4 | 16 | 0000, 0101, 1111 |
| 8 | 256 | 00110011, 01010101 |
| 16 | 65,536 | 1010101010101010 |



## 35 Intensity Level Resolution (cont…)




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



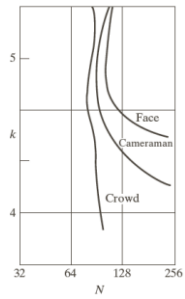
## 36 Intensity Level Resolution (cont…)

Low Detail | Medium Detail | High Detail

Images taken from Gonzalez & Woods, Digital Image Processing (2002)

## 37 Intensity Level Resolution (cont…)

- *Isopreference* curves represent the dependence between intensity and spatial resolutions.
  - Points lying on a curve represent images of "equal" quality as described by observers.
  - The curves become more vertical as the degree of detail increases (a lot of detail need less intensity levels).




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 38 Resolution: How Much Is Enough?

The big question with resolution is always *how much is enough*?

- This all depends on what is in the image and what you would like to do with it
- Key questions include
  - Does the image look aesthetically pleasing?
  - Can you see what you need to see within the image?



## 39 Resolution: How Much Is Enough? (cont…)

The picture on the right is fine for counting the number of cars, but not for reading the number plate



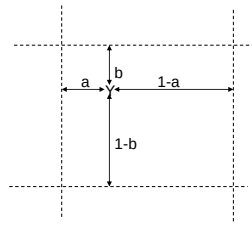
## 40 Interpolation

- The process of using known data to estimate values at unknown locations
- Basic operation for shrinking, zooming, rotation and translation
  - e.g. a 500x500 image has to be enlarged by 1.5 to 750x750 pixels
  - Create an imaginary 750x750 grid with the same pixel spacing as the original and then shrink it to 500x500
  - The 750x750 shrunk pixel spacing will be less than the spacing in the original image.
  - Pixel values have to be determined in between the original pixel locations



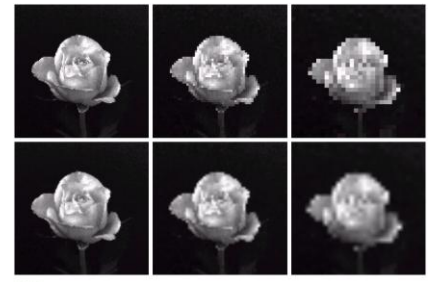
## 41 Interpolation (cont.)

- How to determine pixel values
  - Nearest neighbour
  - Bilinear
  - Bicubic
  - 2D sinc






## 42 Interpolation (cont...)



a b c
d e f
**FIGURE 2.25** Top row: images zoomed from 128 × 128, 64 × 64, and 32 × 32 pixels to 1024 × 1024 pixels, using nearest neighbor gray-level interpolation. Bottom row: same sequence, but using bilinear interpolation.

Images taken from Gonzalez & Woods, Digital Image Processing (2002)

## 43 Distances between pixels

- For pixels $p(x,y)$, $q(s,t)$ and $z(v,w)$, $D$ is a distance function or metric if:

$$a)\ D(p,q) \geq 0\ (D(p,q) = 0\ iff\ \ p = q),$$
$$b)\ D(p,q) = D(q,p),$$
$$c)\ D(p,z) \leq D(p,q) + D(q,z).$$

- The Euclidean distance between $p$ and $q$ is defined as:

$$D_e(p,q) = \left[(x-s)^2 + (y-t)^2\right]^{\frac{1}{2}}$$

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 44 Distances between pixels (cont.)

- The city-block or $D_4$ distance between p and q is defined as:

$$D_4(p,q) = |x-s| + |y-t|$$

- Pixels having the city-block distance from a pixel $(x,y)$ less than or equal to some value $T$ form a diamond centered at $(x,y)$ . For example, for $T$=2:

| | | | | |
|---|---|---|---|---|
| | | 2 | | |
| | 2 | 1 | 2 | |
| 2 | 1 | 0 | 1 | 2 |
| | 2 | 1 | 2 | |
| | | 2 | | |

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 45 Distances between pixels (cont.)

- The chessboard or $D_8$ distance between $p$ and $q$ is defined as:

$$D_8(p,q) = \max(|x-s|, |y-t|)$$

- Pixels having the city-block distance from a pixel $(x,y)$ less than or equal to some value $T$ form a square centered at $(x,y)$. For example, for $T$=2:

| | | | | |
|---|---|---|---|---|
| 2 | 2 | 2 | 2 | 2 |
| 2 | 1 | 1 | 1 | 2 |
| 2 | 1 | 0 | 1 | 2 |
| 2 | 1 | 1 | 1 | 2 |
| 2 | 2 | 2 | 2 | 2 |

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



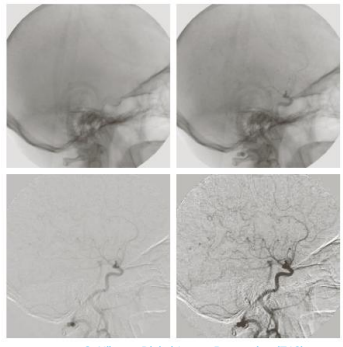
## 46 Mathematical operations used in digital image processing

- Arithmetic operations (e.g image subtraction pixel by pixel)
- Matrix and vector operations
- Linear (e.g. sum) and nonlinear operations (e.g. min and max)
- Set and logical operations
- Spatial and neighbourhood operations (e.g. local average)
- Geometric spatial transformations (e.g. rotation)

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 47 Image subtraction



a b
c d
**FIGURE 2.28** Digital subtraction angiography. (a) Mask image. (b) A live image. (c) Difference between (a) and (b). (d) Enhanced difference image. (Figures (a) and (b) courtesy of The Image Sciences Institute, University Medical Center, Utrecht, The Netherlands.)

