27 - Image Warping dan Image Morphing

Bahan Kuliah IF4073 Interpretasi dan Pengolahan Citra

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ITB

SUMBER (REFERENSI):

1. Alexei Efros, *Image Warping, 15-463: Computational Photography*, CMU, Fall 2008
2. Connelly Barnes, *Image Warping / Morphing, Computational Photography*.
3. Yao Wang, *EL512 Image Processing, Geometric Transformations: Warping, Registration, Morphing*, Polytchnic University, Brooklyn

Image Warping

http://www.jeffrey-martin.com

15-463: Computational Photography
Alexei Efros, CMU, Fall 2008

Some slides from Steve Seitz

Image warping example (Sumber: Wikipedia)

Image Warping / Morphing

[Wolberg 1996, Recent Advances in Image Morphing]

Computational Photography

Connelly Barnes

Some slides from Fredo Durand, Bill Freeman, James Hays

EL512 --- Image Processing

Geometric Transformations: Warping, Registration, Morphing

Yao Wang
Polytechnic University, Brooklyn, NY 11201

With contribution from Zhu Liu, Onur Guleryuz, and
Partly based on
A. K. Jain, Fundamentals of Digital Image Processing

What is Geometric Transformation?

- So far, the image processing operations we have discussed modify the color values of pixels in a given image
- With geometric transformation, we modify the positions of pixels in a image, but keep their colors unchanged
  - To create special effects
  - To register two images taken of the same scene at different times
  - To morph one image to another

Image Transformations

image filtering: change ***range*** of image

$$g(x) = T(f(x))$$

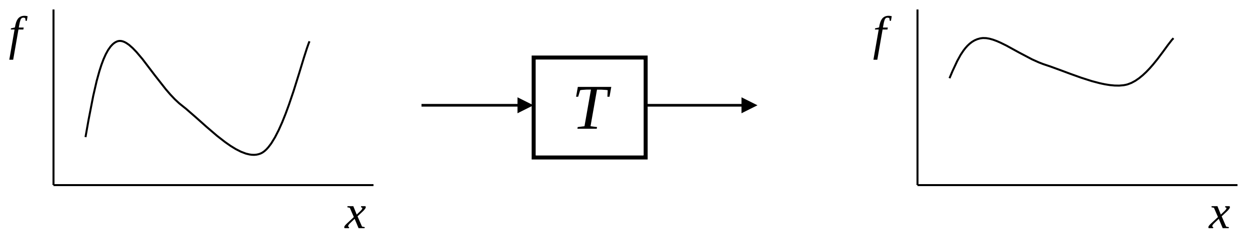


image warping: change ***domain*** of image

$$g(x) = f(T(x))$$

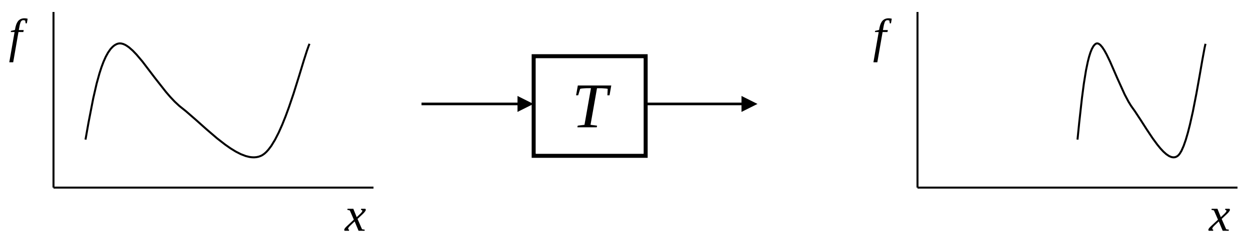


Image Transformations

image filtering: change ***range*** of image

$$g(x) = T(f(x))$$

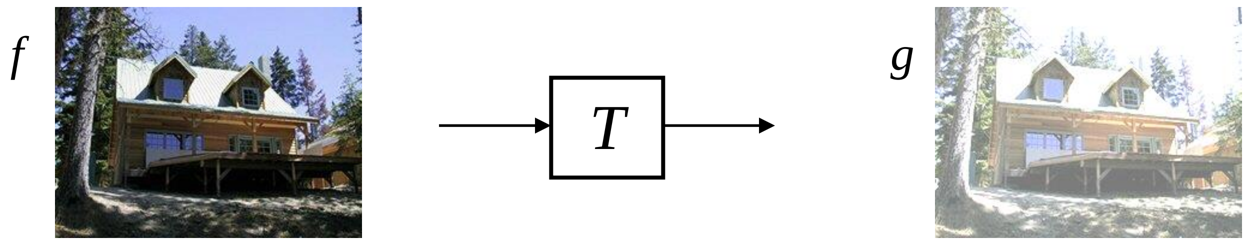


image warping: change ***domain*** of image

$$g(x) = f(T(x))$$

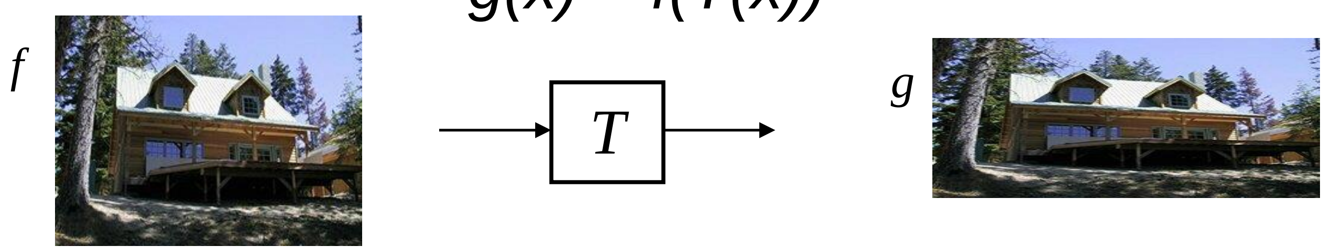
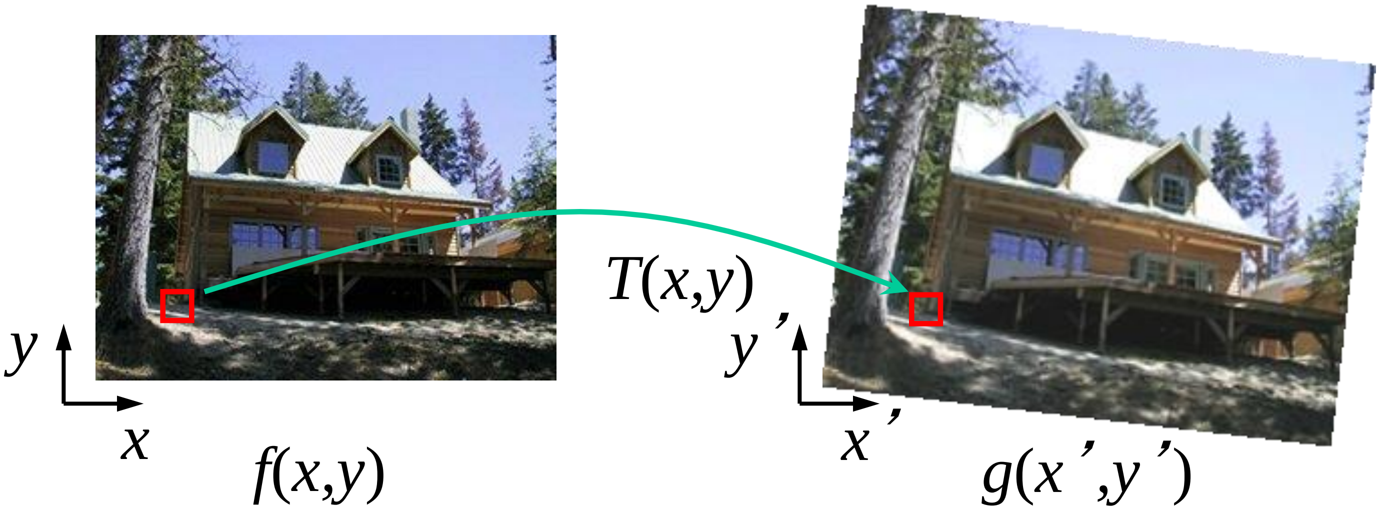


Image Warping



Given a coordinate transform $(x',y') = T(x,y)$ and a source image $f(x,y)$, how do we compute a transformed image $g(x',y') = f(T(x,y))$?

