Image Acquisition, Geometric Transformations, and Image Interpolation

Image Processing

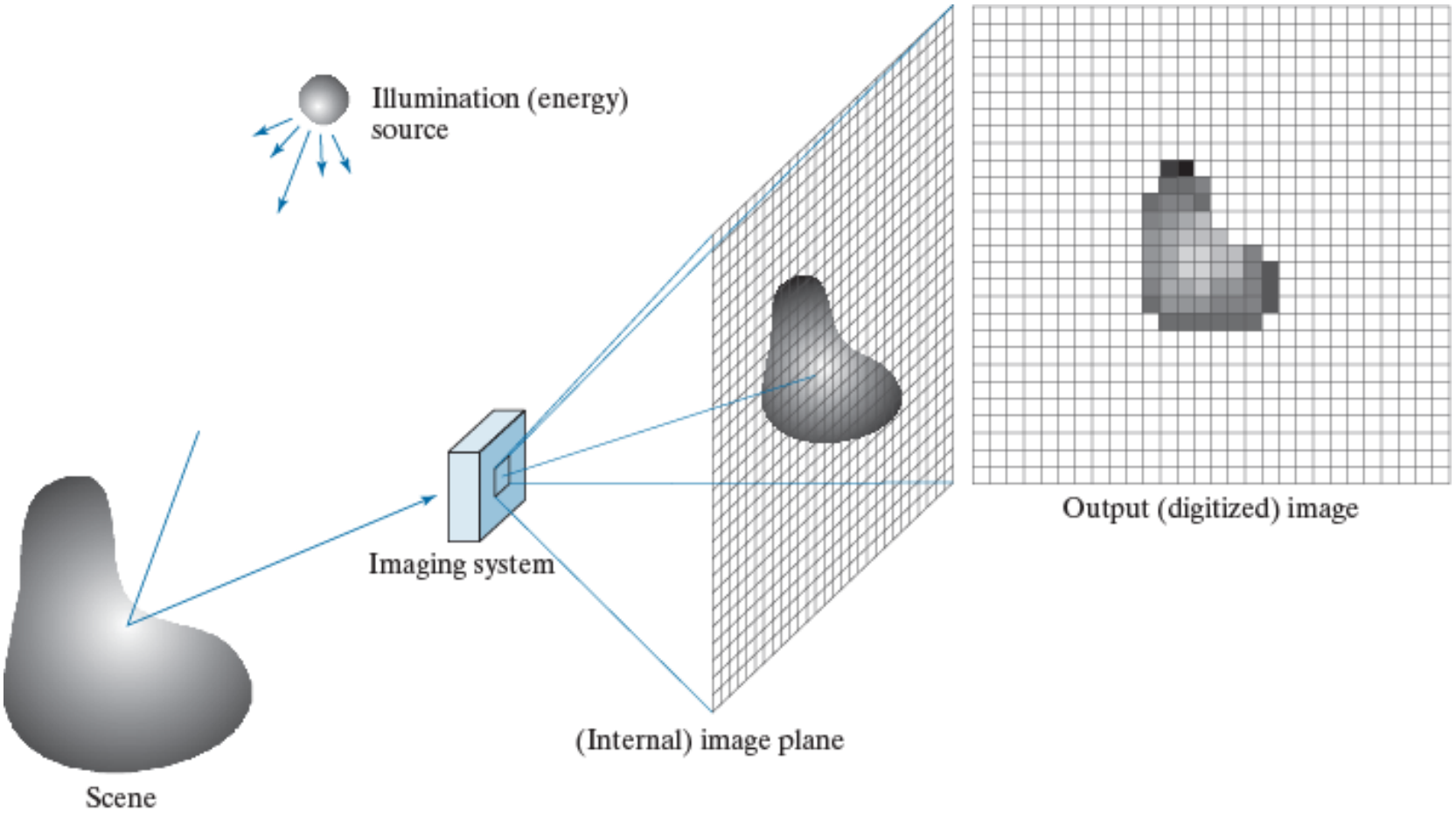
CSE 166

Lecture 2

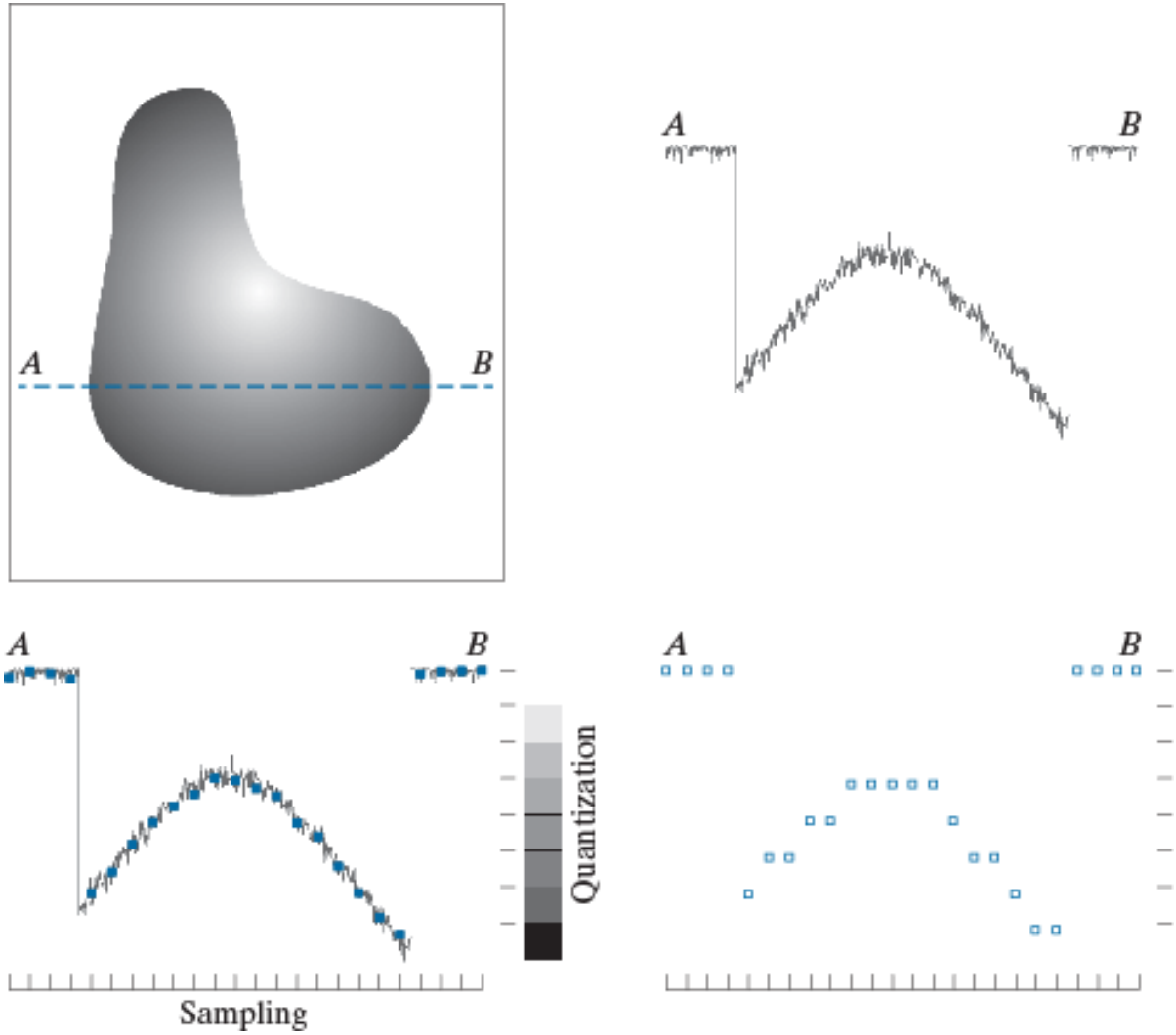
Announcements

- Assignment 1 will be released today
  - Due Apr 8, 11:59 PM
- Reading
  - Chapter 2: Digital Image Fundamentals
    - Sections 2.3, 2.4, and 2.5

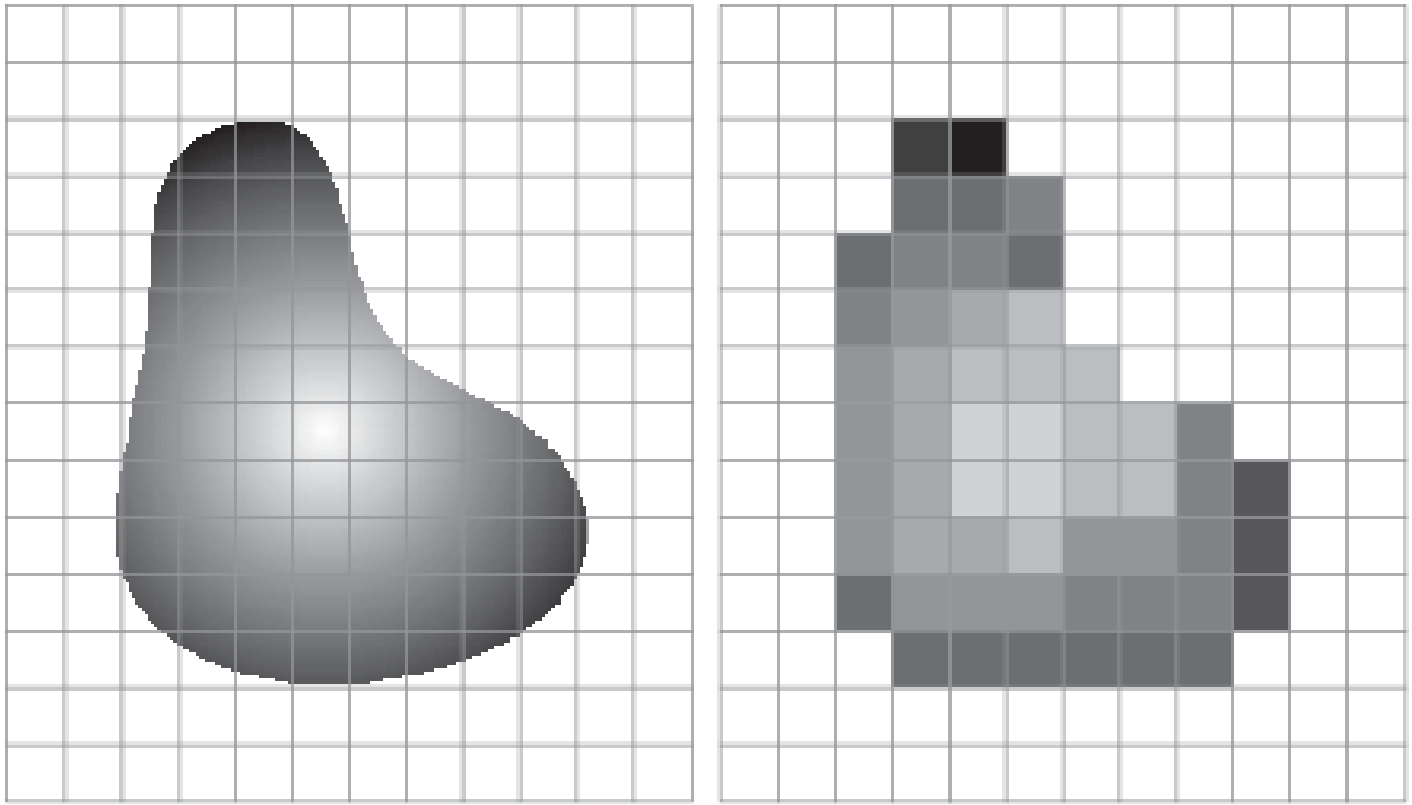
Image acquisition



Digitization, one row of image

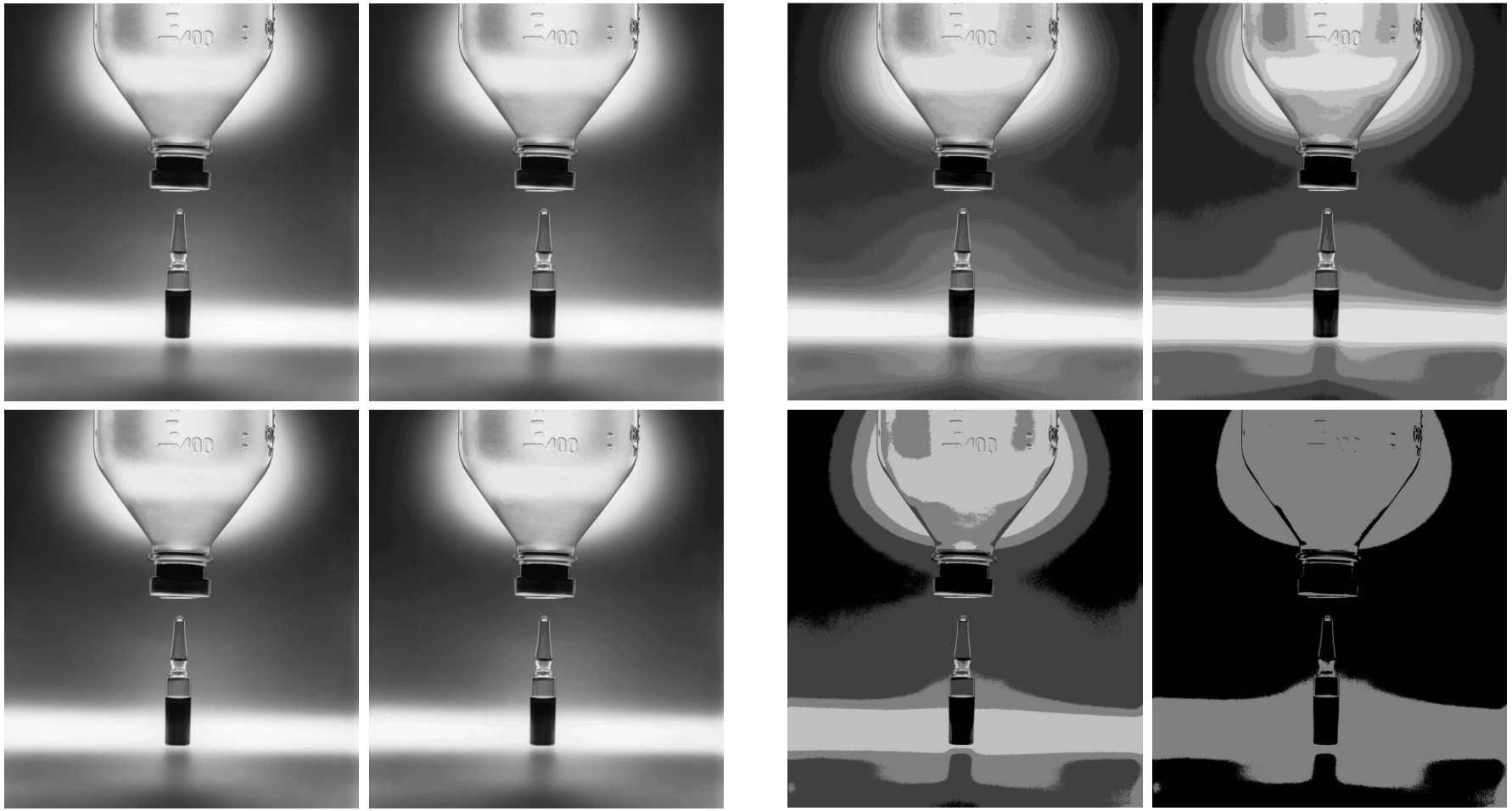


Digitization, whole image



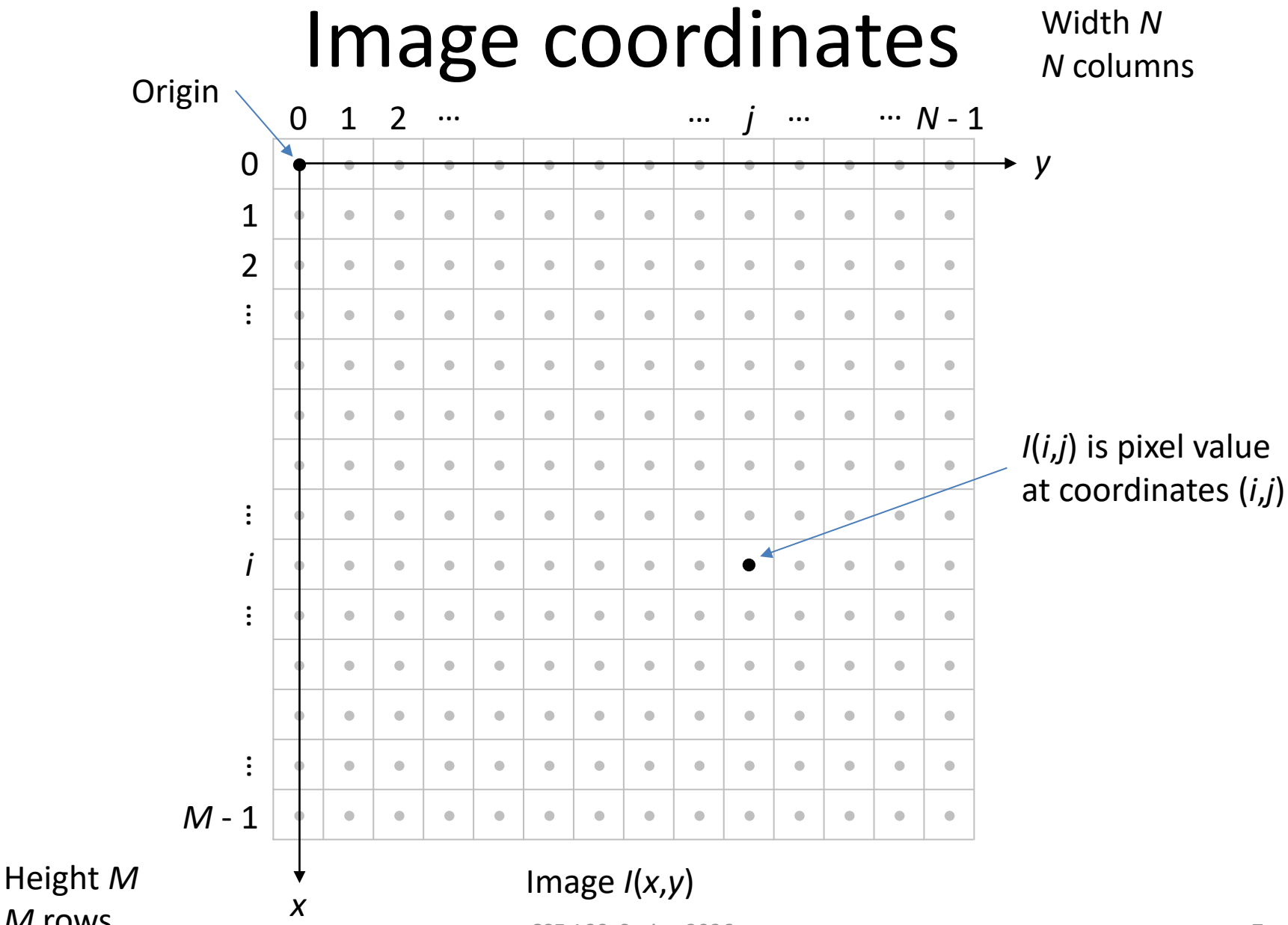
Number of quantization levels

256 128 16 8



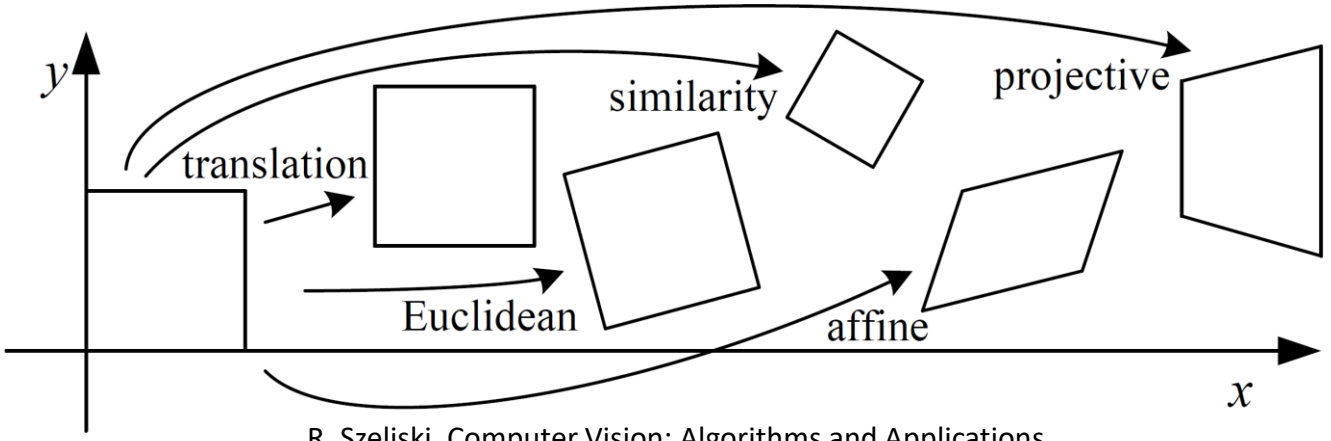
64 32 4 2

Image coordinates



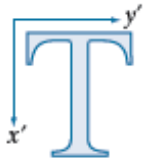
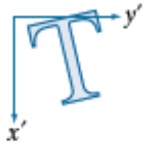
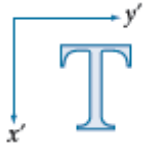
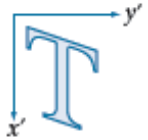
Geometric transformations

