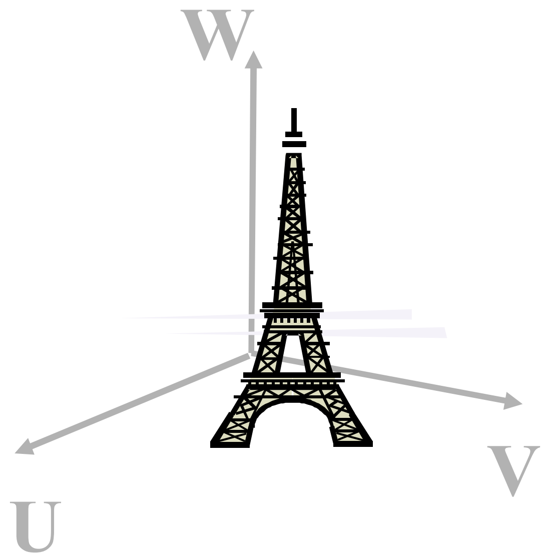
Lecture 13:
Camera Projection II

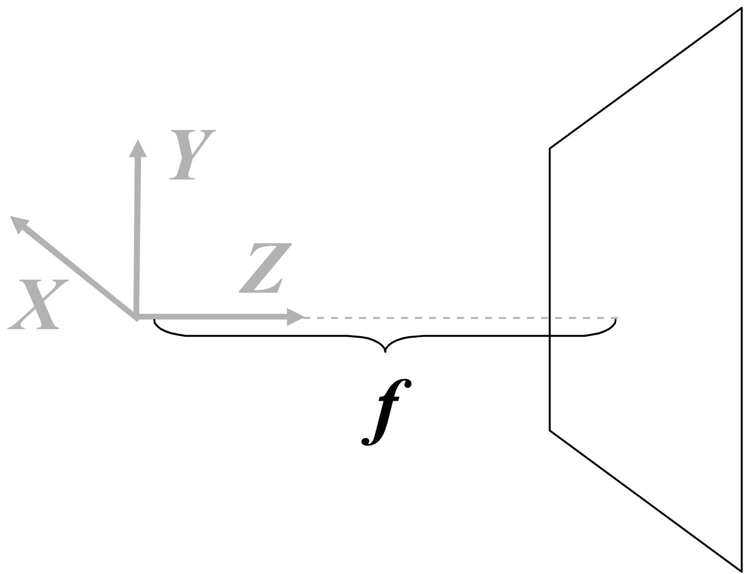
Reading: T&V Section 2.4

Recall: Imaging Geometry

Object of Interest in World Coordinate System (U,V,W)



Imaging Geometry



Camera Coordinate System (X,Y,Z).

- Z is optic axis
- Image plane located f units out along optic axis
- f is called focal length

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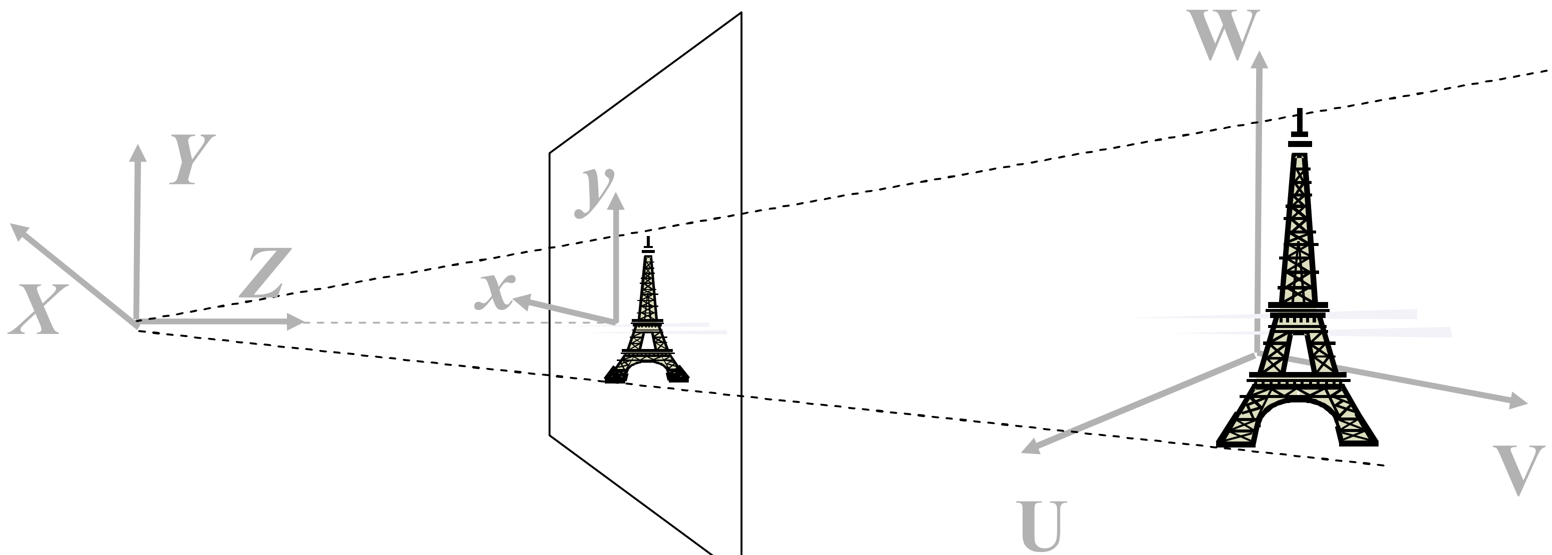
Imaging Geometry