Parametric (global) warping

Examples of parametric warps:

translation

rotation

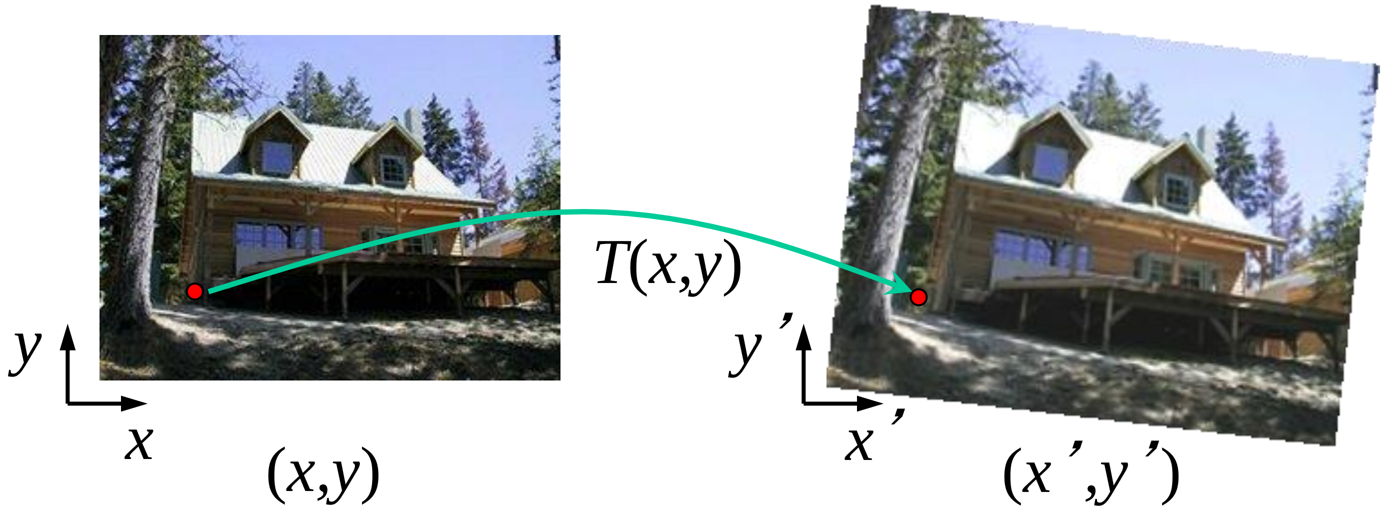
aspect

affine

perspective

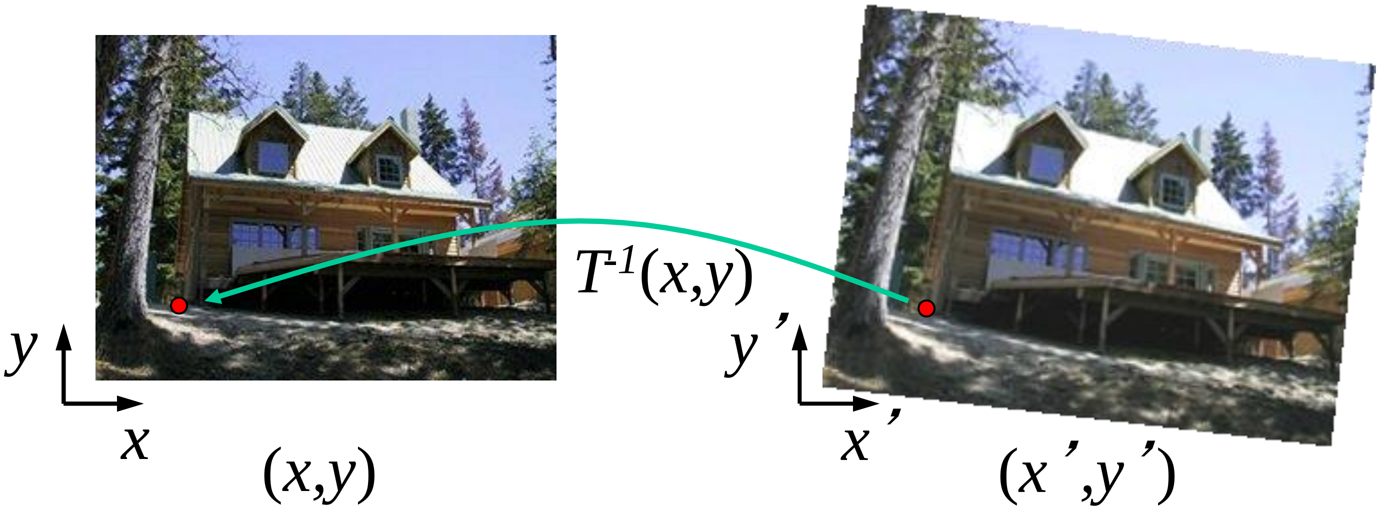
cylindrical

Forward warping



Send each pixel (x,y) to its corresponding location $(x',y') = T(x,y)$ in the second image

Inverse warping



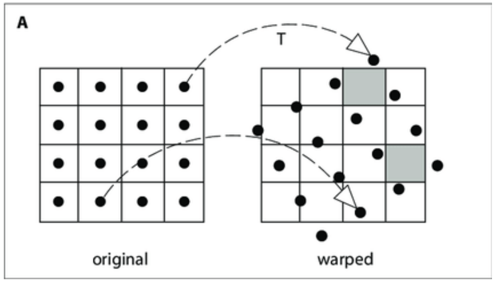
Get each pixel color $g(x',y')$ from its corresponding location

$(x,y) = T^{-1}(x',y')$ in the first image

Applying a warp: use inverse

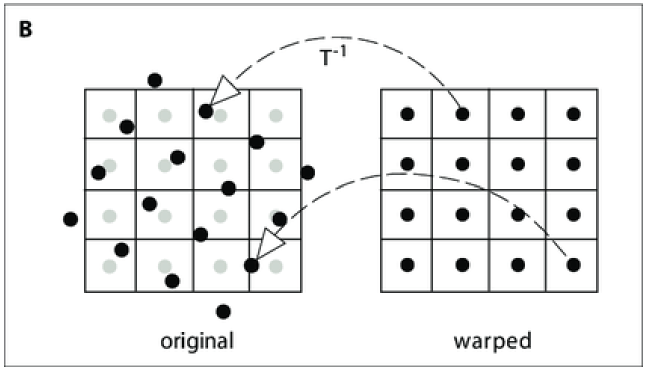
Forward warp:

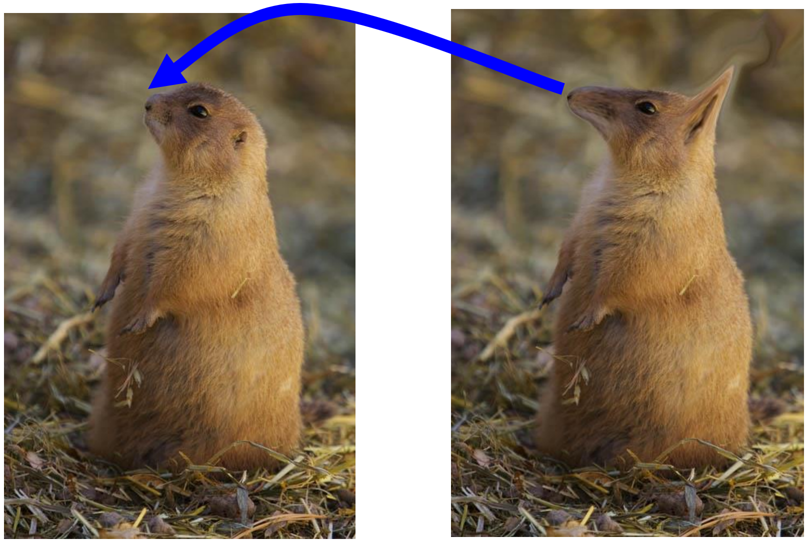
- For each pixel in **input** image
  - Paste color **to warped** location in output
    - Problem: gaps