- Geometric transformations map n-dimensional geometric primitives to n-dimensional geometric primitives (e.g., 2D to 2D, 3D to 3D)
  - Example 2D geometric transformations



R. Szeliski, Computer Vision: Algorithms and Applications

Geometric transformations

Transformation Name	Affine Matrix, A	Coordinate Equations	Example
Identity	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x' = x$ $y' = y$	
Scaling/Reflection (For reflection, set one scaling factor to −1 and the other to 0)	$\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x' = c_x x$ $y' = c_y y$	
Rotation (about the origin)	$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x' = x\cos\theta - y\sin\theta$ $y' = x\sin\theta + y\cos\theta$	
Translation	$\begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$	$x' = x + t_x$ $y' = y + t_y$	
Shear (vertical)	$\begin{bmatrix} 1 & s_v & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x' = x + s_v y$ $y' = y$	
Shear (horizontal)	$\begin{bmatrix} 1 & 0 & 0 \\ s_h & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$x' = x$ $y' = s_h x + y$	

Geometric transformations

- Translation

$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$
$$\mathbf{x}' = \mathtt{H}_{\mathrm{t}}\mathbf{x}$$

- Rotation

$$x' = x\cos\theta - y\sin\theta$$
$$y' = x\sin\theta + y\cos\theta$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$
$$\mathbf{x}' = \mathtt{H}_{\mathrm{R}}\mathbf{x}$$

- Euclidean transformation
  - Rotation and translation

$$x' = x\cos\theta - y\sin\theta + t_x$$
$$y' = x\sin\theta + y\cos\theta + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & t_x \\ \sin\theta & \cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$
$$\mathbf{x}' = \mathtt{H}_{\mathrm{E}}\mathbf{x}$$

Geometric transformations

- Similarity transformation
  - Scale, rotation, and translation

$$x' = sx\cos\theta - sy\sin\theta + t_x$$
$$y' = sx\sin\theta + sy\cos\theta + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} s\cos\theta & -s\sin\theta & t_x \\ s\sin\theta & s\cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathtt{H}_\mathrm{S}\mathbf{x}$$

- Affine transformation
  - Linear transformation and translation

$$x' = a_{11}x + a_{12}y + a_{13}$$
$$y' = a_{21}x + a_{22}y + a_{23}$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

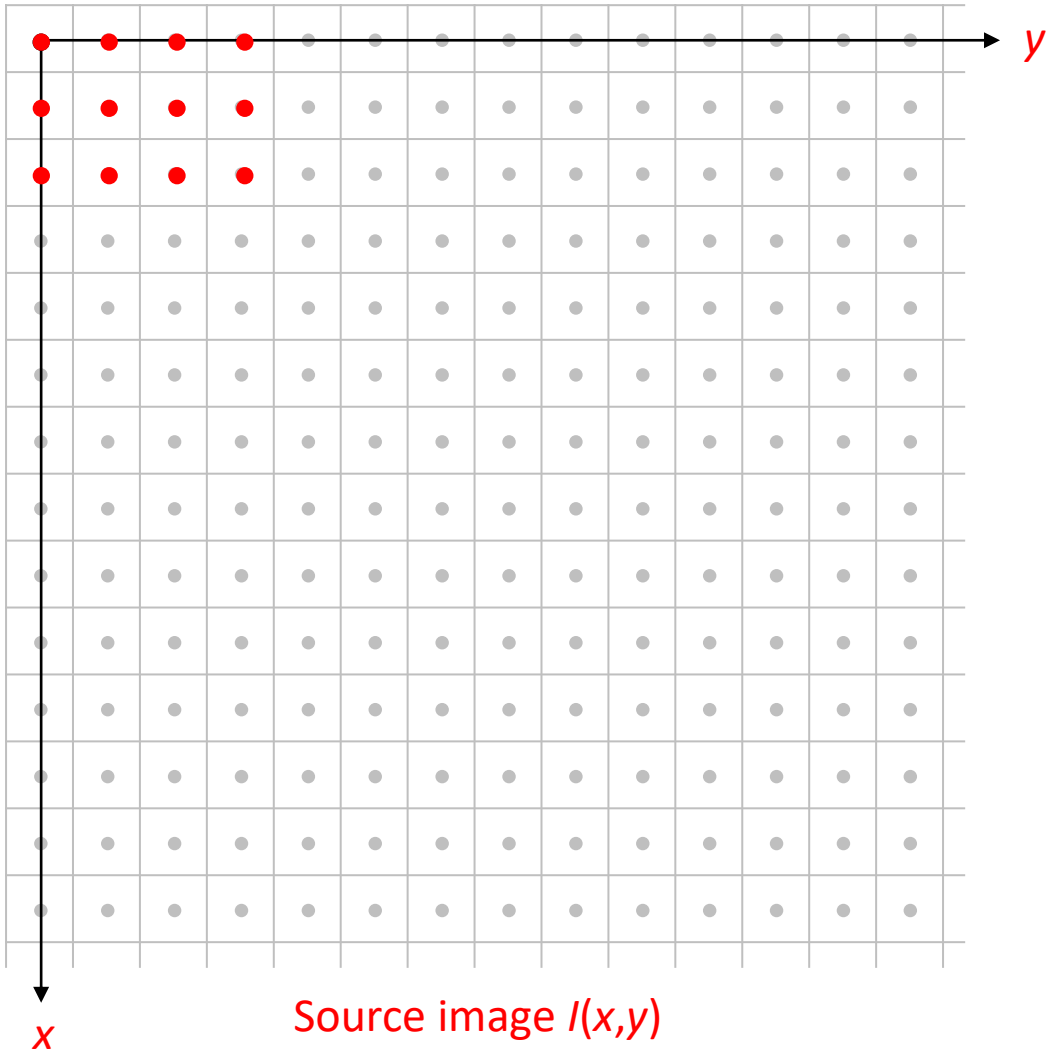
$$\mathbf{x}' = \mathtt{H}_\mathrm{A}\mathbf{x}$$

Geometric transformations

- Example 1
  - Translation

    $t_x = 5$

    $t_y = 3$



$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

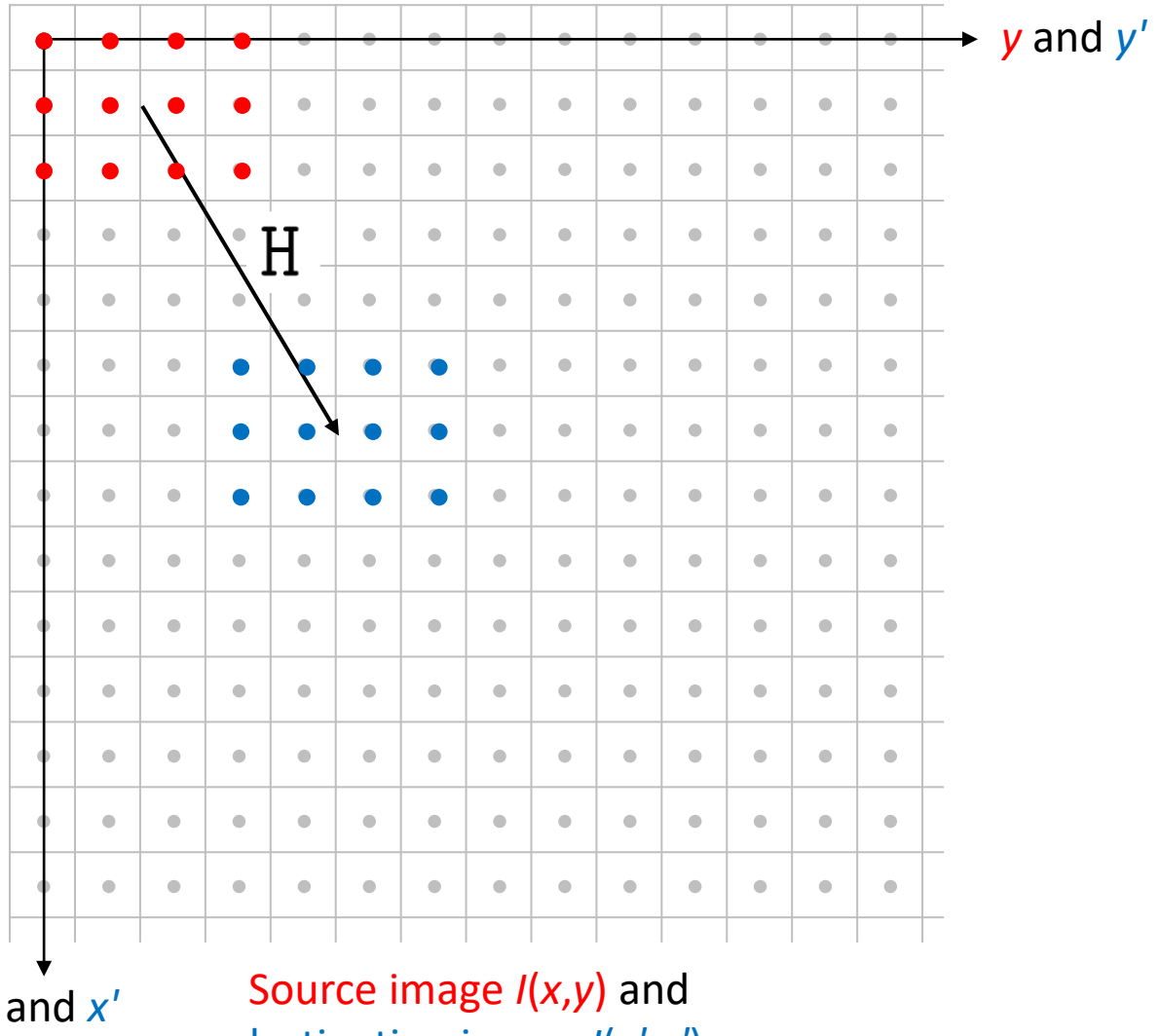
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 1
  - Translation

    $t_x = 5$

    $t_y = 3$



Source image $I(x,y)$ and destination image $J(x',y')$

$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

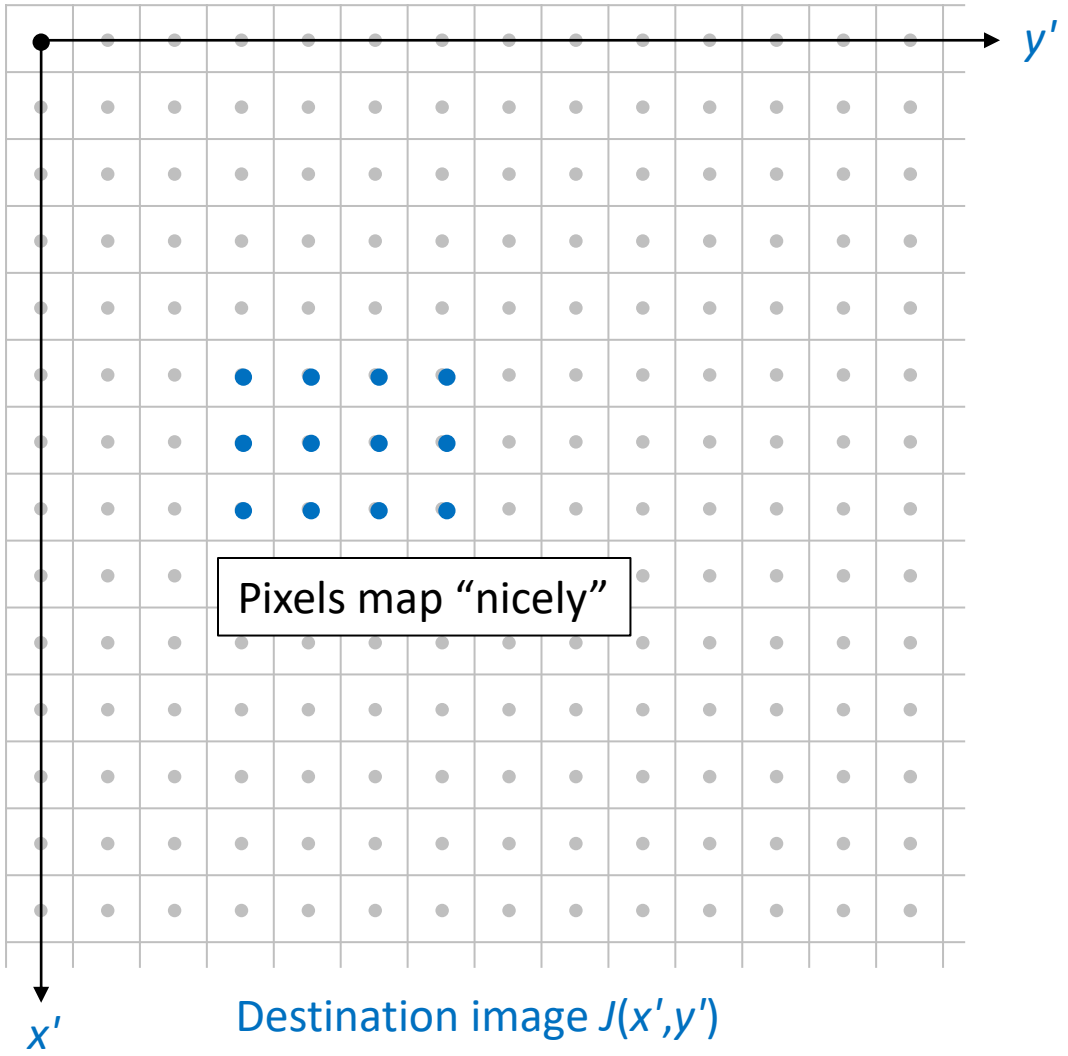
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 1
  - Translation

    $t_x = 5$

    $t_y = 3$



$$x' = x + t_x$$
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$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 2
  - Translation