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 48 Image multiplication

a b c
**FIGURE 2.29** Shading correction. (a) Shaded SEM image of a tungsten filament and support, magnified approximately 130 times. (b) The shading pattern. (c) Product of (a) by the reciprocal of (b). (Original image courtesy of Mr. Michael Shaffer, Department of Geological Sciences, University of Oregon, Eugene.)

Images taken from Gonzalez & Woods, Digital Image Processing (2002)

## 49 Image multiplication (cont.)

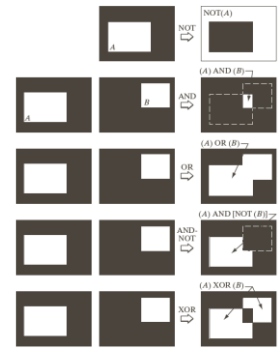
a b c

**FIGURE 2.30** (a) Digital dental X-ray image. (b) ROI mask for isolating teeth with fillings (white corresponds to 1 and black corresponds to 0). (c) Product of (a) and (b).

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



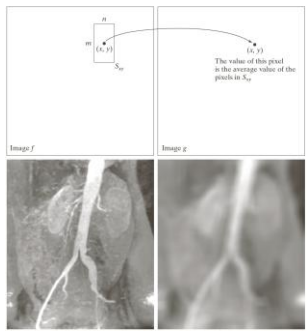
## 50 Logical operator




Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 51 Neighbourhood operation



Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 52 A note on arithmetic operations

- Most images are displayed at 8 bits (0-255).
- When images are saved in standard formats like TIFF or JPEG the conversion to this range is automatic.
- However, the approach used for the conversion depends on the software package.
  - The difference of two images is in the range [-255, 255] and the sum is in the range [0, 510].
  - Many packages simply set all negative values to 0 and all values exceeding 255 to 255 which is undesirable.

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 53 A note on arithmetic operations (cont.)

- An approach that guarantees that the full range is captured into a fixed number of bits is the following:
- At first, make the minimum value of the image equal to zero:

$$f_m = f - \min(f)$$

- Then perform intensity scaling to $[0, K]$

$$f_s = \frac{f_m}{\max(f_m)} K$$

Images taken from Gonzalez & Woods, Digital Image Processing (2002)



## 54 Geometric spatial transformations

- A common geometric transformation is the *affine* transform

$$[x \quad y \quad 1] = [u \quad v \quad 1]\mathbf{T} = [u \quad v \quad 1]\begin{bmatrix} t_{11} & t_{11} & 0 \\ t_{21} & t_{12} & 0 \\ t_{31} & t_{13} & 1 \end{bmatrix}$$

- It may translate, rotate, scale and sheer an image depending on the value of the elements of $\mathbf{T}$
- To avoid empty pixels we implement the *inverse mapping*
- Interpolation is essential

Images taken from Gonzalez & Woods, Digital Image Processing (2002)

# Geometric spatial transformations (cont.)



**TABLE 2.2**
Affine transformations based on Eq. (2.6–23).

| Transformation Name | Affine Matrix, T | Coordinate Equations | Example |
|---|---|---|---|
| Identity | $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ | $x = v$<br>$y = w$ | |
| Scaling | $\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$ | $x = c_x v$<br>$y = c_y w$ | |
| Rotation | $\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$ | $x = v\cos\theta - w\sin\theta$<br>$y = v\cos\theta + w\sin\theta$ | |
| Translation | $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ t_x & t_y & 1 \end{bmatrix}$ | $x = v + t_x$<br>$y = w + t_y$ | |
| Shear (vertical) | $\begin{bmatrix} 1 & 0 & 0 \\ s_v & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ | $x = v + s_v w$<br>$y = w$ | |
| Shear (horizontal) | $\begin{bmatrix} 1 & s_h & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ | $x = v$<br>$y = s_h v + w$ | |





# Geometric spatial transformations (cont.)



- The effects and importance of interpolation in image transformations

a b c d

**FIGURE 2.36** (a) A 300 dpi image of the letter T. (b) Image rotated 21° clockwise using nearest neighbor interpolation to assign intensity values to the spatially transformed pixels. (c) Image rotated 21° using bilinear interpolation. (d) Image rotated 21° using bicubic interpolation. The enlarged sections show edge detail for the three interpolation approaches.





# Image Registration



- Estimate the transformation parameters between two images.
- Very important application of digital image processing.
  - Single and multimodal
  - Temporal evolution and quantitative analysis (medicine, satellite images)
- A basic approach is to use control points (user defined or automatically detected) and estimate the elements of the transformation matrix by solving a linear system.





# Image Registration (cont.)



Manually selected landmarks