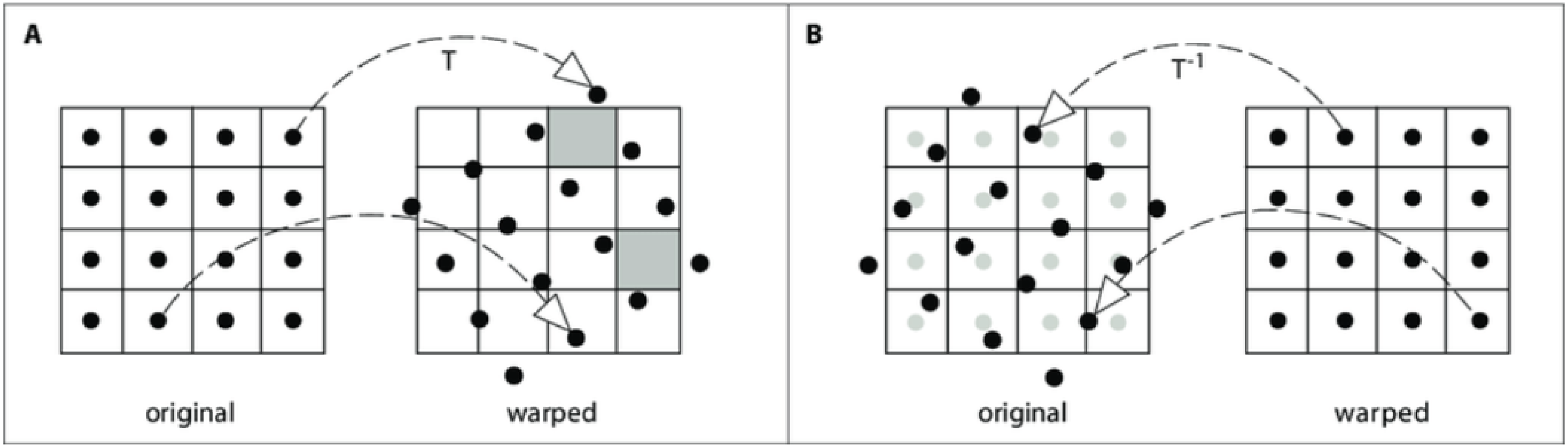


Inverse warp

- For each pixel in **output** image
  - Lookup color **from inverse-warped** location







2.: Forward and backward image warping. In the case of foward warping (A), holes can occur in the warped image, marked in gray. Backward warping (B) eliminates this problem since intensities at locations that do not coincide with pixel coordinates can be obtained from the original image using an interpolation scheme.

Sumber: Non-rigid Registration Using Free-form Deformations
Authors: Loren Arthur Schwarz

Parametric (global) warping

$$\longrightarrow \boxed{T} \longrightarrow$$

p = (x,y) **p’** = (x’,y’)

Transformation T is a coordinate-changing machine:

$$p' = T(p)$$

What does it mean that *T* is global?

- Is the same for any point p
- can be described by just a few numbers (parameters)

Let’s represent *T* as a matrix:

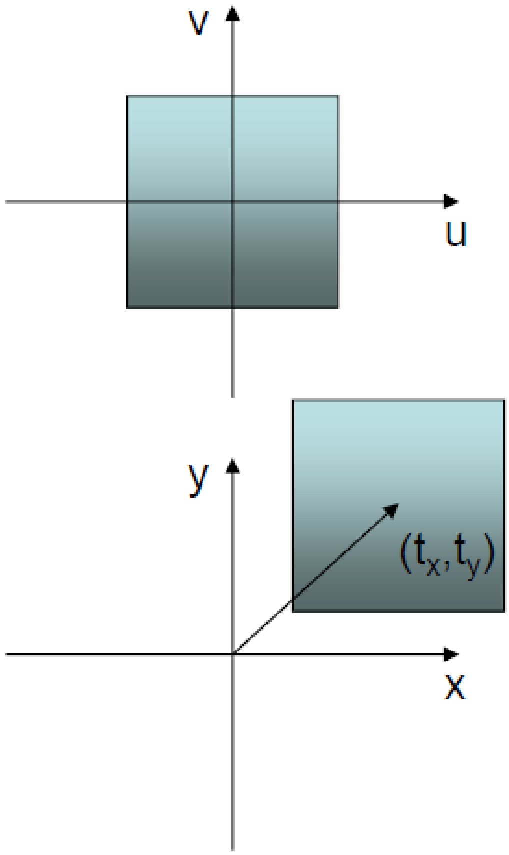
$$p' = \mathbf{M}p$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \mathbf{M} \begin{bmatrix} x \\ y \end{bmatrix}$$

Translation

- Translation is defined by the following mapping functions:

$$\begin{cases} x = u + t_x \\ y = v + t_y \end{cases} \quad and \quad \begin{matrix} u = x - t_x \\ v = y - t_y \end{matrix}$$



- In matrix notation

$$\mathbf{x} = \mathbf{u} + \mathbf{t}, \quad \mathbf{u} = \mathbf{x} - \mathbf{t}$$

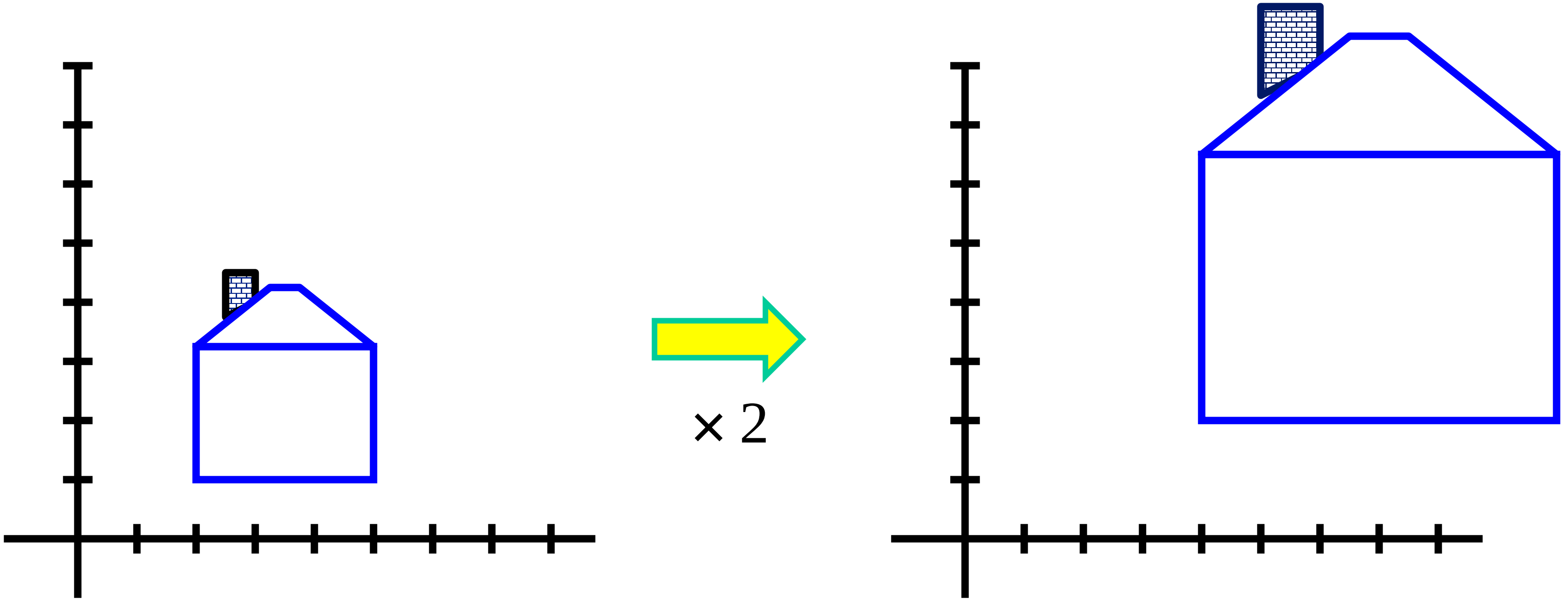
where

$$\mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} u \\ v \end{bmatrix}, \quad \mathbf{t} = \begin{bmatrix} t_x \\ t_y \end{bmatrix}.$$