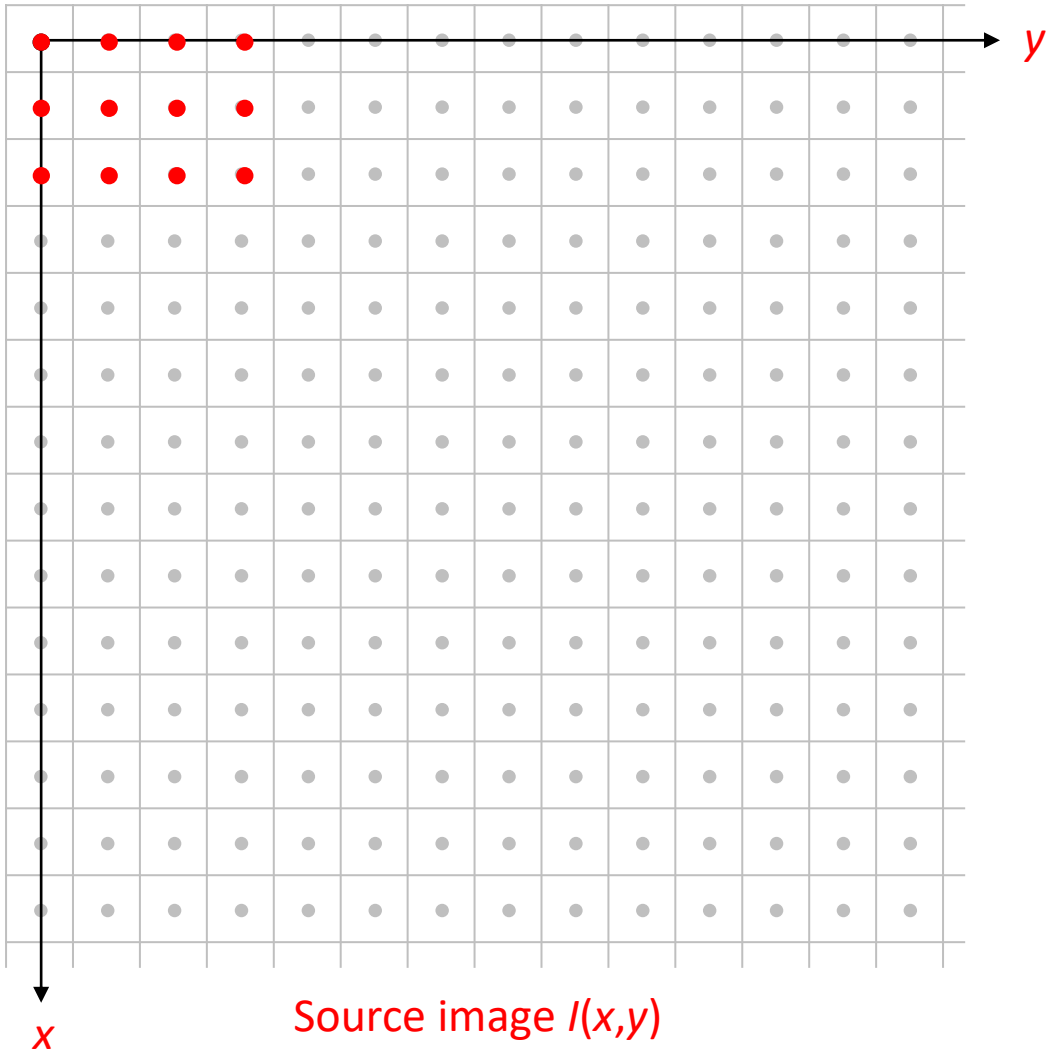
    t_x = 5.2

    t_y = 3.6

$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

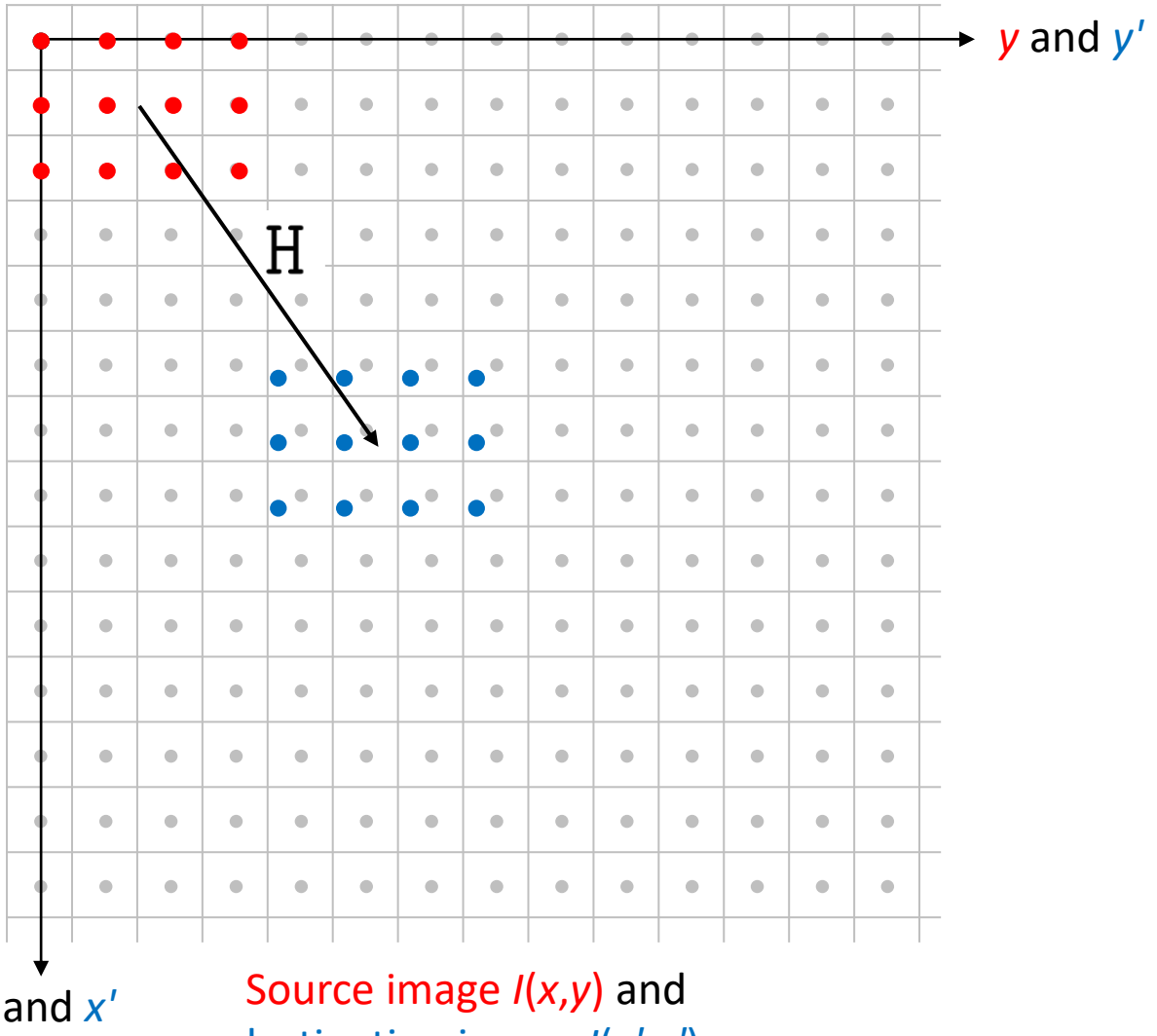


Geometric transformations

- Example 2
  - Translation

    $t_x = 5.2$

    $t_y = 3.6$



Source image $I(x,y)$ and destination image $J(x',y')$

$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 2
  - Translation

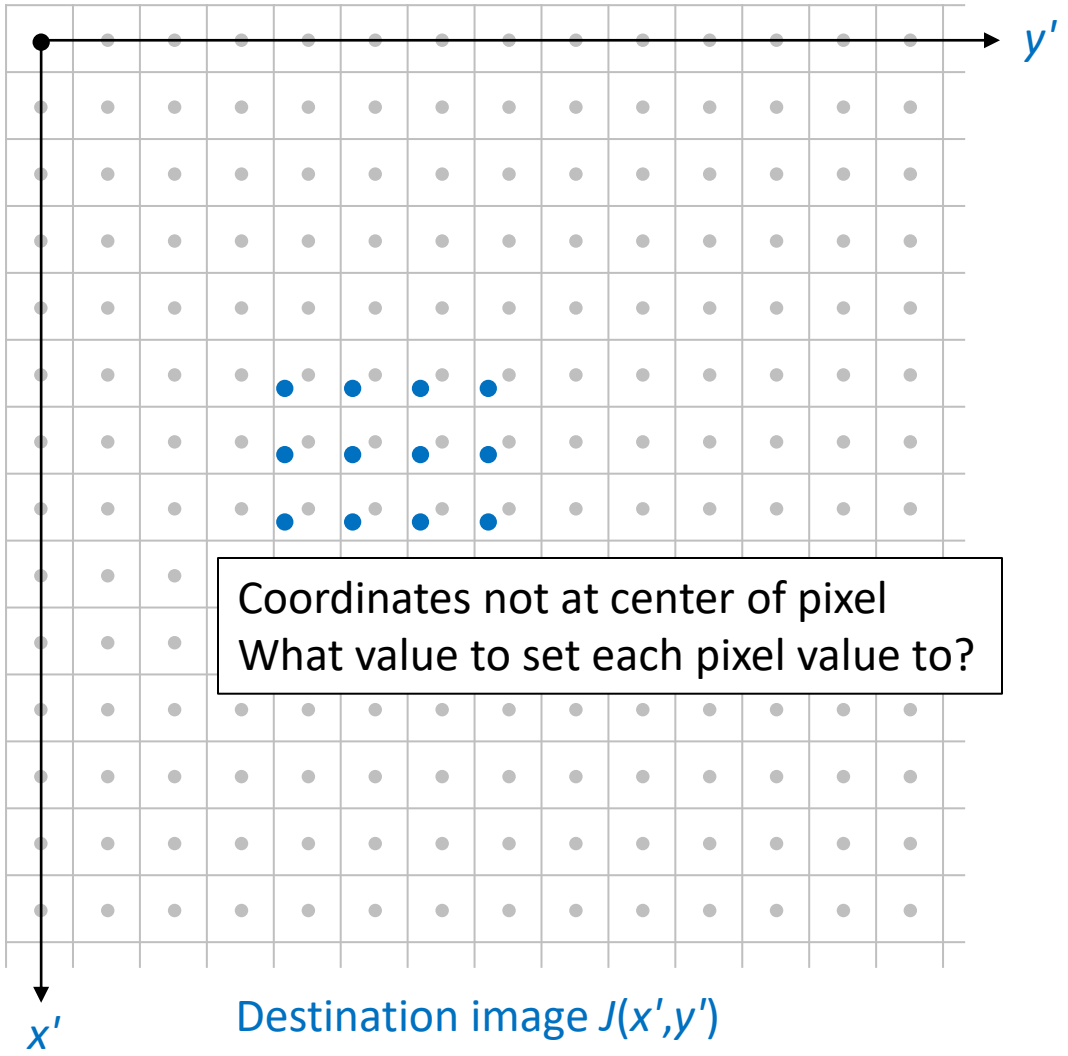
    $t_x = 5.2$

    $t_y = 3.6$

$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

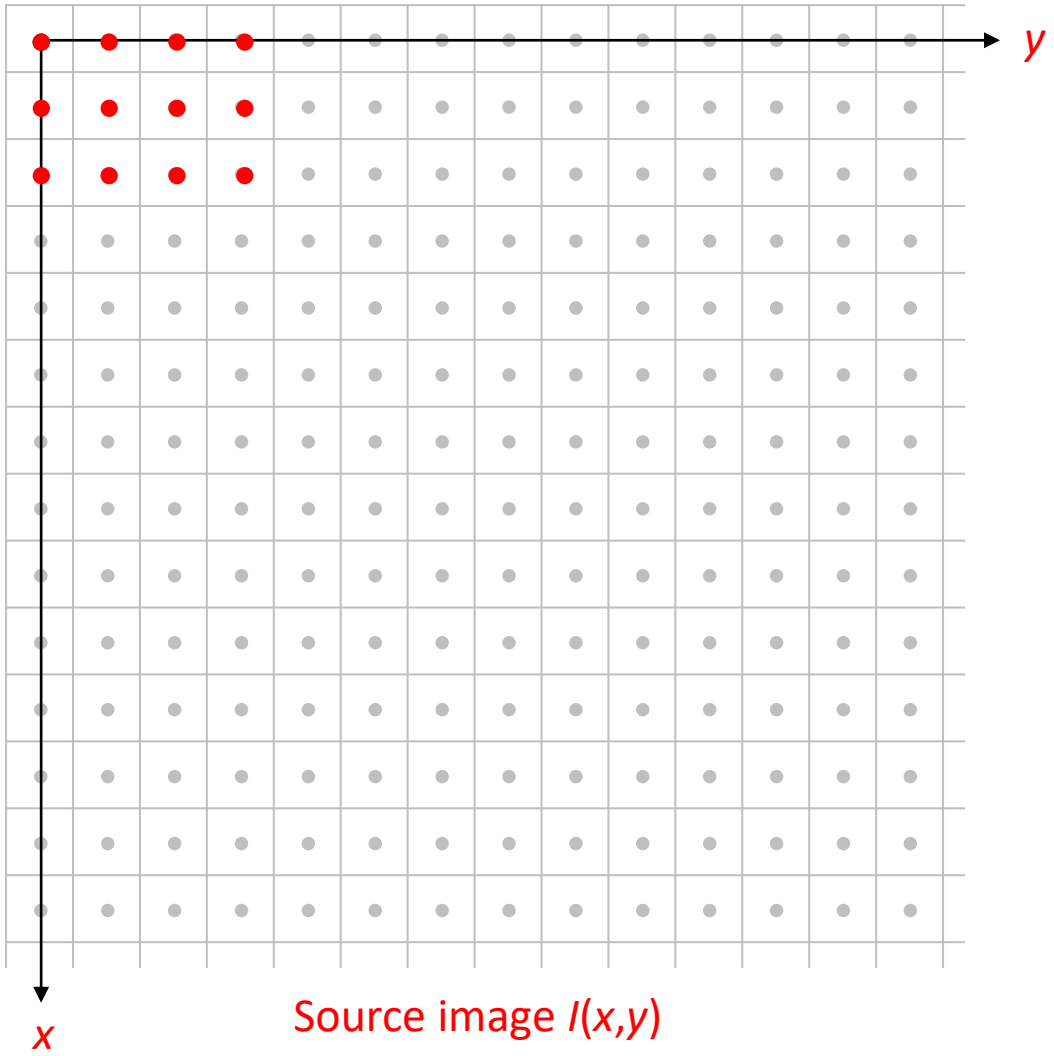


Geometric transformations

- Example 3
  - Scale by 0.5

    $c_x = 0.5$

    $c_y = 0.5$



Source image $I(x,y)$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$

Geometric transformations

- Example 3
  - Scale by 0.5

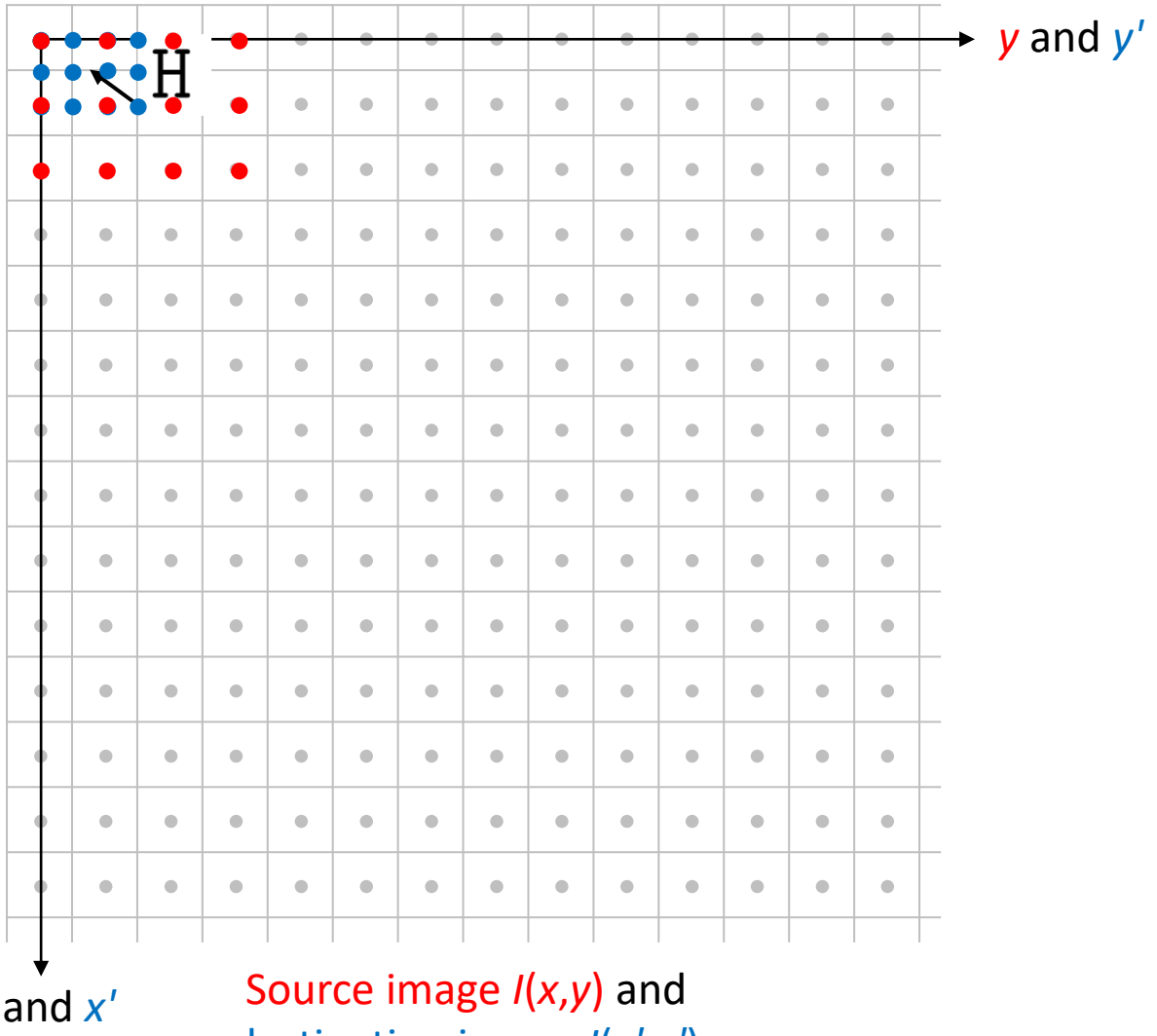
    $c_x = 0.5$

    $c_y = 0.5$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Source image $I(x,y)$ and destination image $J(x',y')$

Geometric transformations

- Example 3
  - Scale by 0.5

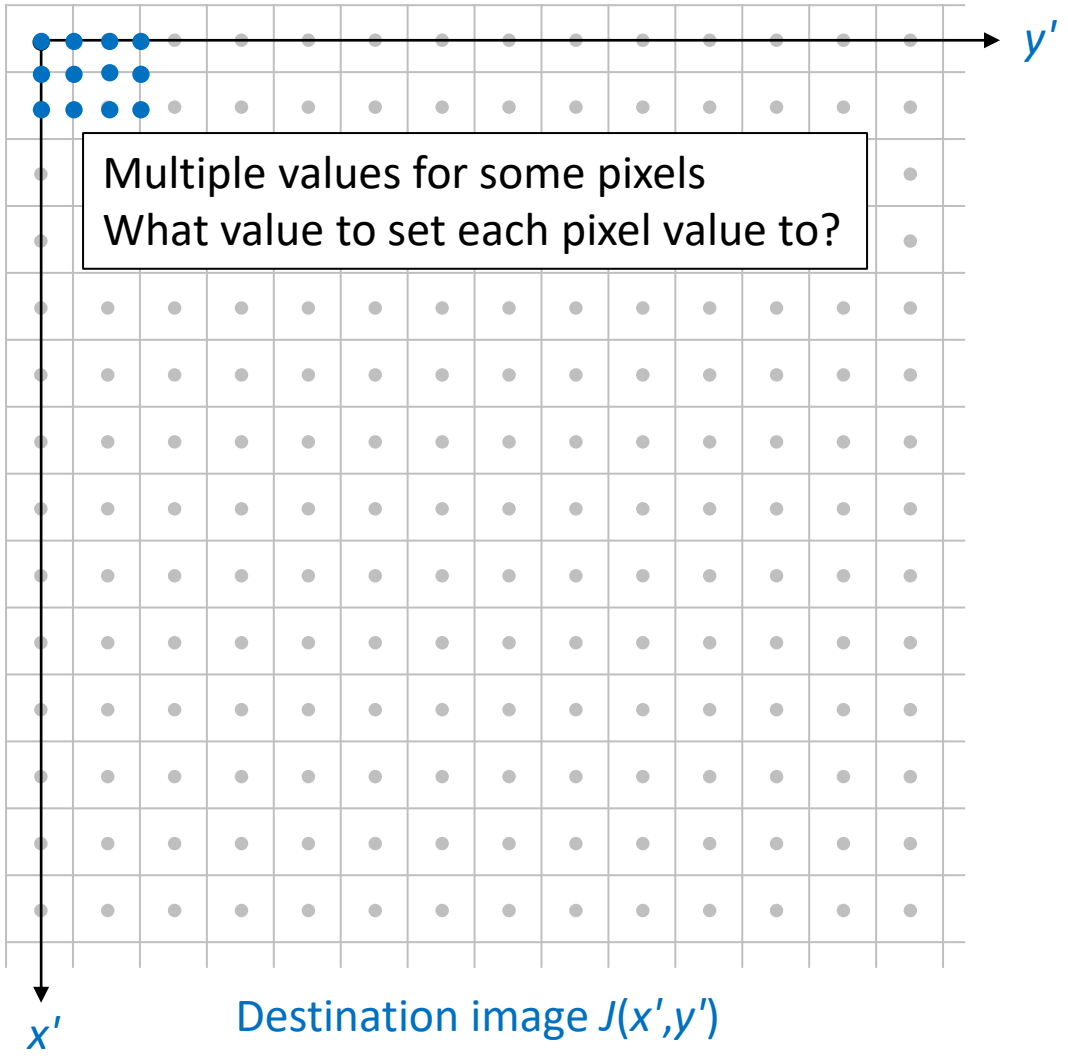
$c_x = 0.5$

$c_y = 0.5$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Geometric transformations

- Example 4
  - Scale by 2

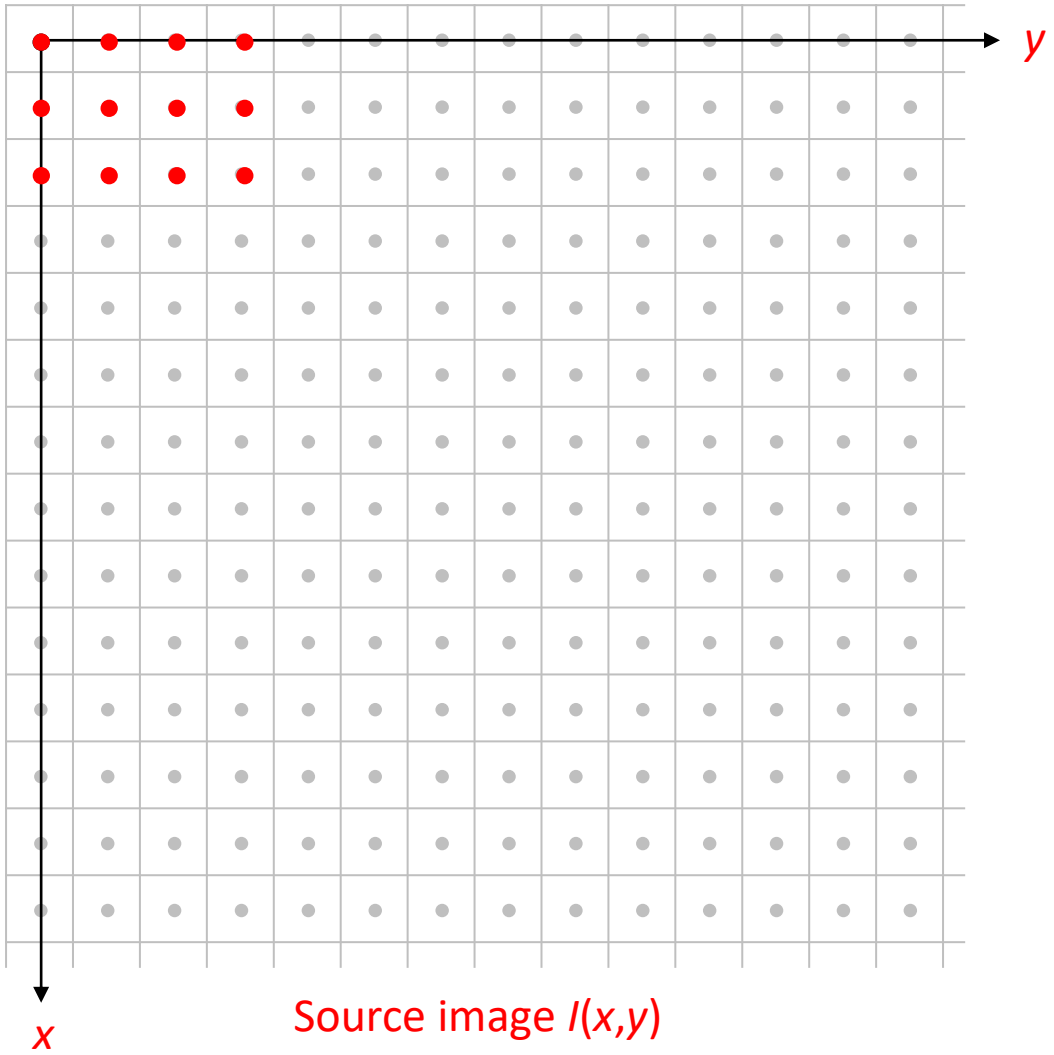
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Source image *I*(*x*,*y*)

Geometric transformations

- Example 4
  - Scale by 2

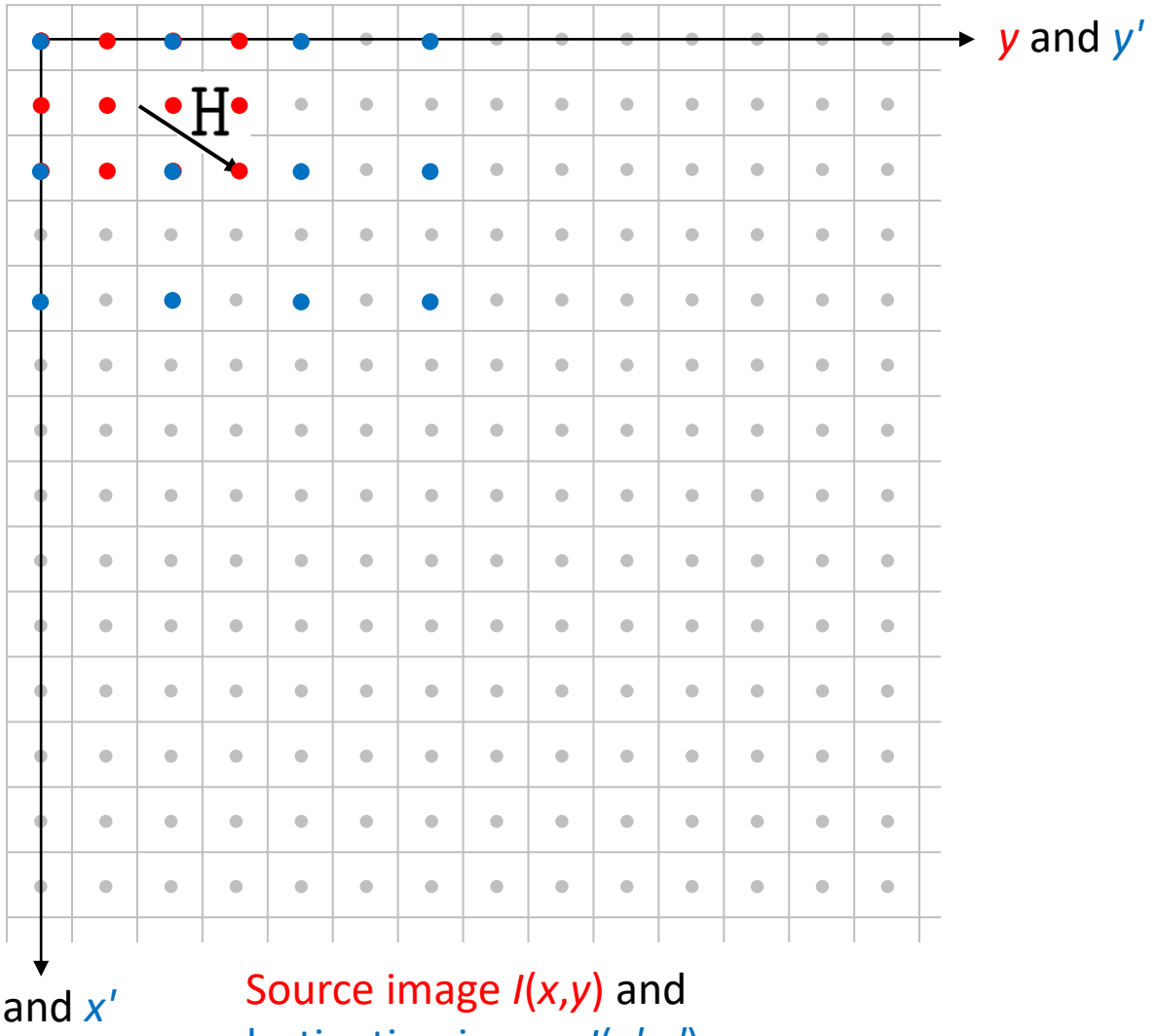
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Source image $I(x,y)$ and destination image $J(x',y')$

Geometric transformations

- Example 4
  - Scale by 2

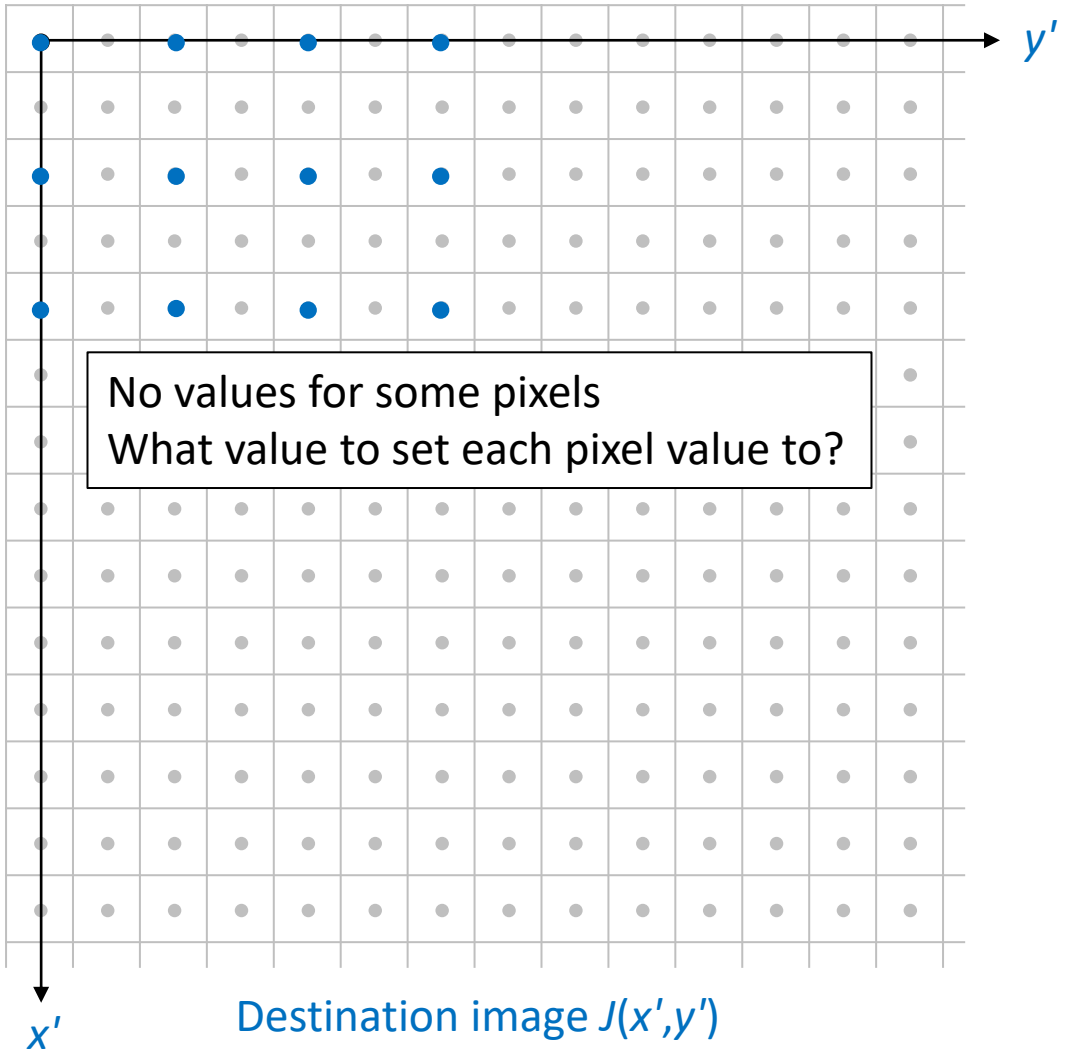
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$

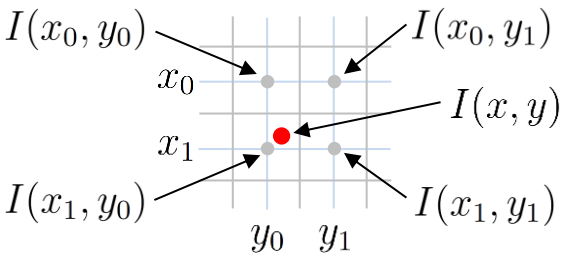


Geometric transformations

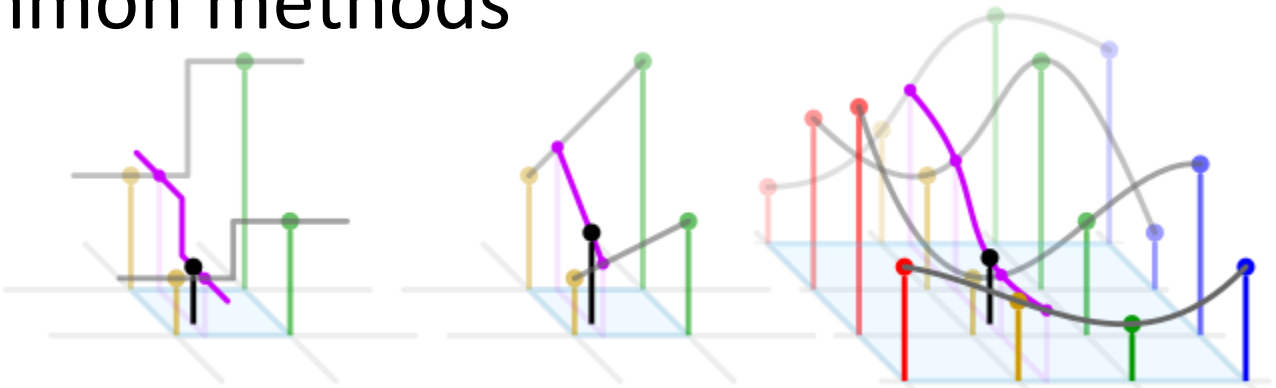
- Problem
  - In general, pixels in the source image will not map "nicely" to pixels in the destination image
- Solution
  - Instead of mapping each pixel in the source image to the destination image, **inverse** map each pixel coordinate in the destination image to the source image then set destination image pixel value to the source image **interpolated** pixel value at the point mapped to

Interpolation

- Estimate *I*(*x*,*y*)



- Common methods



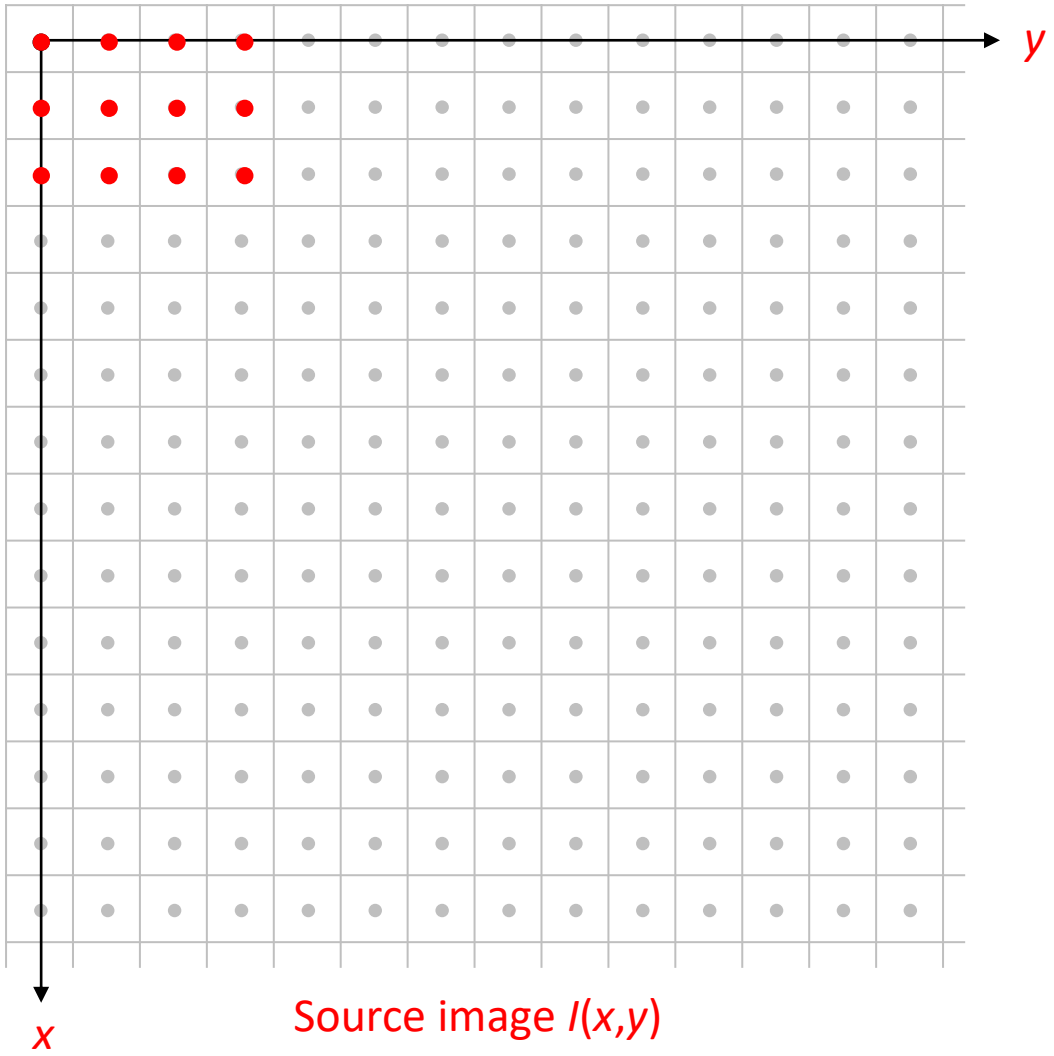
Nearest neighbor Bilinear Bicubic

Geometric transformations

- Example 1
  - Translation

    $t_x = 5$

    $t_y = 3$



$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

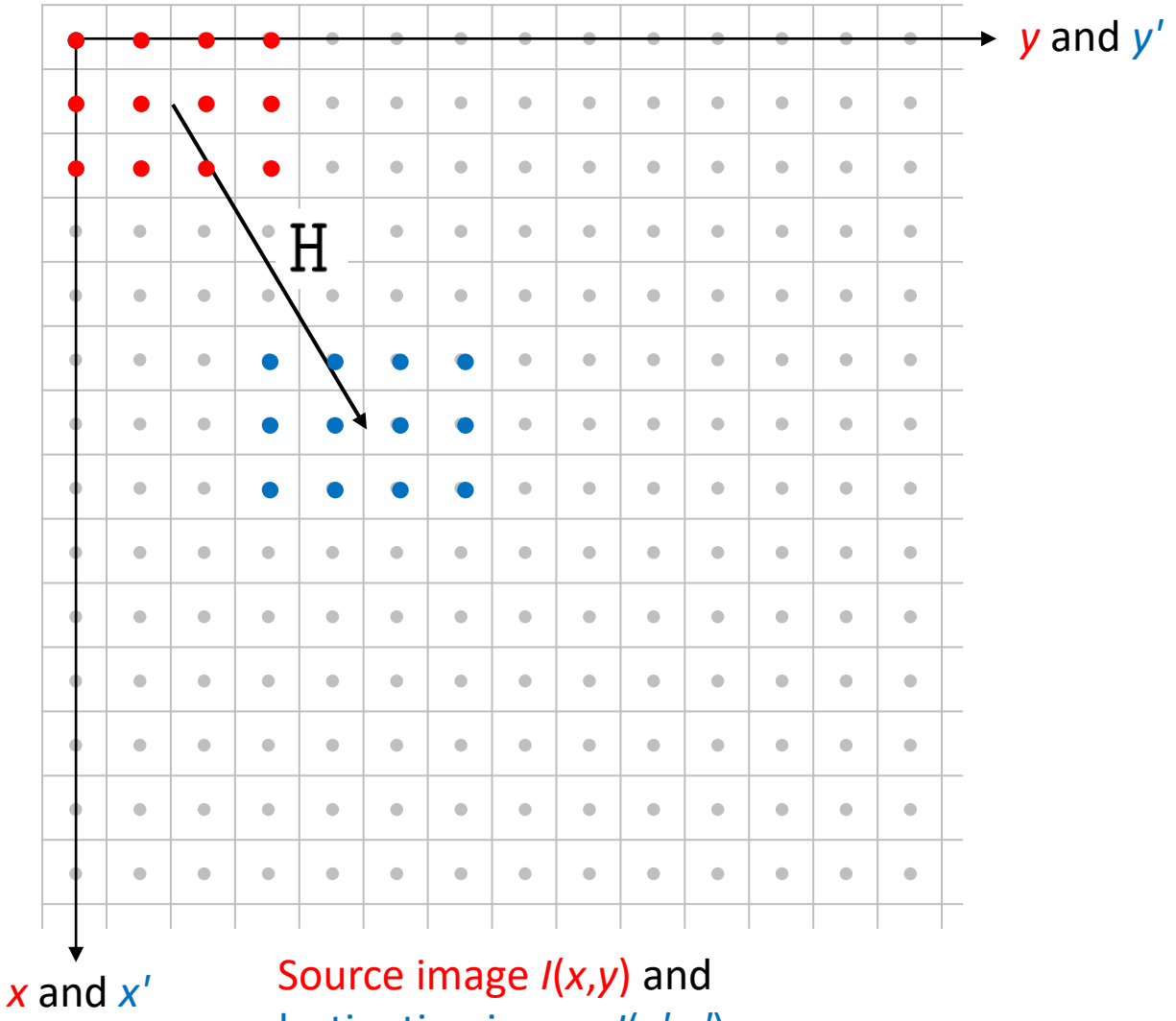
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 1
  - Translation