Scaling

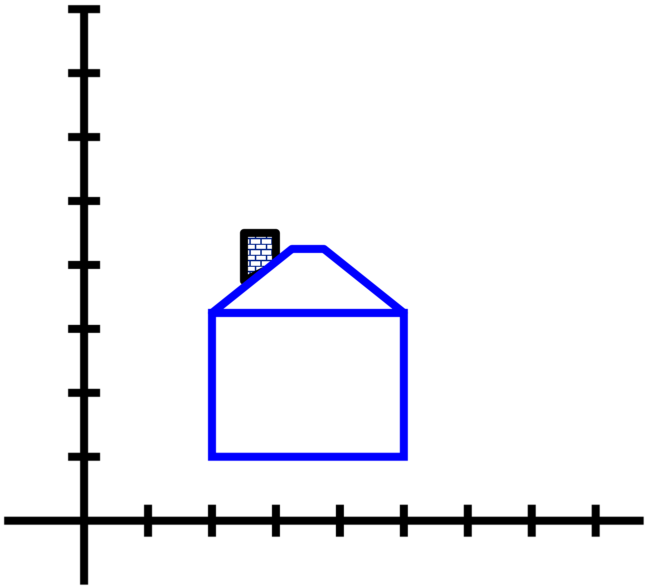
Scaling a coordinate means multiplying each of its components by a scalar

Uniform scaling means this scalar is the same for all components:

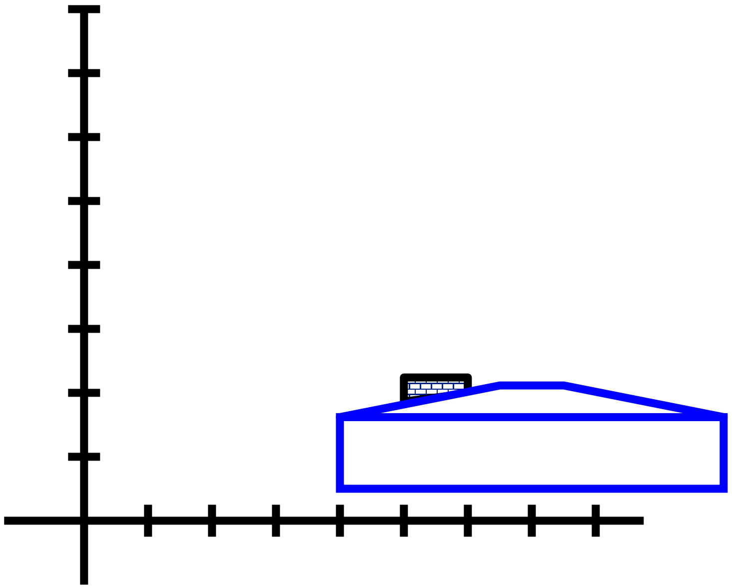


Scaling

Non-uniform scaling: different scalars per component:



$X \times 2$,
$Y \times 0.5$



Scaling

- Scaling is defined by

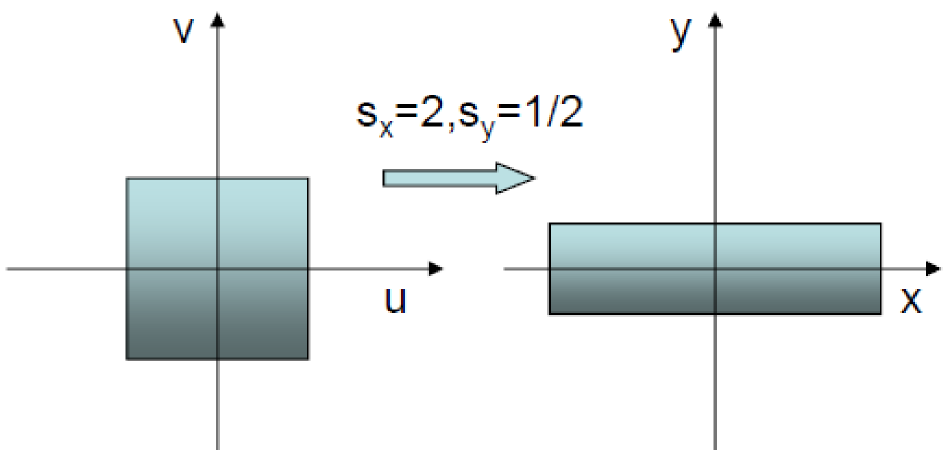
$$\begin{cases} x = s_x u \\ y = s_y v \end{cases} \quad and \quad \begin{cases} u = x / s_x \\ v = y / s_y \end{cases}$$

- Matrix notation

$$\mathbf{x} = \mathbf{S}\mathbf{u}, \quad \mathbf{u} = \mathbf{S}^{-1}\mathbf{x}$$

where

$$\mathbf{S} = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix}$$



- If $s_x < 1$ and $s_y < 1$, this represents a minification or shrinking, if $s_x > 1$ and $s_y > 1$, it represents a magnification or zoom.

Scaling

Scaling operation:

$$x' = ax$$

$$y' = by$$

Or, in matrix form:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \underbrace{\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}}_{\textit{scaling matrix } S} \begin{bmatrix} x \\ y \end{bmatrix}$$

What's inverse of S?

Rotation

- Rotation by an angle of θ is defined by

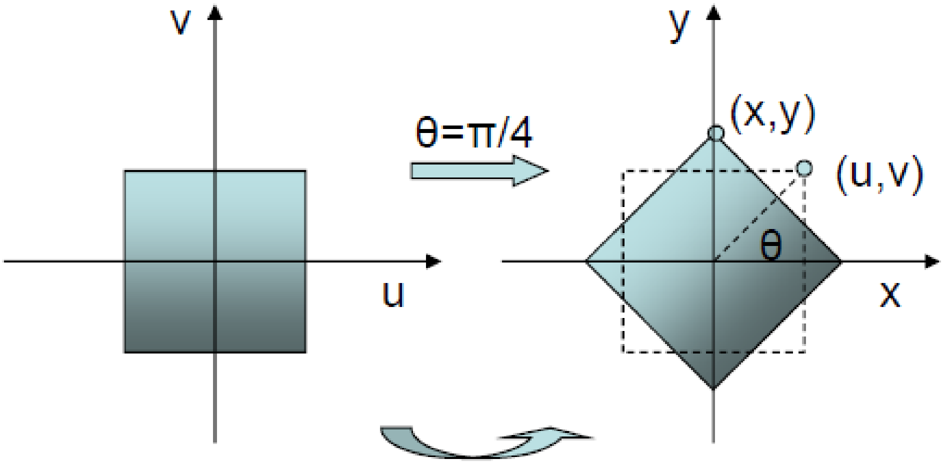
$$\begin{cases} x = u\cos\theta - v\sin\theta \\ y = u\sin\theta + v\cos\theta \end{cases} \quad and \quad \begin{cases} u = x\cos\theta + y\sin\theta \\ v = -x\sin\theta + y\cos\theta \end{cases}$$

- In matrix format

$$\mathbf{x} = \mathbf{R}\mathbf{u}, \quad \mathbf{u} = \mathbf{R}^T\mathbf{x}$$

where

$$\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$



- **R** is a unitary matrix: $\mathbf{R}^{-1} = \mathbf{R}^T$

B translation

B rotation

Translation: $x(k,l) = k + 50; y(k,l) = l;$

Rotation: $x(k,l) = (k - x_0)cos(\theta) + (l - y_0)sin(\theta) + x_0;$

$$y(k,l) = -(k - x_0)sin(\theta) + (l - y_0)cos(\theta) + y_0;$$

$x_0 = y_0 = 256.5$ the center of the image $\mathbf{A}$, $\theta = \pi/6$

By Onur Guleyuz

2x2 Matrices

What types of transformations can be represented with a 2x2 matrix?

2D Identity?

$$x' = x$$
$$y' = y$$

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

2D Scale around (0,0)?

$$\boldsymbol{x}' = \boldsymbol{s}_x * \boldsymbol{x}$$
$$\boldsymbol{y}' = \boldsymbol{s}_y * \boldsymbol{y}$$

$$\begin{bmatrix} \boldsymbol{x}' \\ \boldsymbol{y}' \end{bmatrix} = \begin{bmatrix} \boldsymbol{s}_x & 0 \\ 0 & \boldsymbol{s}_y \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{bmatrix}$$

2x2 Matrices

What types of transformations can be represented with a 2x2 matrix?

2D Rotate around (0,0)?

$$x' = \cos\Theta * x - \sin\Theta * y$$
$$y' = \sin\Theta * x + \cos\Theta * y$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\Theta & -\sin\Theta \\ \sin\Theta & \cos\Theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

2D Shear?

$$\boldsymbol{x' = x + sh_x * y}$$
$$\boldsymbol{y' = sh_y * x + y}$$

$$\begin{bmatrix} \boldsymbol{x'} \\ \boldsymbol{y'} \end{bmatrix} = \begin{bmatrix} 1 & \boldsymbol{sh_x} \\ \boldsymbol{sh_y} & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{bmatrix}$$

2x2 Matrices

What types of transformations can be represented with a 2x2 matrix?