    $t_x = 5$

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$$x' = x + t_x$$
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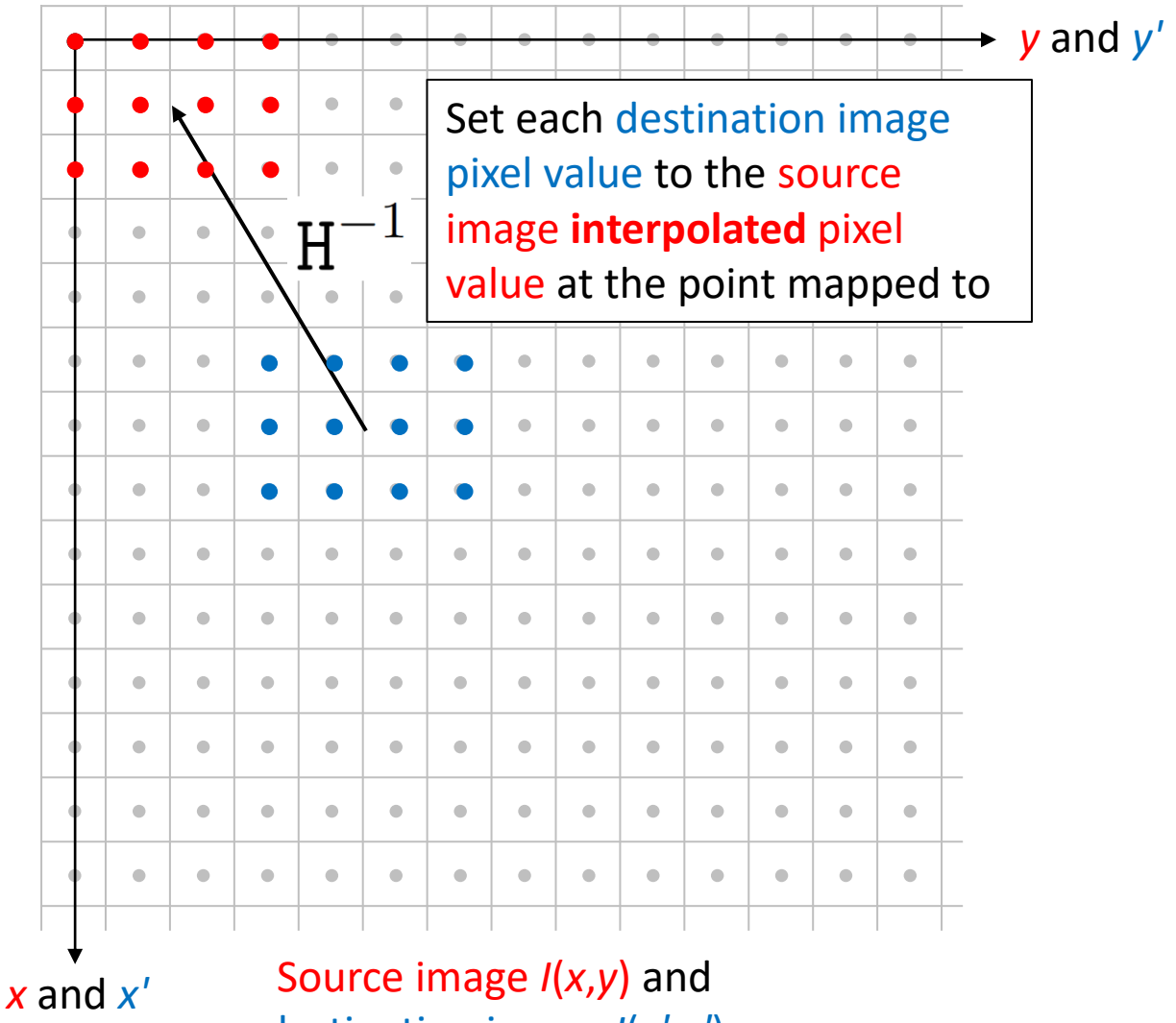
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Inverse transform

- Example 1

$$\mathbf{x}' = \mathbf{H}\mathbf{x}$$
$$\mathbf{x} = \mathbf{H}^{-1}\mathbf{x}'$$

- Also called backward transform

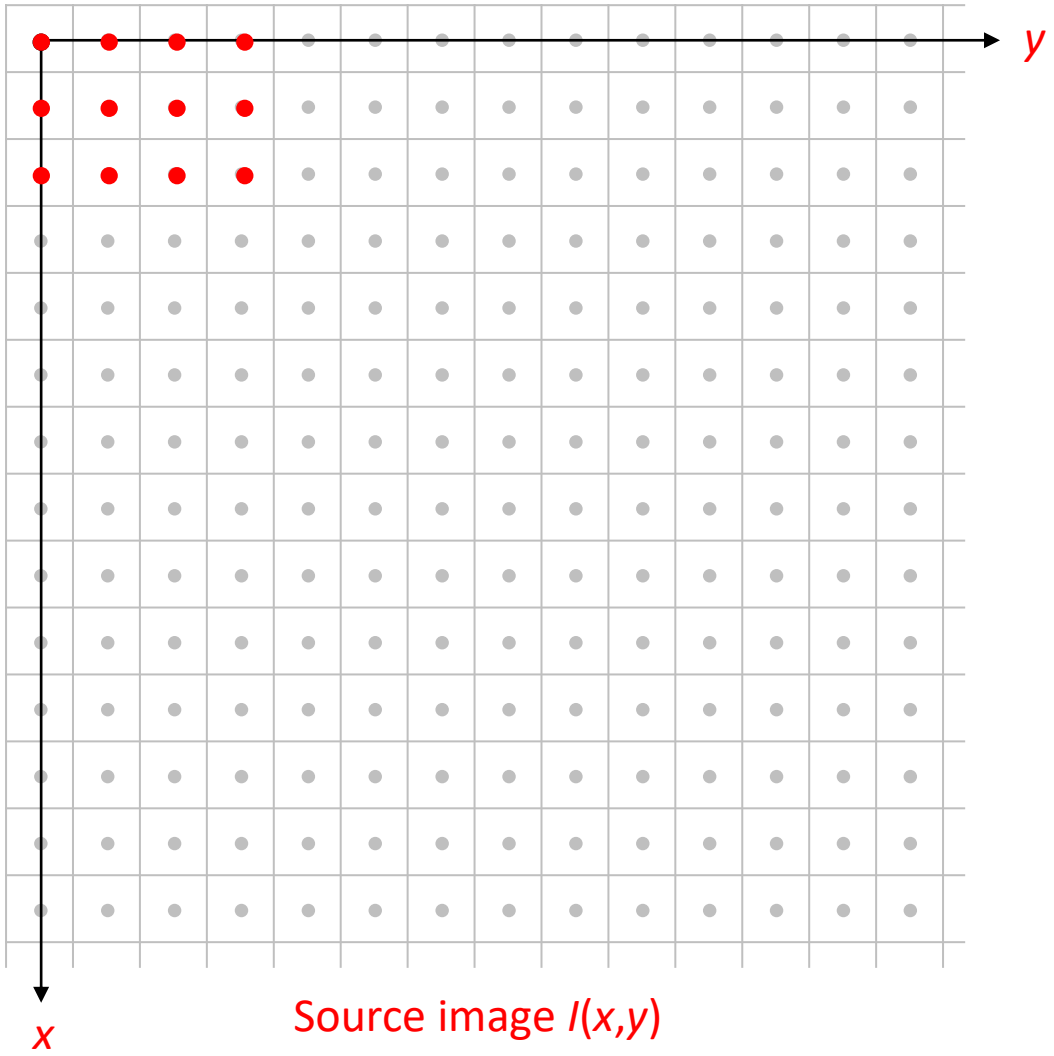


Geometric transformations

- Example 2
  - Translation

    t_x = 5.2

    t_y = 3.6



$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

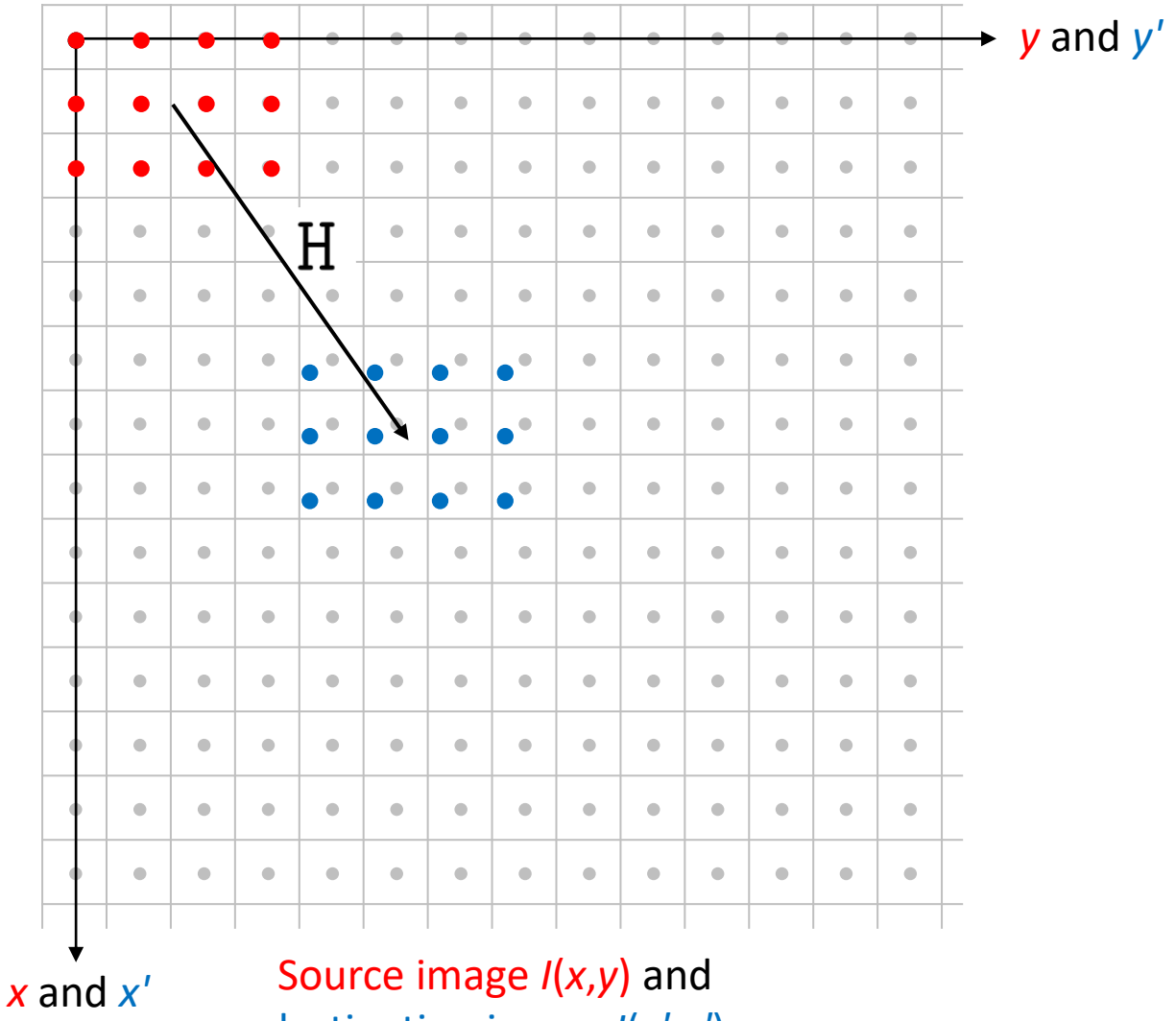
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 2
  - Translation

    $t_x = 5.2$

    $t_y = 3.6$



Source image $I(x,y)$ and destination image $J(x',y')$

$$x' = x + t_x$$
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$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Geometric transformations

- Example 2
  - Translation

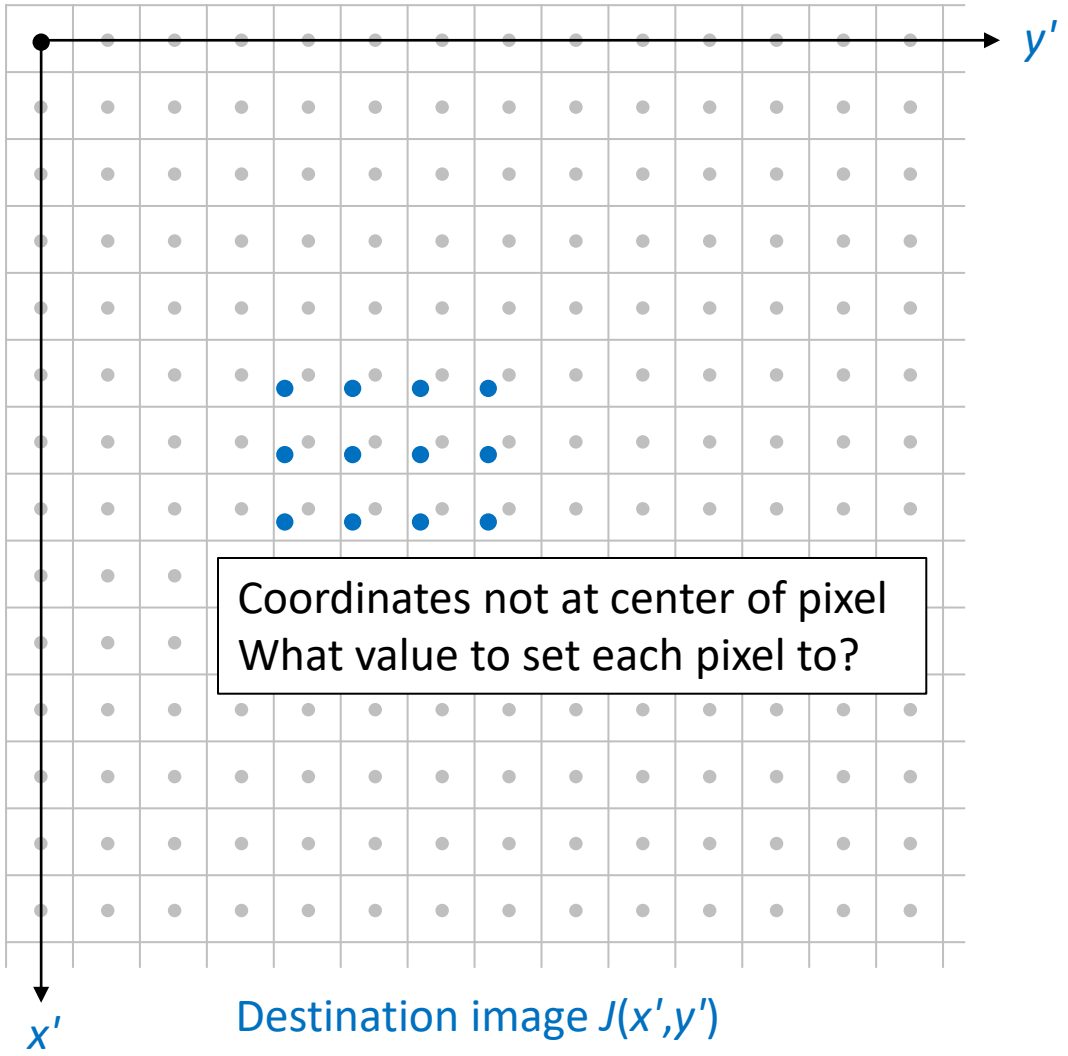
    $t_x = 5.2$

    $t_y = 3.6$

$$x' = x + t_x$$
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$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

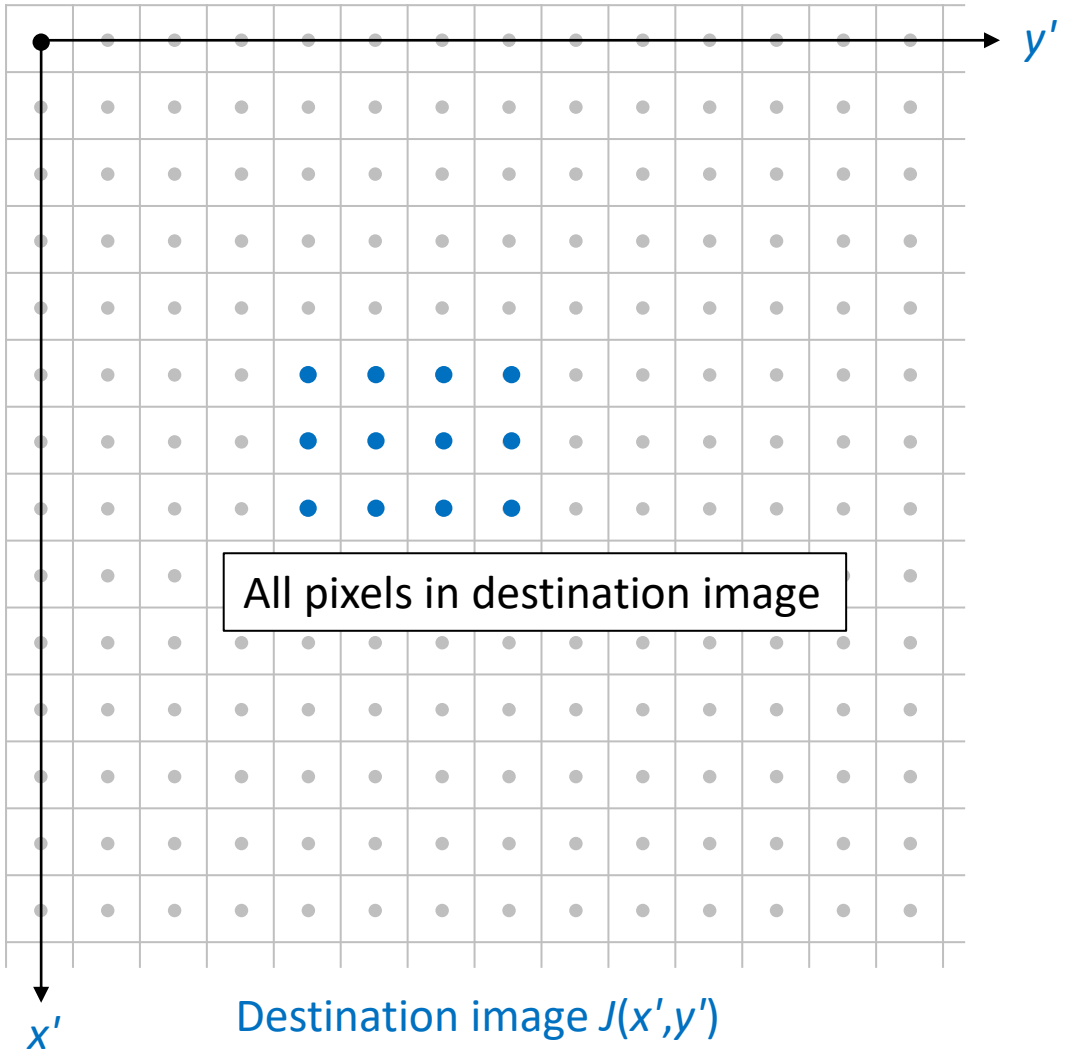


Geometric transformations

- Example 2
  - Translation

    $t_x = 5.2$

    $t_y = 3.6$



$$x' = x + t_x$$
$$y' = y + t_y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