2D Mirror about Y axis?

$$x' = -x$$
$$y' = y$$

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

2D Mirror over (0,0)?

$$x' = -x$$
$$y' = -y$$

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

2x2 Matrices

What types of transformations can be represented with a 2x2 matrix?

2D Translation?

$$\boldsymbol{x}' = \boldsymbol{x} + \boldsymbol{t}_x$$

$$\boldsymbol{y}' = \boldsymbol{y} + \boldsymbol{t}_y$$

NO!

Only linear 2D transformations can be represented with a 2x2 matrix

All 2D Linear Transformations

Linear transformations are combinations of …

- Scale,
- Rotation,
- Shear, and
- Mirror

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

Properties of linear transformations:

- Origin maps to origin
- Lines map to lines
- Parallel lines remain parallel
- Ratios are preserved
- Closed under composition

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} e & f \\ g & h \end{bmatrix} \begin{bmatrix} i & j \\ k & l \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

Geometric Transformation

- A geometric transformation refers to a combination of translation, scaling, and rotation, with a general form of

$$\mathbf{x} = \mathbf{RS}(\mathbf{u} + \mathbf{t}) = \mathbf{Au} + \mathbf{b},$$

$$\mathbf{u} = \mathbf{A}^{-1}(\mathbf{x} - \mathbf{b}) = \mathbf{A}^{-1}\mathbf{x} + \mathbf{c},$$

$$\textit{with } \mathbf{A} = \mathbf{RS},\ \mathbf{b} = \mathbf{RSt},\ \mathbf{c} = -\mathbf{t}.$$

- Note that interchanging the order of operations will lead to different results.

Affine Mapping

- All possible geometric transformations are special cases of the *Affine Mapping*:

$$\begin{cases} x = a_0 + a_1 u + a_2 v \\ y = b_0 + b_1 u + b_2 v \end{cases} \quad or \quad \mathbf{x} = \mathbf{A}\mathbf{u} + \mathbf{b}$$

$$\mathbf{A} = \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix}, \qquad \mathbf{b} = \begin{bmatrix} a_0 \\ b_0 \end{bmatrix}$$

- When A is a orthonormal matrix, it corresponds to a rotation matrix, and the corresponding affine mapping reduces to a geometric mapping.

Matlab Functions

- T = MAKETFORM('affine',U,X) builds a TFORM struct for a
- two-dimensional affine transformation that maps each row of U
- to the corresponding row of X. U and X are each 3-by-2 and
- define the corners of input and output triangles. The corners
- may not be collinear.
- Example
- -------
- Create an affine transformation that maps the triangle with vertices
- (0,0), (6,3), (-2,5) to the triangle with vertices (-1,-1), (0,-10),
- (4,4):
-

```
u = [ 0   6  -2]';
v = [ 0   3   5]';
x = [-1   0   4]';
y = [-1 -10   4]';
tform = maketform('affine',[u v],[x y]);
```

- G = MAKETFORM('affine',T) builds a TFORM struct G for an N-dimensional affine transformation. T defines a forward transformation such that TFORMFWD(U,T), where U is a 1-by-N vector, returns a 1-by-N vector X such that X = U * T(1:N,1:N) + T(N+1,1:N).T has both forward and inverse transformations. N=2 for 2D image transformation

In MATLAB notation

$$T = \begin{bmatrix} a_1 & b_1 & 0 \\ a_2 & b_2 & 0 \\ a_0 & b_0 & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{A}^T & 0 \\ \mathbf{b}^T & 1 \end{bmatrix}$$

- B = IMTRANSFORM(A,TFORM, INTERP) transforms the image A according to the 2-D spatial transformation defined by TFORMB; INTERP specifies the interpolation filter
- Example 1
- ---------
- Apply a horizontal shear to an intensity image.
-
- I = imread('cameraman.tif');
- tform = maketform('affine',[1 0 0; .5 1 0; 0 0 1]);
- J = imtransform(I,tform);
- figure, imshow(I), figure, imshow(J)

- Show in class

Horizontal Shear Example

tform = maketform('affine',[1 0 0; .5 1 0; 0 0 1]);
In MATLAB, 'affine' transform is defined by:
[a1,b1,0;a2,b2,0;a0,b0,1]

With notation used in this lecture note

$$\mathbf{A} = \begin{bmatrix} 1 & 0.5 \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{b} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Note in this example, first coordinate indicates horizontal position, second coordinate indicate vertic

MATLAB function for image warping

- B = IMTRANSFORM(A,TFORM, INTERP) transforms the image A according to the 2-D spatial transformation defined by TFORM
- INTERP specifies the interpolation filter
- Example 1
-     ---------
-     Apply a horizontal shear to an intensity image.
-
-         I = imread('cameraman.tif');
-         tform = maketform('affine',[1 0 0; .5 1 0; 0 0 1]);
-         J = imtransform(I,tform);
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Horizontal Shear Example

tform = maketform('affine',[1 0 0; .5 1 0; 0 0 1]);
In MATLAB, 'affine' transform is defined by:
[a1,b1,0;a2,b2,0;a0,b0,1]

With notation used in this lecture note

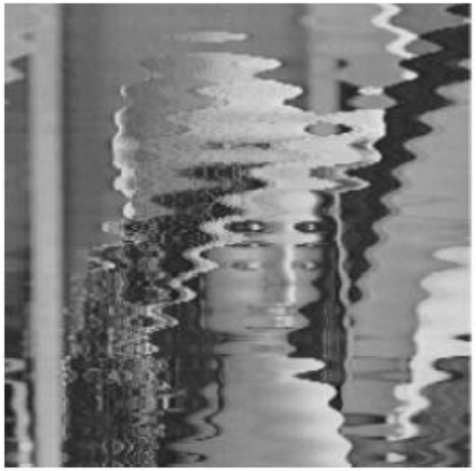
$$\mathbf{A} = \begin{bmatrix} 1 & 0.5 \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{b} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Note in this example, x, u indicates vertical position, y, v indicate horizontal position

Example of Image Warping (1)

WAVE1

WAVE2



wave1:$x(u,v)=u+20\sin(2\pi v/128)$;$y(u,v)=v$;
wave2:$x(u,v)=u+20\sin(2\pi u/30)$;$y(u,v)=v$.

By Onur Guleyuz

Example of Image Warping (2)

WARP

SWIRL

WARP $x(u,v) = sign(u-x_0)*(u-x_0)^2/x_0 + x_0; y(u,v) = v$

SWIRL
$$x(u,v) = (u-x_0)\cos(\theta) + (v-y_0)\sin(\theta) + x_0;$$
$$y(u,v) = -(u-x_0)\sin(\theta) + (v-y_0)\cos(\theta) + y_0;$$
$$r = ((u-x_0)^2 + (v-y_0)^2)^{1/2}, \theta = \pi r/512.$$

By Onur Guleyuz

Homogeneous Coordinates

Q: How can we represent translation as a 3x3 matrix?

$$x' = x + t_x$$

$$y' = y + t_y$$

Homogeneous Coordinates

Homogeneous coordinates

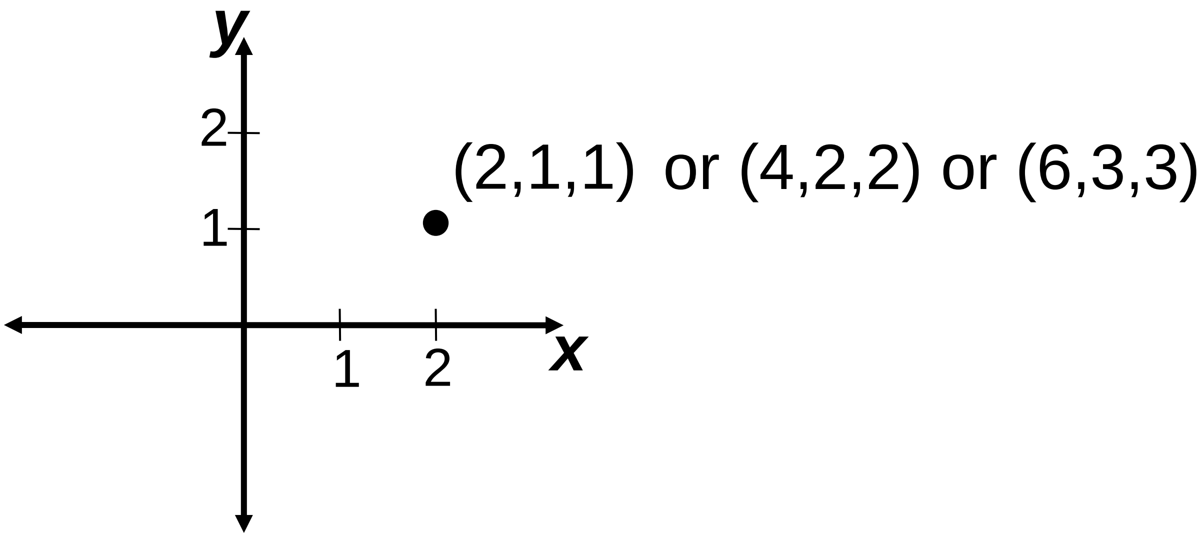
- represent coordinates in 2 dimensions with a 3-vector

$$\begin{bmatrix} x \\ y \end{bmatrix} \xrightarrow{\text{homogeneou s coords}} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Homogeneous Coordinates