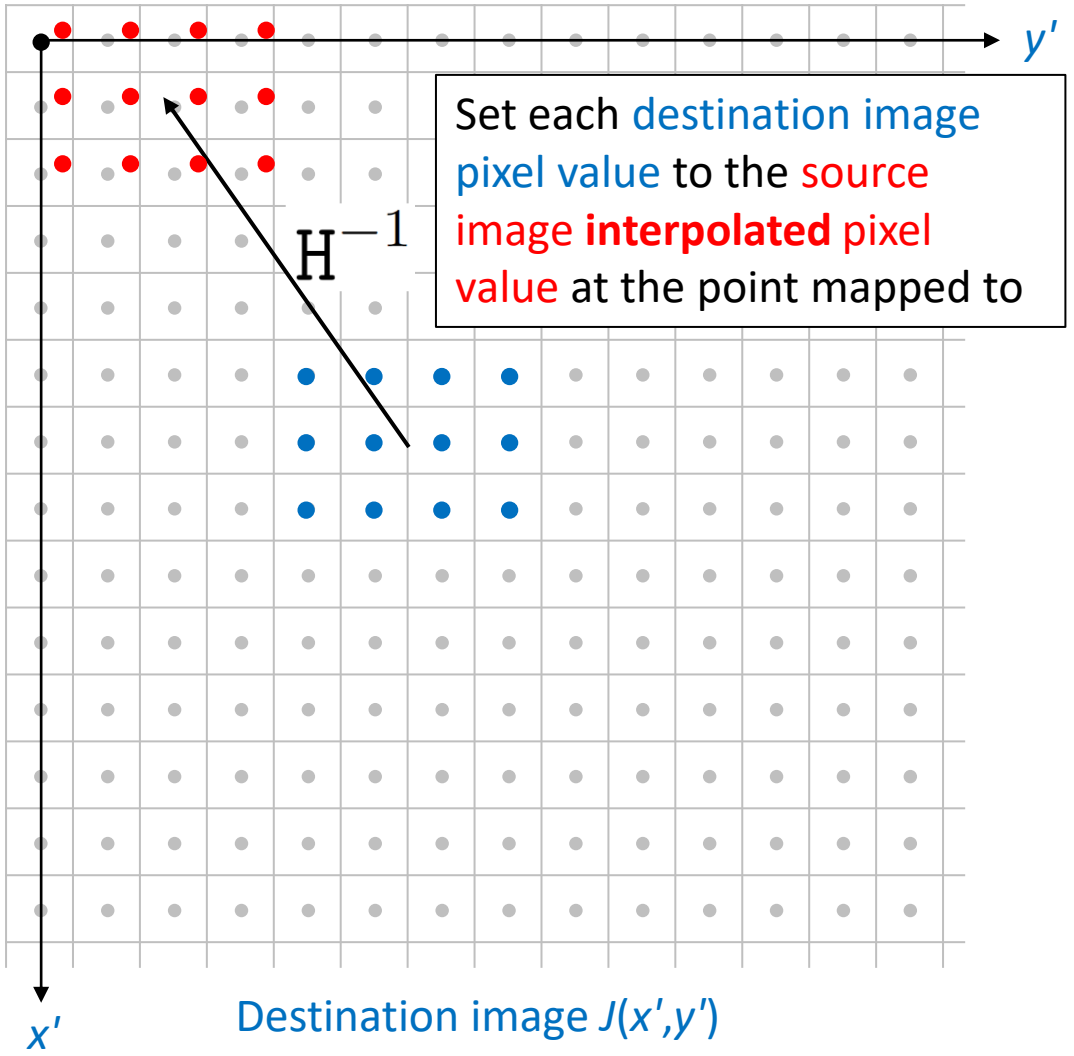
$$\mathbf{x}' = \mathrm{H_t}\mathbf{x}$$

Inverse transform

- Example 2

$$\mathbf{x}' = \mathbf{H}\mathbf{x}$$
$$\mathbf{x} = \mathbf{H}^{-1}\mathbf{x}'$$

- Also called backward transform

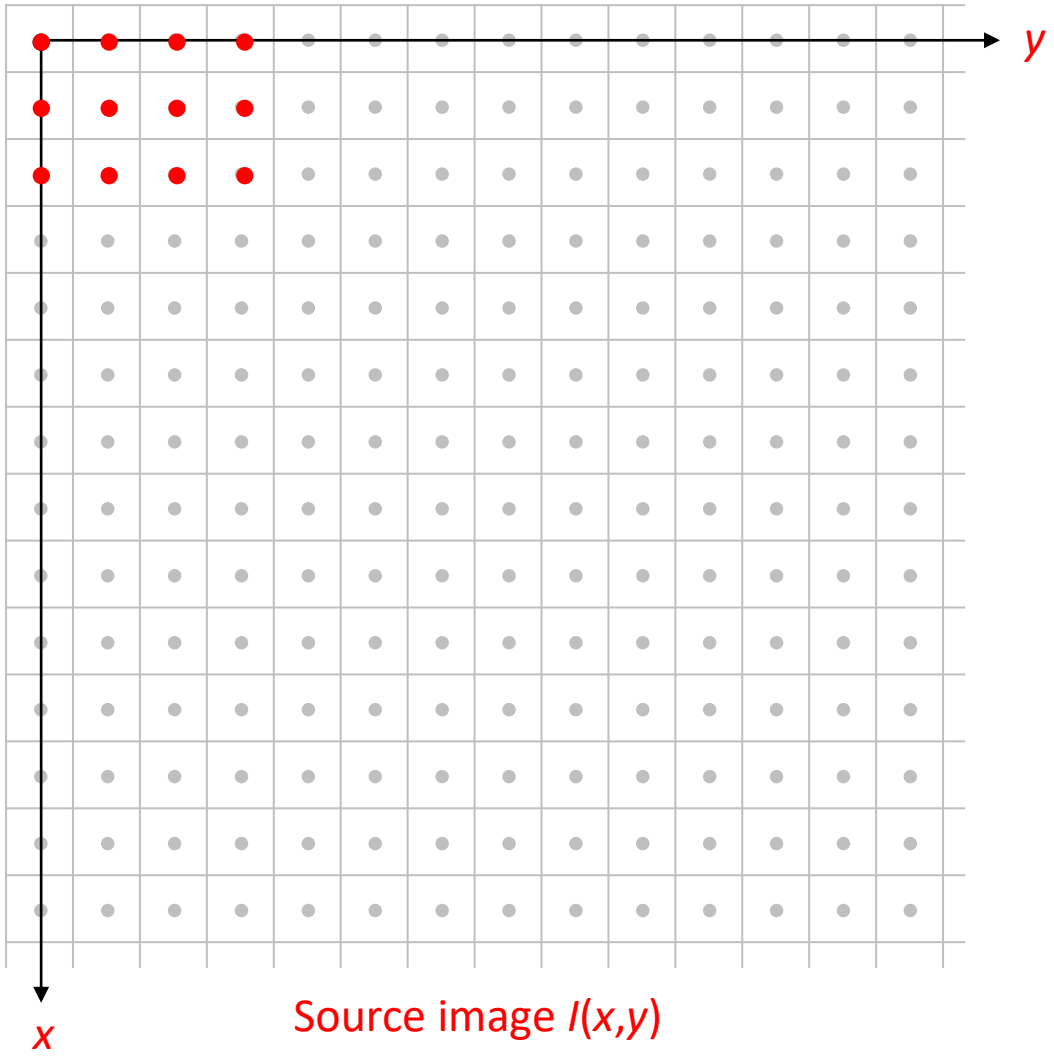


Geometric transformations

- Example 3
  - Scale by 0.5

    $c_x = 0.5$

    $c_y = 0.5$



$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

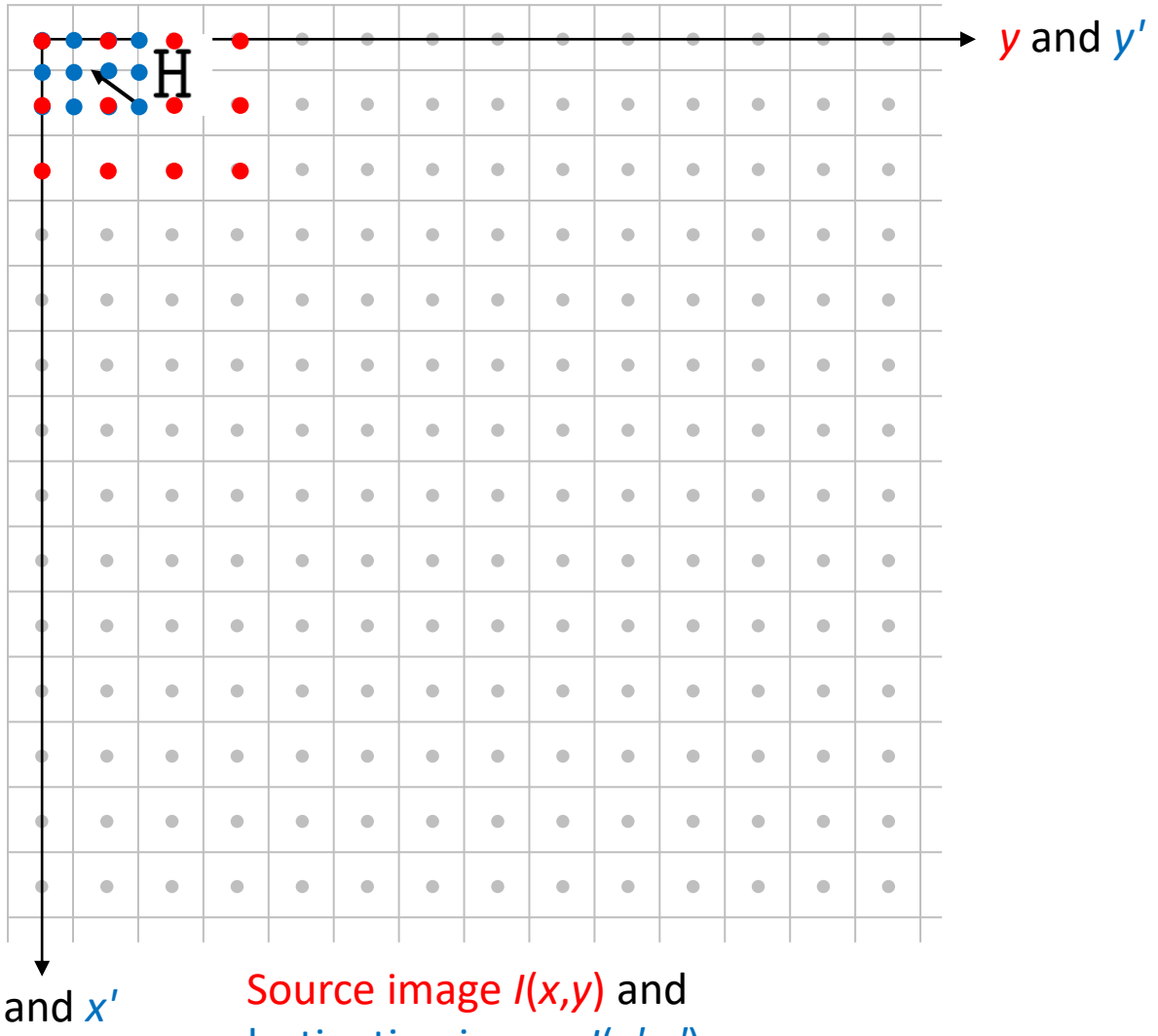
$$\mathbf{x}' = \mathrm{H_c}\mathbf{x}$$

Geometric transformations

- Example 3
  - Scale by 0.5

    $c_x = 0.5$

    $c_y = 0.5$



Source image $I(x,y)$ and destination image $J(x',y')$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$

Geometric transformations

- Example 3
  - Scale by 0.5

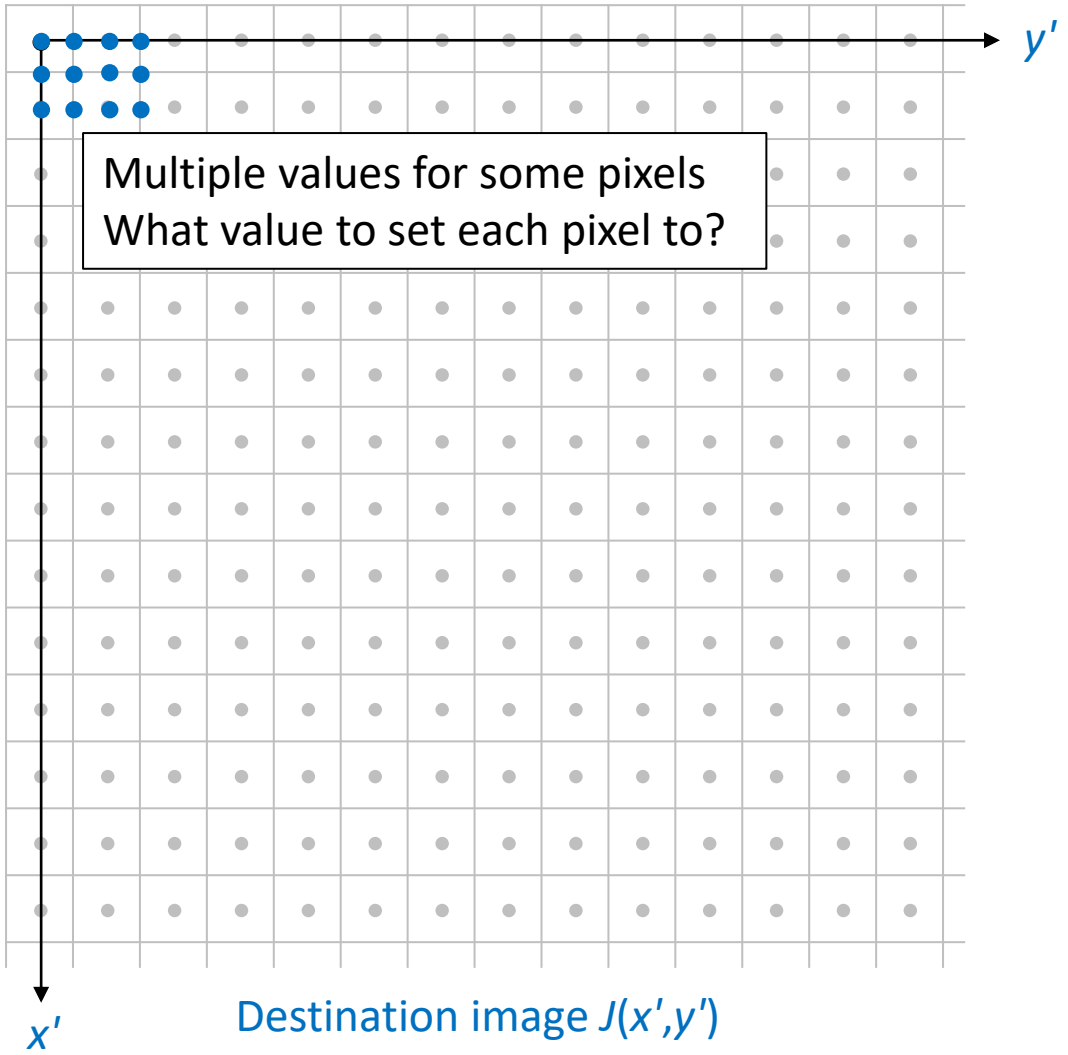
$c_x = 0.5$

$c_y = 0.5$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Geometric transformations

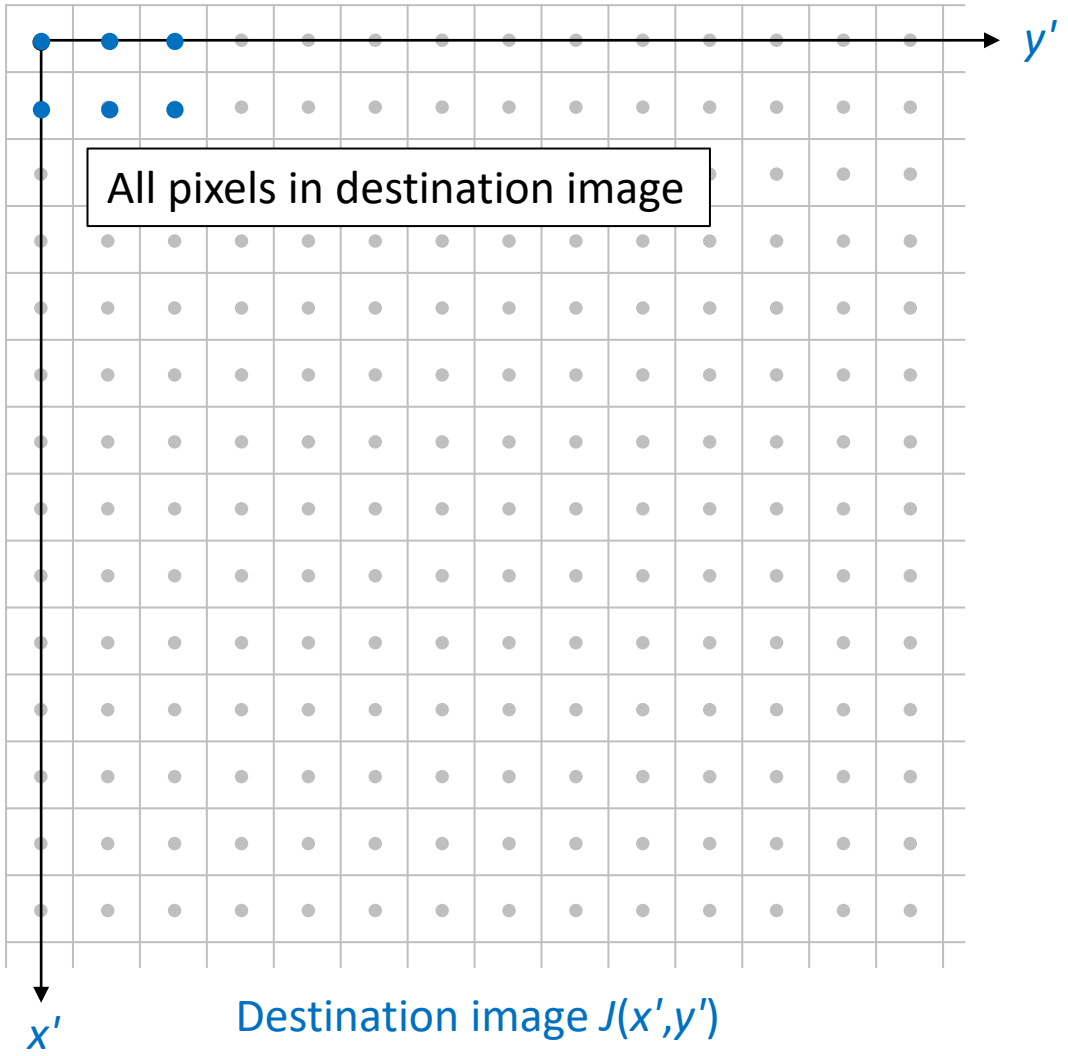
- Example 3
  - Scale by 0.5

    $c_x = 0.5$

    $c_y = 0.5$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$
$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$

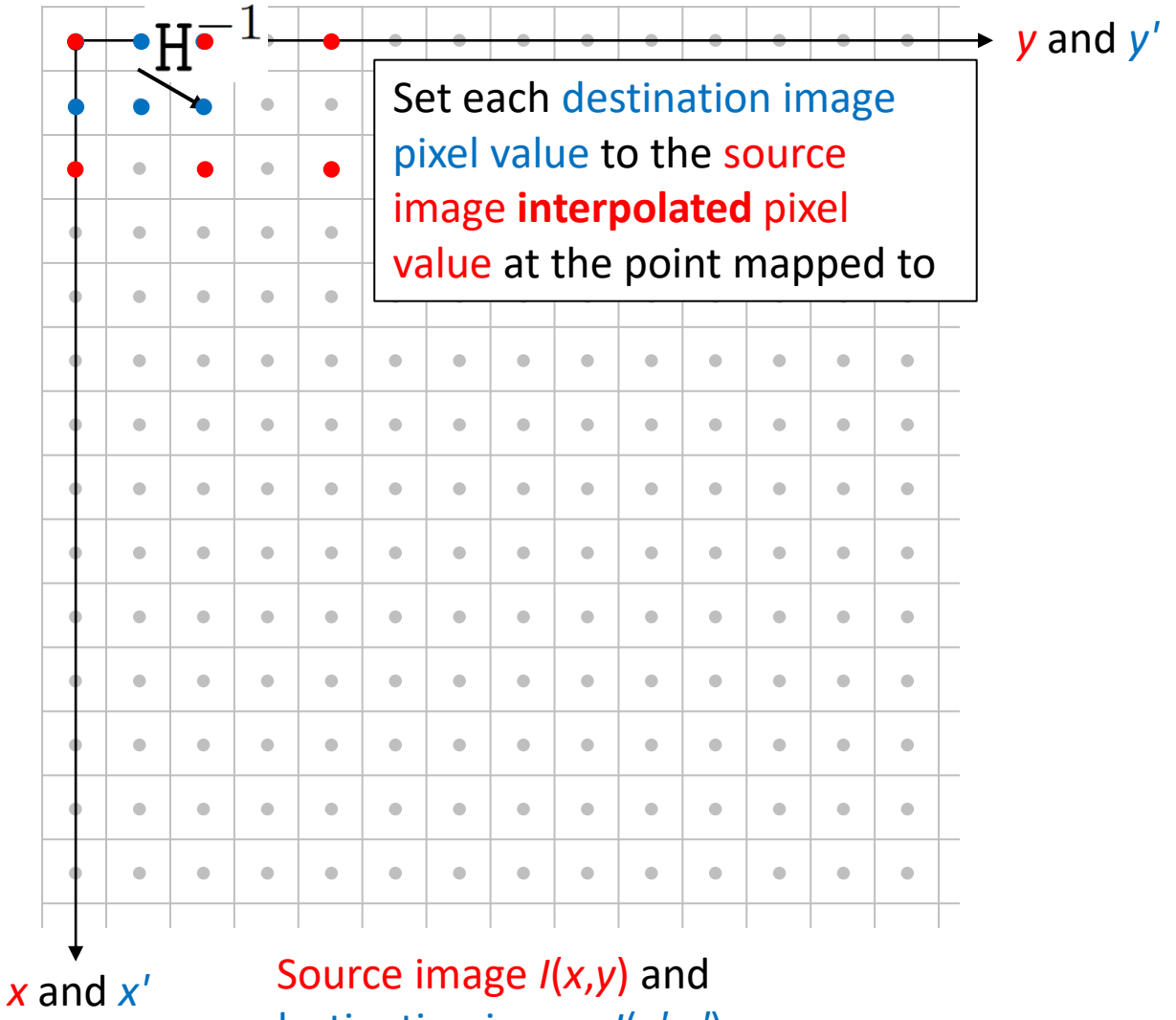


Inverse transform

- Example 3

$$\mathbf{x}' = \mathbf{H}\mathbf{x}$$
$$\mathbf{x} = \mathbf{H}^{-1}\mathbf{x}'$$

- Also called backward transform



Geometric transformations

- Example 4
  - Scale by 2

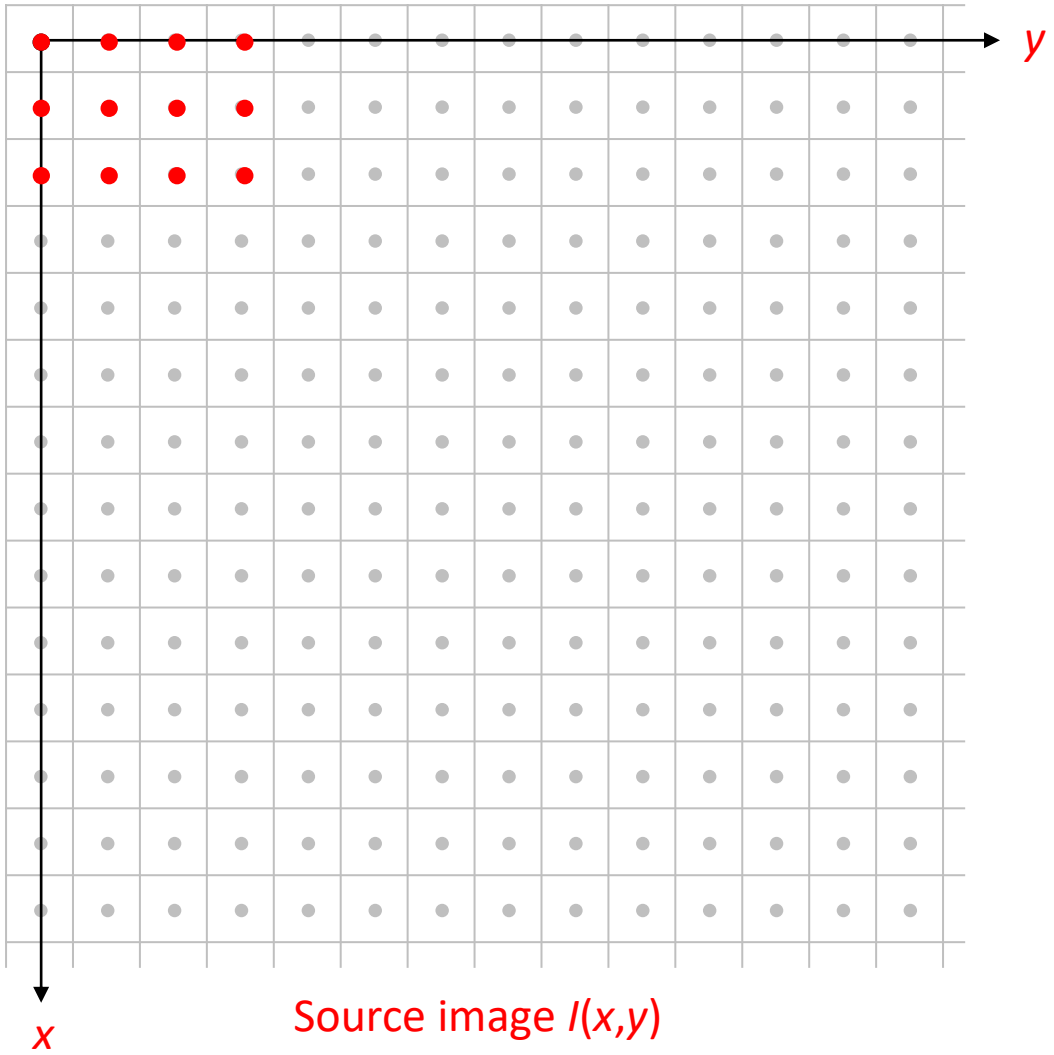
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Geometric transformations

- Example 4
  - Scale by 2

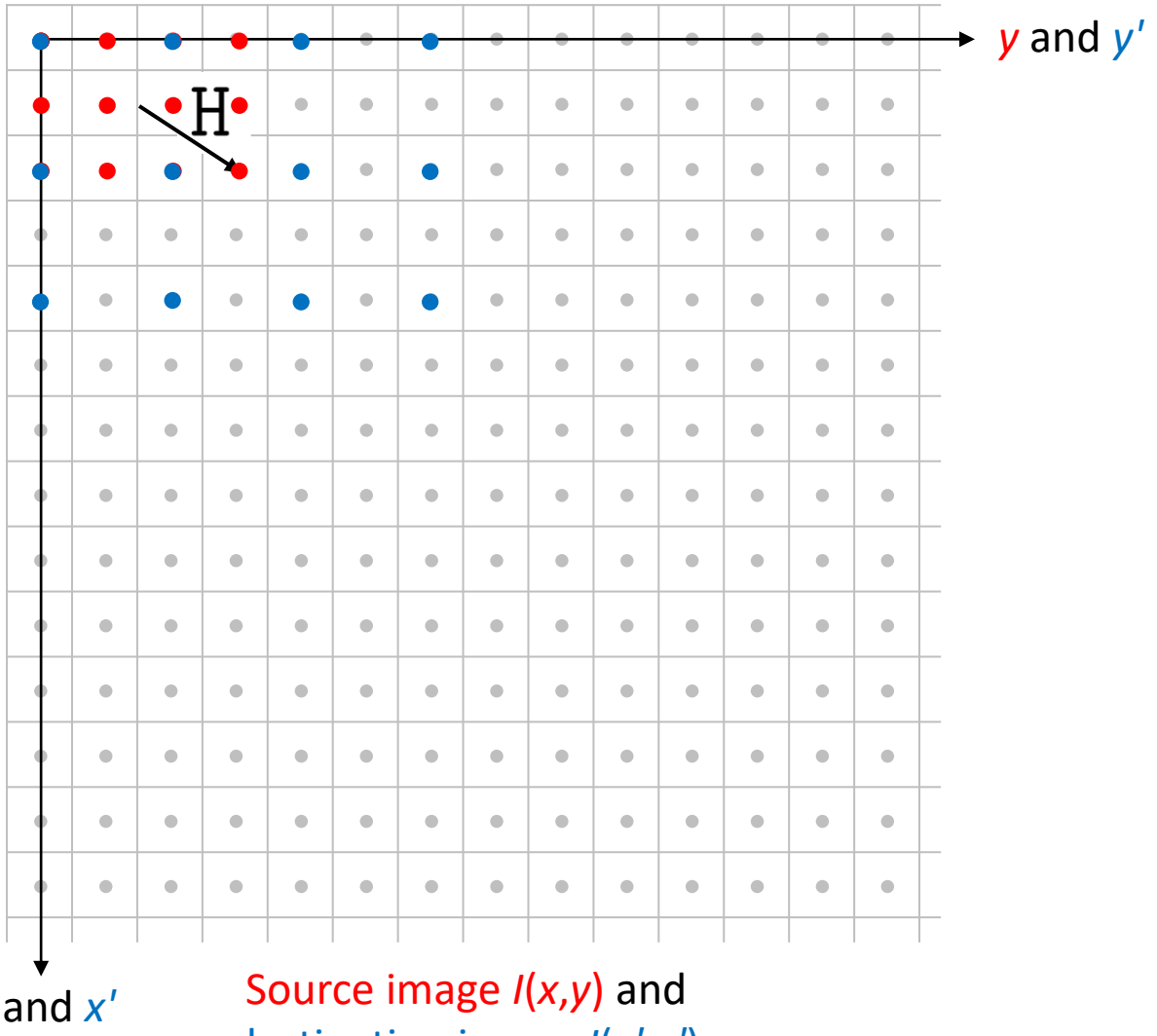
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_c \mathbf{x}$$



Source image $I(x,y)$ and destination image $J(x',y')$

Geometric transformations

- Example 4
  - Scale by 2

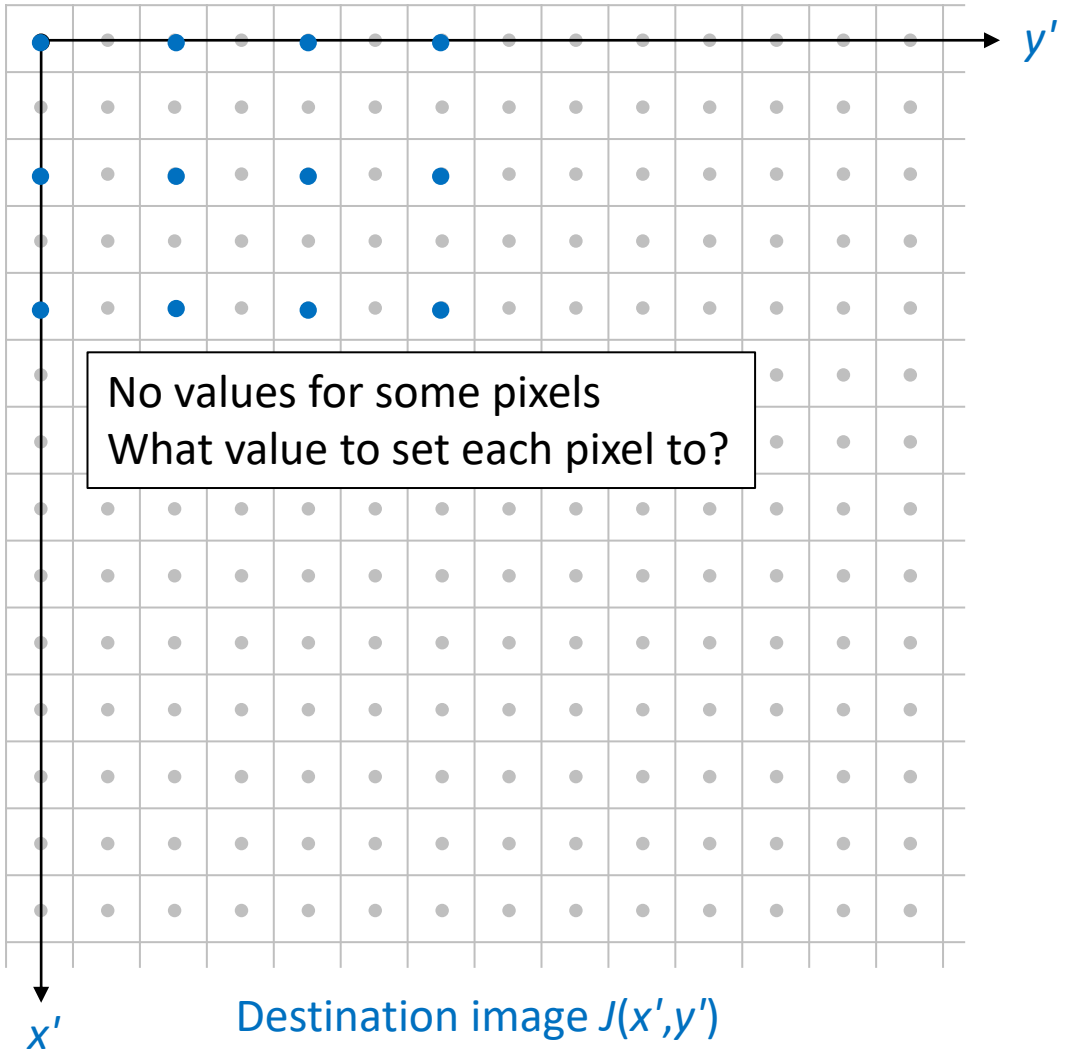
$c_x = 2$

$c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H_c}\mathbf{x}$$



Geometric transformations

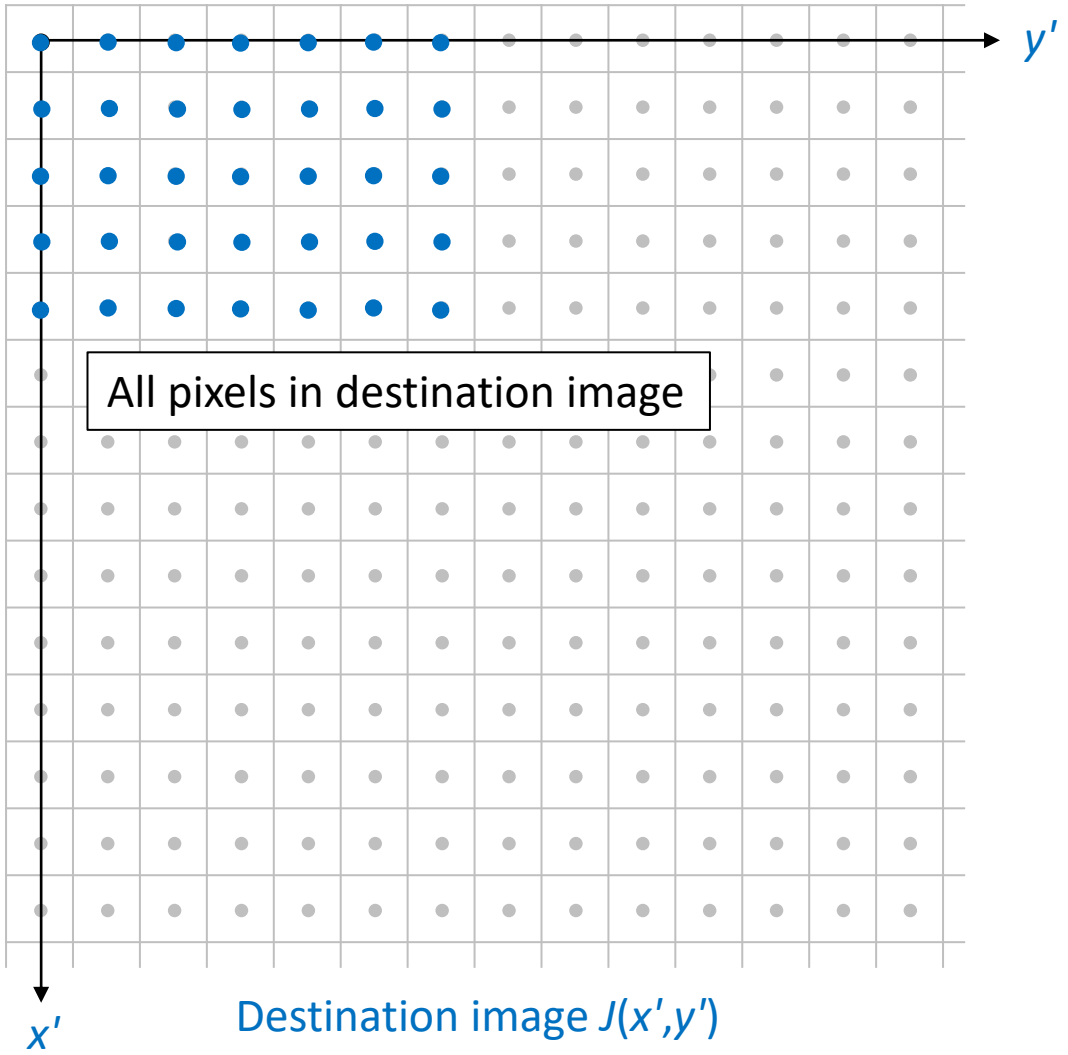
- Example 4
  - Scale by 2

    $c_x = 2$

    $c_y = 2$

$$x' = c_x x$$
$$y' = c_y y$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$
$$\mathbf{x}' = \mathrm{H_c}\mathbf{x}$$