Add a 3rd coordinate to every 2D point

- (x, y, w) represents a point at location (x/w, y/w)
- (x, y, 0) represents a point at infinity
- (0, 0, 0) is not allowed



Convenient coordinate system to represent many useful transformations

Homogeneous Coordinates

Q: How can we represent translation as a 3x3 matrix?

$$x' = x + t_x$$

$$y' = y + t_y$$

A: Using the rightmost column:

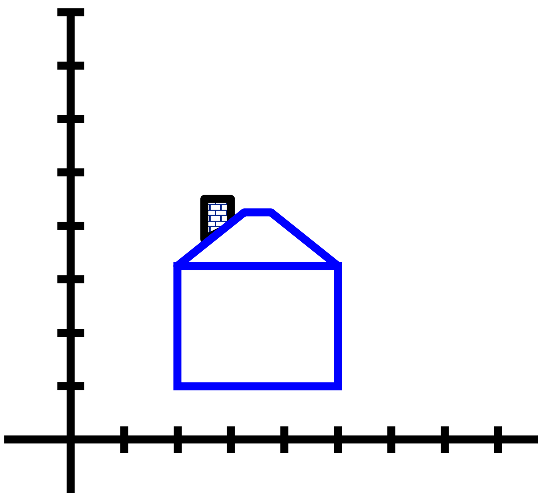
$$\mathbf{T}\mathit{ranslation} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

Translation

Example of translation

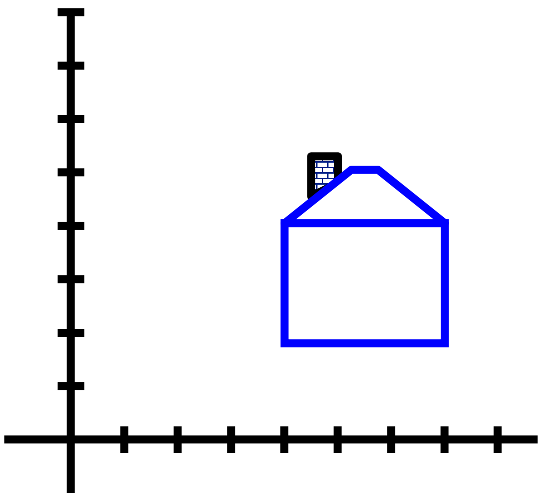
Homogeneous Coordinates

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



$t_x = 2$

$t_y = 1$



Basic 2D Transformations

Basic 2D transformations as 3x3 matrices

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

Translate

$$\begin{bmatrix} \boldsymbol{x}' \\ \boldsymbol{y}' \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{s}_x & 0 & 0 \\ 0 & \boldsymbol{s}_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ 1 \end{bmatrix}$$

Scale

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

Rotate

$$\begin{bmatrix} \boldsymbol{x}' \\ \boldsymbol{y}' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & \boldsymbol{sh}_x & 0 \\ \boldsymbol{sh}_y & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ 1 \end{bmatrix}$$

Shear

Matrix Composition

Transformations can be combined by matrix multiplication

$$\begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} = \left(\begin{bmatrix} 1 & 0 & tx \\ 0 & 1 & ty \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\Theta & -\sin\Theta & 0 \\ \sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} sx & 0 & 0 \\ 0 & sy & 0 \\ 0 & 0 & 1 \end{bmatrix} \right) \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

p' **=** $T(t_x,t_y)$ $R(\Theta)$ $S(s_x,s_y)$ **p**

Affine Transformations

Affine transformations are combinations of …

- Linear transformations, and
- Translations

$$\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

Properties of affine transformations:

- Origin does not necessarily map to origin
- Lines map to lines
- Parallel lines remain parallel
- Ratios are preserved
- Closed under composition
- Models change of basis

Will the last coordinate *w* always be 1?

Projective Transformations

$$\begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

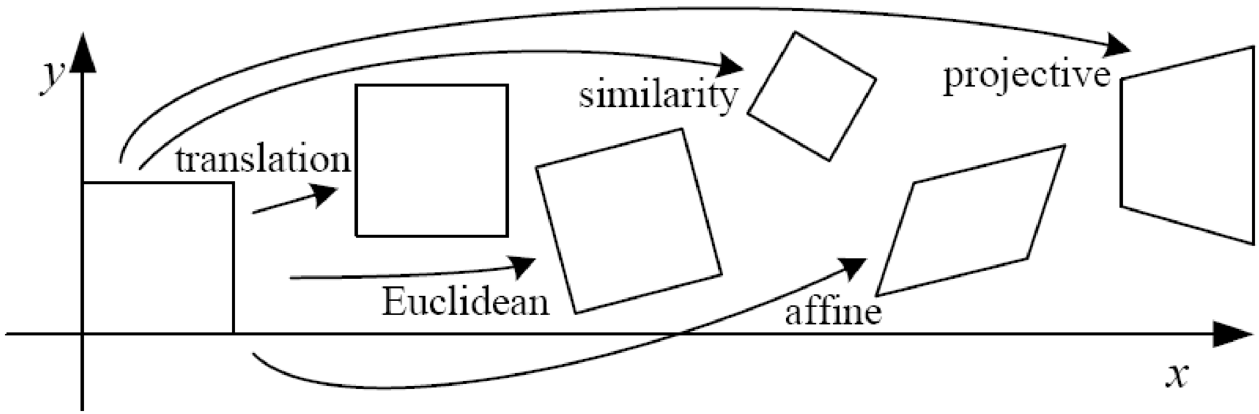
Projective transformations …

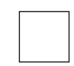
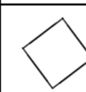
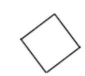
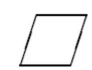
- Affine transformations, and
- Projective warps

Properties of projective transformations:

- Origin does not necessarily map to origin
- Lines map to lines
- Parallel lines do not necessarily remain parallel
- Ratios are not preserved
- Closed under composition
- Models change of basis

2D image transformations



Name	Matrix	# D.O.F.	Preserves:	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$			
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$			
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$			
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{2\times 3}$			
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{3\times 3}$			

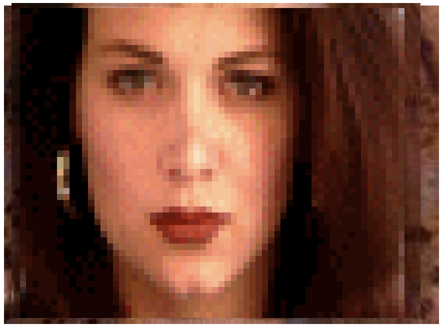
These transformations are a nested set of groups

- Closed under composition and inverse is a member

Image Morphing

- Image morphing has been widely used in movies and commercials to create special visual effects. For example, changing a beauty gradually into a monster.
- The fundamental techniques behind image morphing is image warping.
- Let the original image be f(**u**) and the final image be g(**x**). In image warping, we create g(**x**) from f(**u**) by changing its shape. In image morphing, we use a combination of both f(**u**) and g(**x**) to create a series of intermediate images.

f(u)



g(x)

Examples of Image Morphing

Cross
Dissolve

$I(t) = (1-t)*S+t*T$

Mesh
based

George Wolberg, "Recent Advances in Image Morphing",
Computer Graphics Intl. '96, Pohang, Korea, June 1996.