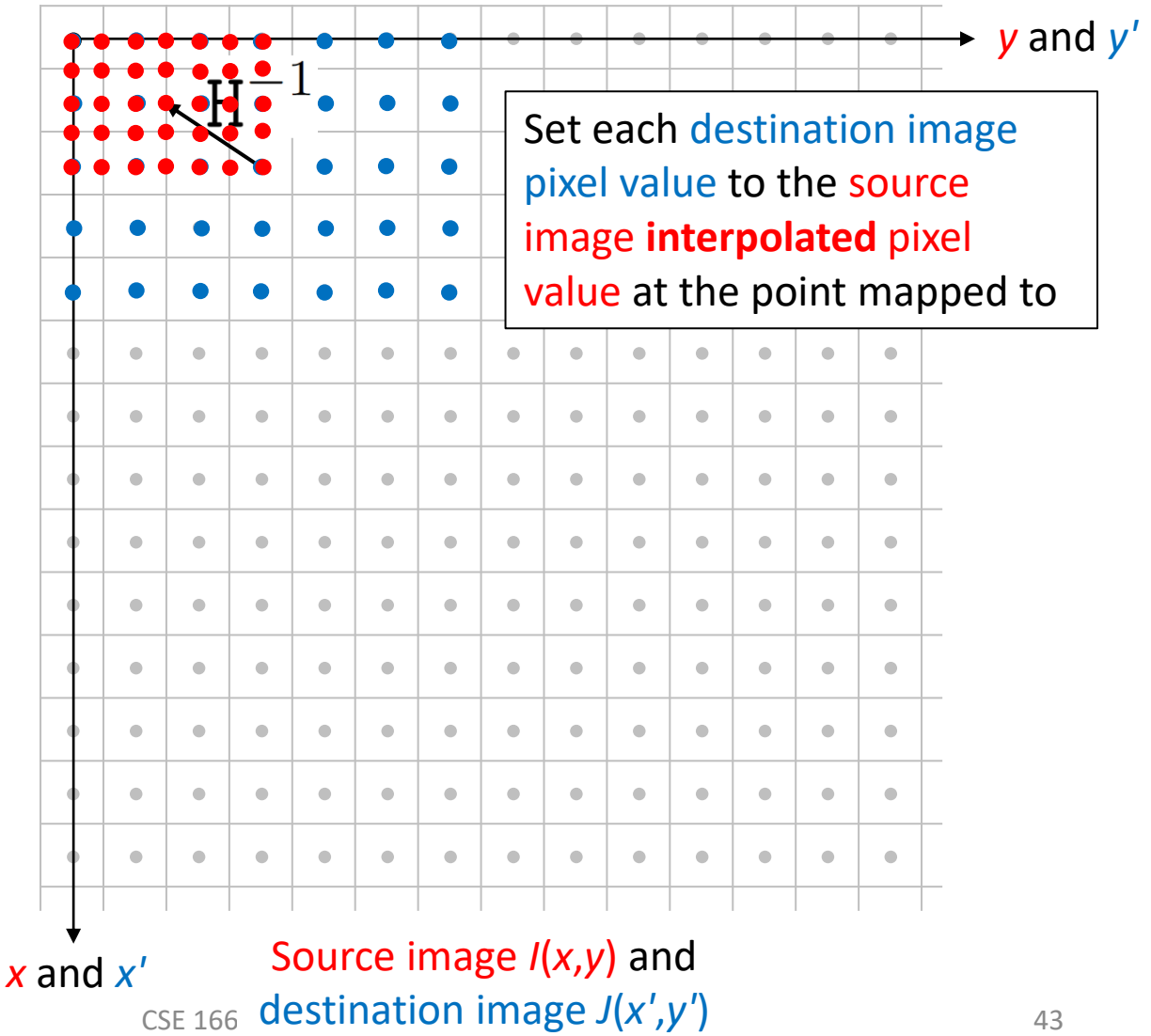


Inverse transform

- Example 4

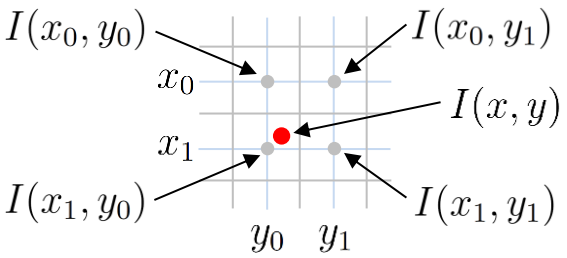
$$\mathbf{x}' = \mathbf{H}\mathbf{x}$$
$$\mathbf{x} = \mathbf{H}^{-1}\mathbf{x}'$$

- Also called backward transform

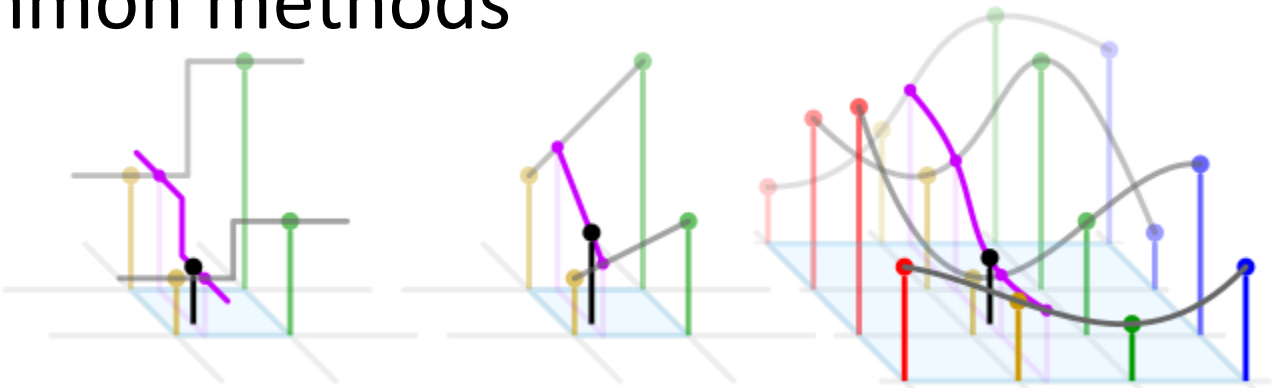


Interpolation

- Estimate *I*(*x*,*y*)

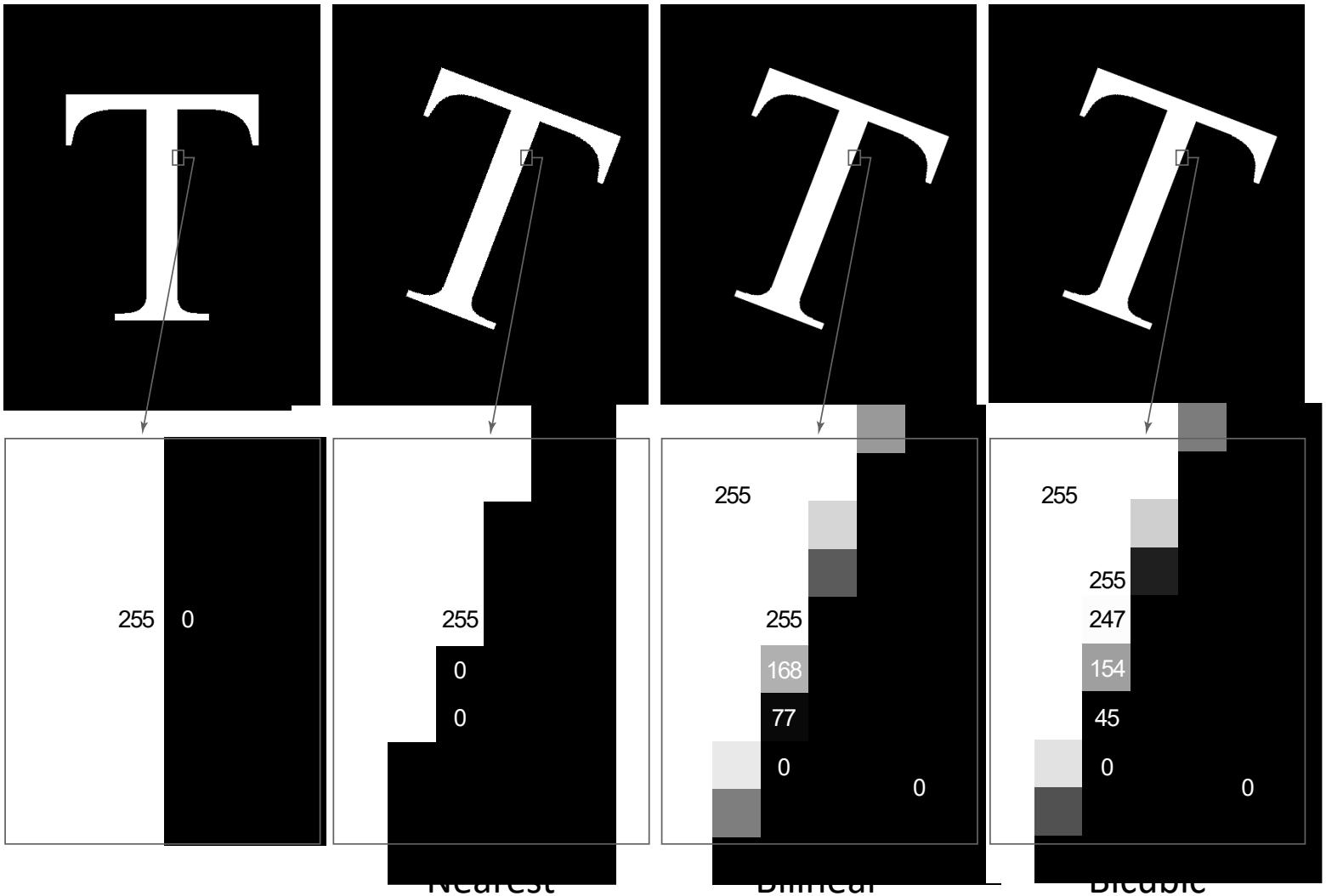


- Common methods



Nearest neighbor Bilinear Bicubic

Transformation with interpolation



Transformation with interpolation

- Nearest neighbor interpolation

$$\mathtt{H} : I(x, y) \mapsto J(x', y')$$

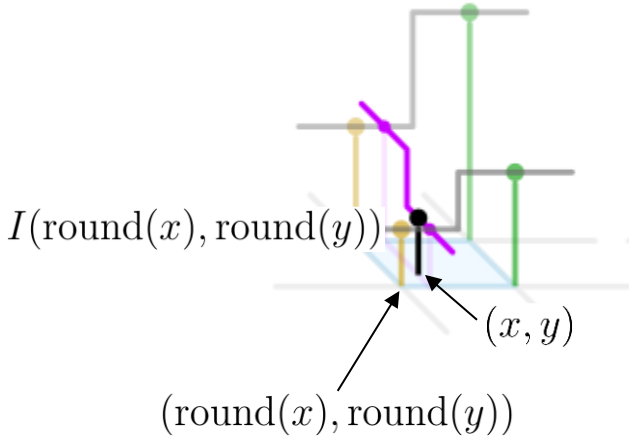
for each (x', y') in J

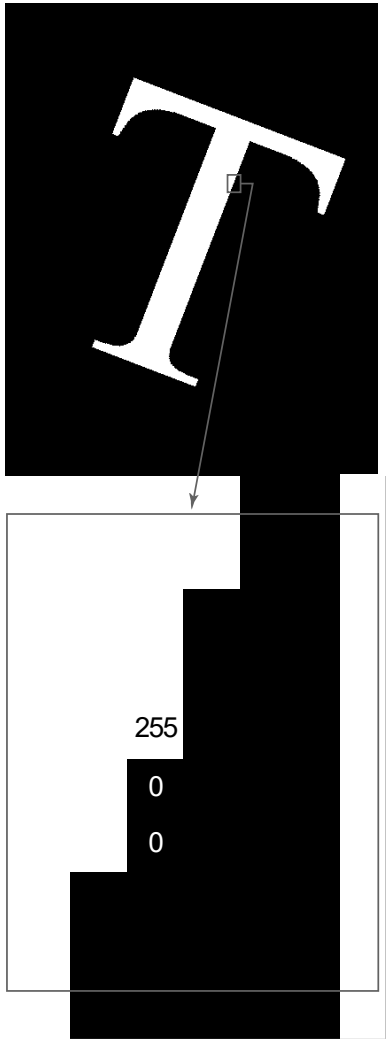
$\mathbf{x} = \mathtt{H}^{-1}\mathbf{x}'$

$J(x', y') = I(\text{round}(x), \text{round}(y))$

end

Important: check that round(*x*) and round(*y*) are in image *I*





Transformation with interpolation

- Linear interpolation

$\mathtt{H} : I(x, y) \mapsto J(x', y')$

for each (x', y') in J

$\mathbf{x} = \mathtt{H}^{-1}\mathbf{x}'$

$x_0 = \lfloor x \rfloor$

$x_1 = x_0 + 1$

$y_0 = \lfloor y \rfloor$

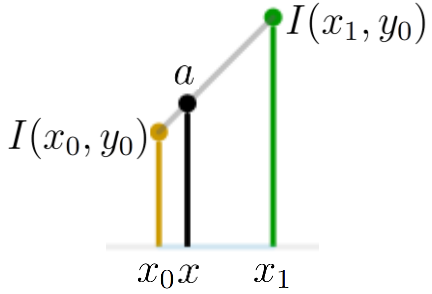
$y_1 = y_0 + 1$

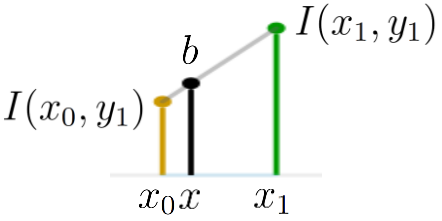
$a = (x_1 - x)I(x_0, y_0) + (x - x_0)I(x_1, y_0)$

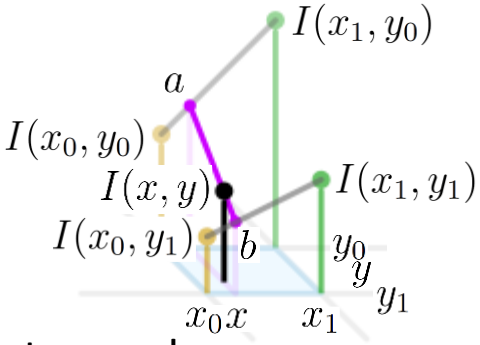
$b = (x_1 - x)I(x_0, y_1) + (x - x_0)I(x_1, y_1)$

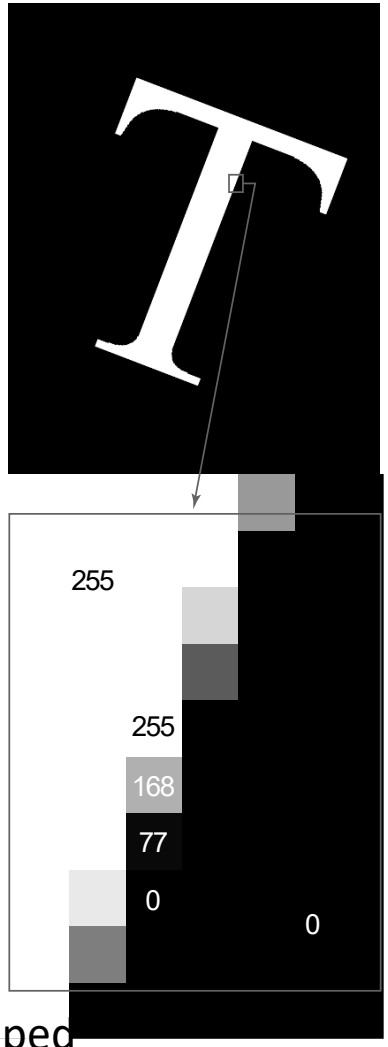
$J(x', y') = (y_1 - y)a + (y - y_0)b$

end









Note x and y axes are swapped

Important: check that x_0, x_1, y_0, and y_1 are in image I

Transforming an image multiple times

- Interpolation is an estimation method
  - Estimation error
- Pixel values in transformed images include estimation error
- Transforming a transformed image (e.g., translate then rotate)
  - Estimate pixel values from estimated pixel values (i.e., compound estimation error)
- The more times an image is transformed, the greater the pixel value error

Composition of transformations

- Example: rotating an image about its center
  - Remember, rotation is about the origin

$$x' = x\cos\theta - y\sin\theta$$
$$y' = x\sin\theta + y\cos\theta$$

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

$$\mathbf{x}' = \mathrm{H}_{\mathrm{R}}\mathbf{x}$$

1. Translation such that image center is mapped to origin
2. Rotation (about origin)
3. Translation such that origin is mapped to image center determined in step 1

Composition of transformations

- Compose multiple transformations and use result to transform an image a single time

First transformation

$$\mathrm{H}_1 : \mathbf{x} \mapsto \mathbf{x}'$$
$$\mathbf{x}' = \mathrm{H}_1\mathbf{x}$$

Second transformation

$$\mathrm{H}_2 : \mathbf{x}' \mapsto \mathbf{x}''$$
$$\mathbf{x}'' = \mathrm{H}_2\mathbf{x}'$$

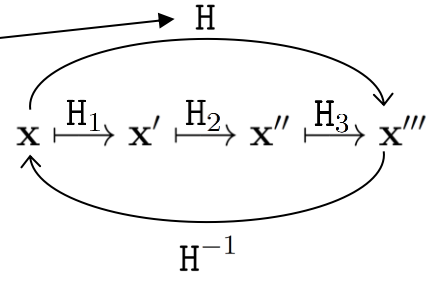
Third transformation

$$\mathrm{H}_3 : \mathbf{x}'' \mapsto \mathbf{x}'''$$
$$\mathbf{x}''' = \mathrm{H}_3\mathbf{x}''$$

$$\mathbf{x}''' = \mathrm{H}_3\mathbf{x}''$$
$$\mathbf{x}''' = \mathrm{H}_3\mathrm{H}_2\mathbf{x}'$$
$$\mathbf{x}''' = \mathrm{H}_3\mathrm{H}_2\mathrm{H}_1\mathbf{x}$$
$$\mathbf{x}''' = \mathrm{H}\mathbf{x} \text{ where } \mathrm{H} = \mathrm{H}_3\mathrm{H}_2\mathrm{H}_1$$

Use this to transform image

"right to left"



Next Lecture

- Intensity transformations
- Reading
  - Chapter 3: Intensity Transformations and Spatial Filtering
    - Sections 3.1, 3.2, and 3.3