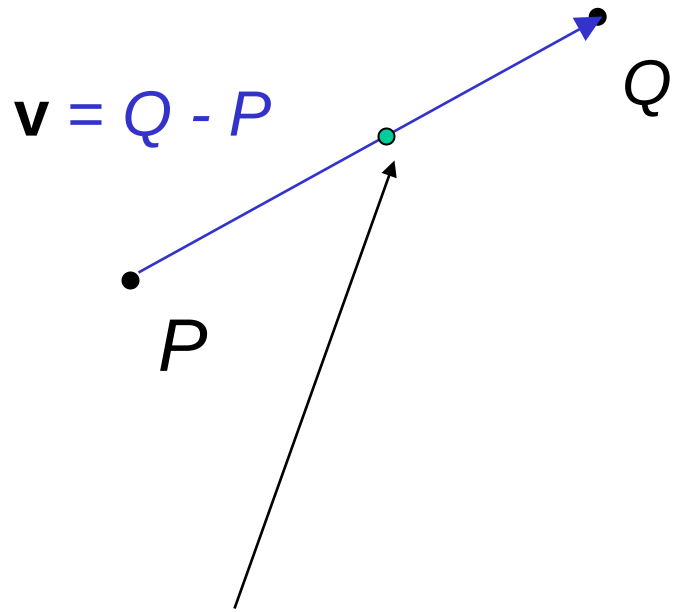
Image Morphing Method

- Suppose the mapping function between the two end images is given as **x=u+d(u)**. **d**(**u**) is the displacement between corresponding points in these two images.
- In image morphing, we create a series of images, starting with f(**u**) at k=0, and ending at g(**x**) at k=K. The intermediate images are a linear combination of the two end images:

$$h_k(\mathbf{u}+s_k\mathbf{d})=(1-s_k)f(\mathbf{u})+s_k g(\mathbf{u}+\mathbf{d}(\mathbf{u})), \quad k=0,1,\ldots,K,$$
$$\text{where } s_k=k/K.$$

Linear Interpolation

How can we linearly transition between point *P* and point *Q*?



$$P + t\,\mathbf{v}$$
$$= (1-t)P + tQ, \qquad \text{e.g. } t = 0.5$$

P and Q can be anything:

- points on a plane (2D) or in space (3D)
- Colors in RGB or HSV (3D)
- Whole images (m-by-n D)… etc.

Idea #1: Cross-Dissolve

Interpolate whole images:

$\text{Image}_{\text{halfway}} = (1-t)*\text{Image}_1 + t*\text{image}_2$

This is called **cross-dissolve** in film industry

But what if the images are not aligned?

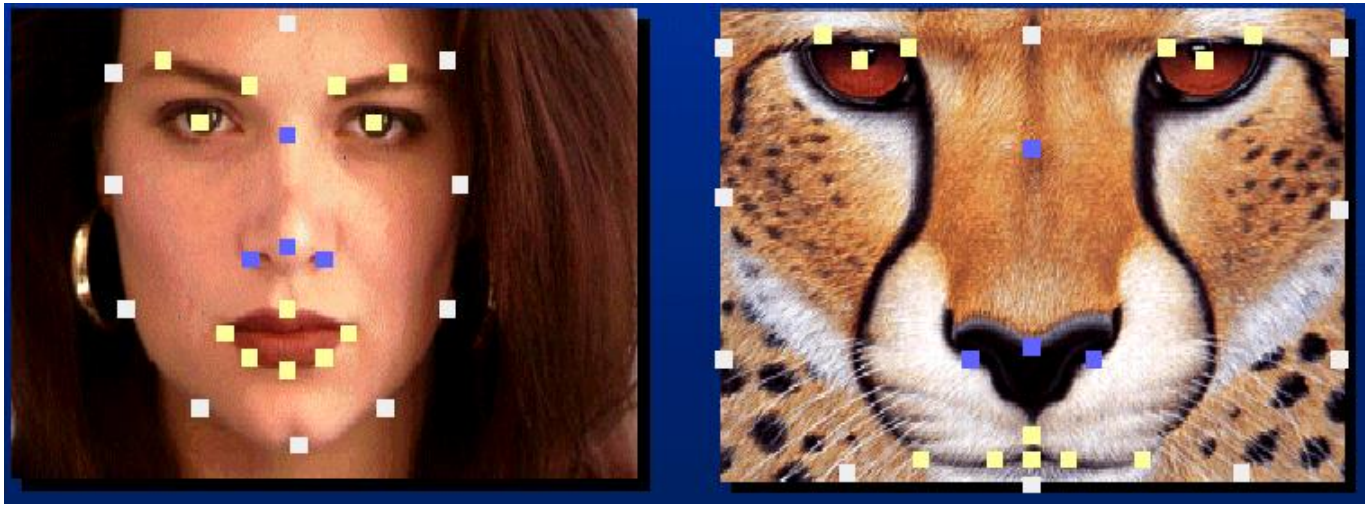
Idea #2: Align, then cross-disolve

Align first, then cross-dissolve

- Alignment using global warp – picture still valid

Full Morphing

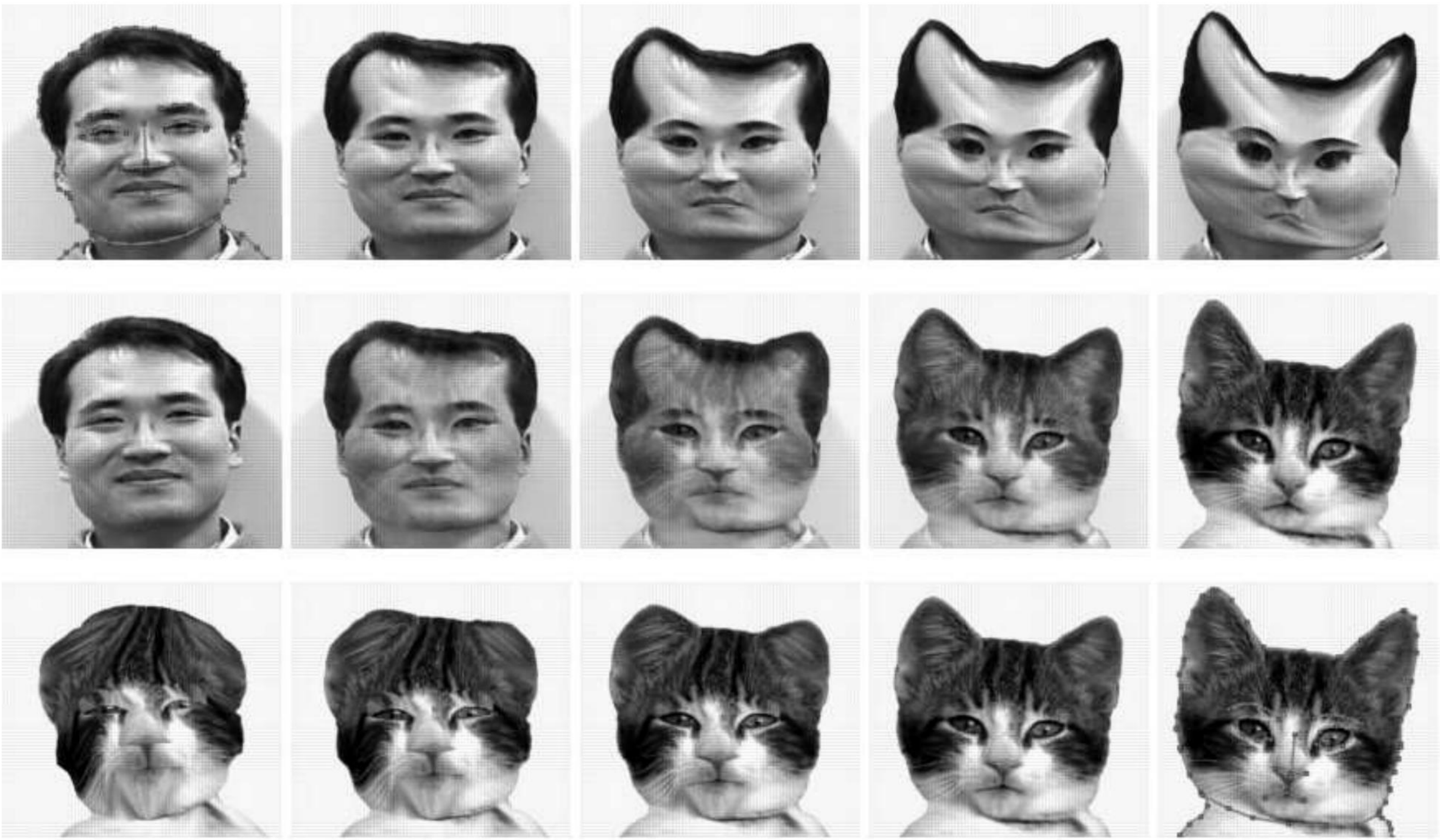
A



B

- What if there is no simple global function that aligns two images?
- User specifies corresponding feature points
- Construct warp animations A -> B and B -> A
- Cross dissolve these

Full Morphing



Full Morphing

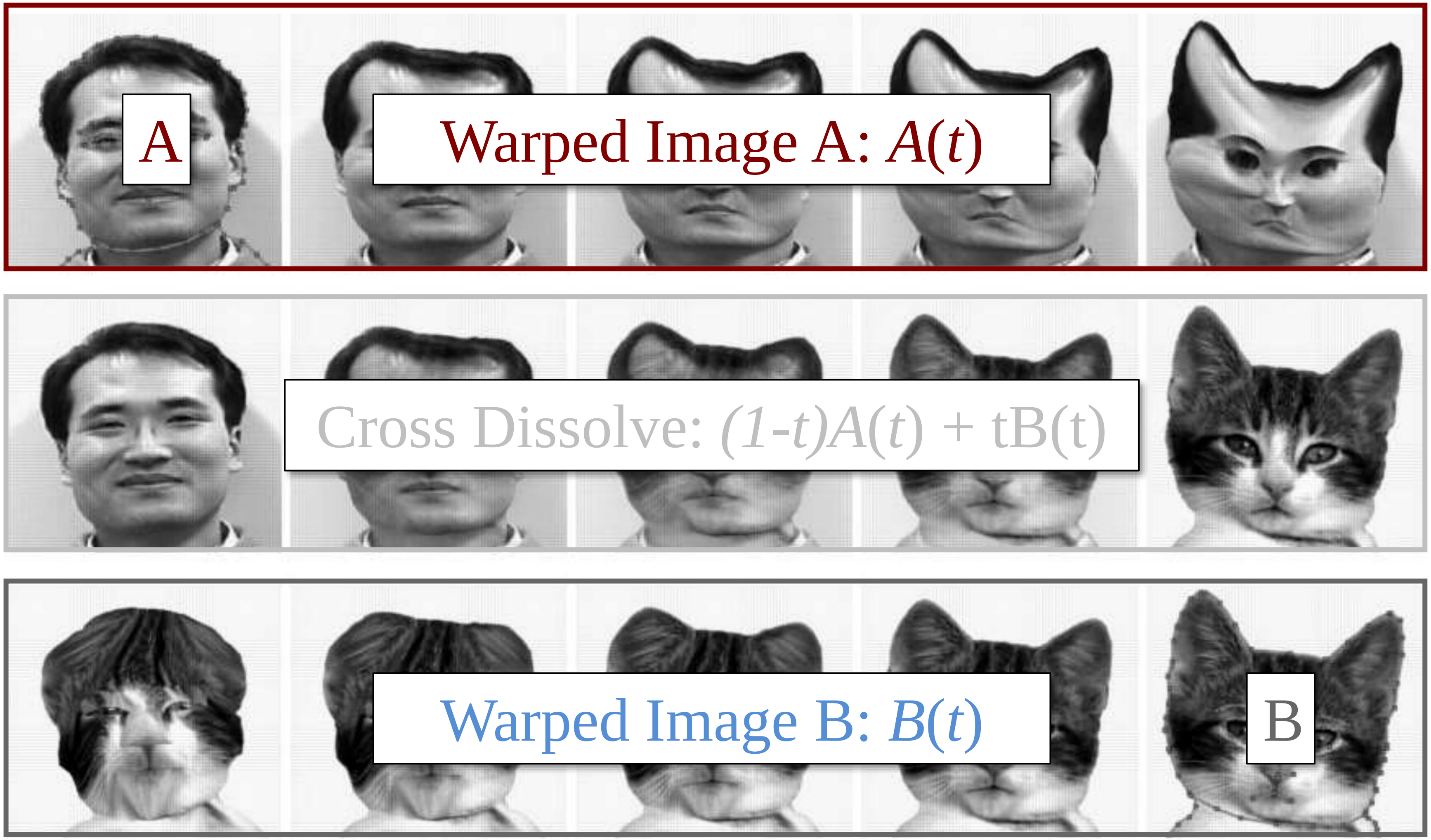
~~Image A~~ ~~Image B~~

1. Find warping fields from user constraints (points or lines):
   Warp field T_{AB}(x, y) that maps A pixel to B pixel
   Warp field T_{BA}(x, y) that maps B pixel to A pixel

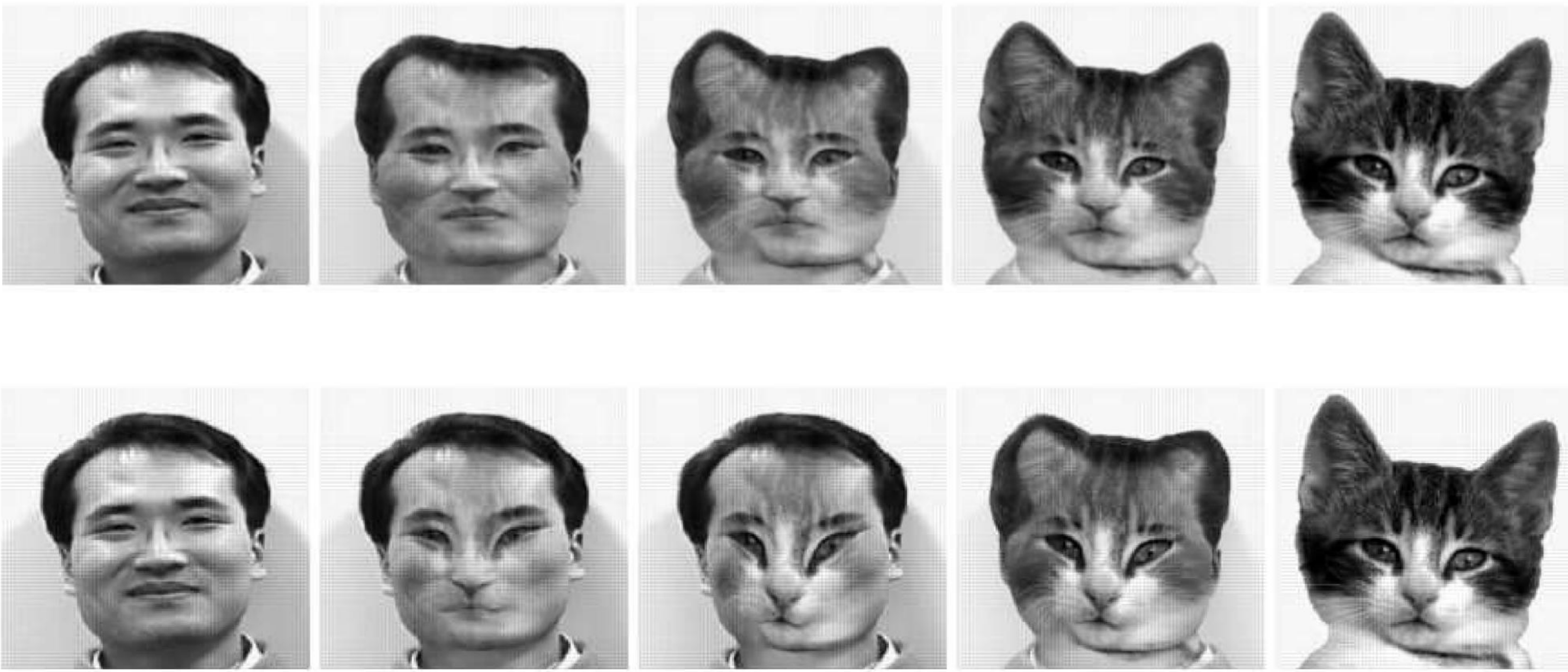
2. Make video $A(t)$ that warps A over time to the shape of B
   Start warp field at identity and linearly interpolate to T_{BA}
   Construct video $B(t)$ that warps B over time to shape of A

3. Cross dissolve these two videos.

Full Morphing



Catman!



Conclusion

Illustrates general principle in graphics:

- First register, then blend

Avoids ghosting

[Michael Jackson - Black or White]