Forward Projection onto image plane.
3D (X,Y,Z) projected to 2D *(x,y)*

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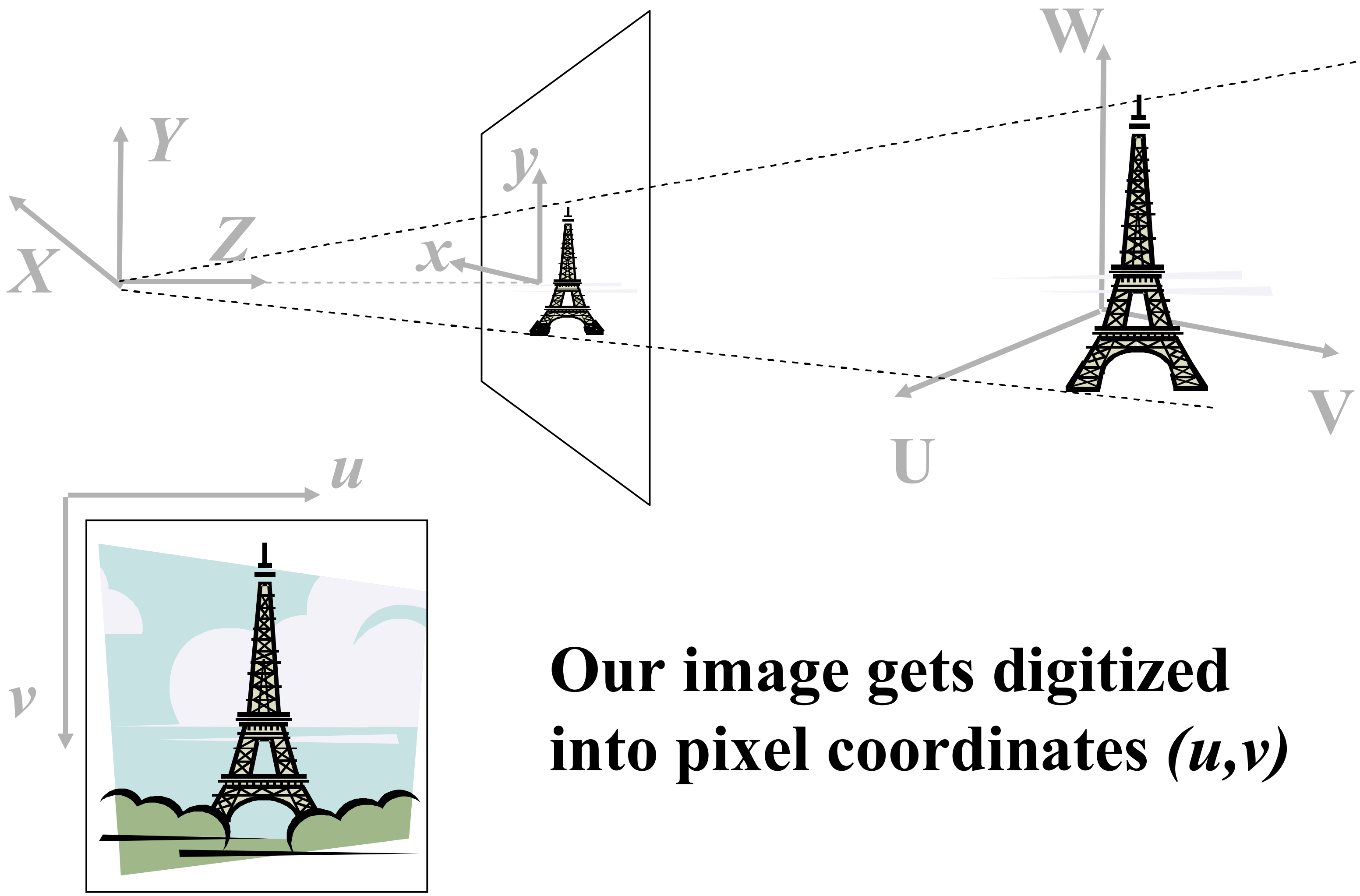
Imaging Geometry



Our image gets digitized into pixel coordinates *(u,v)*

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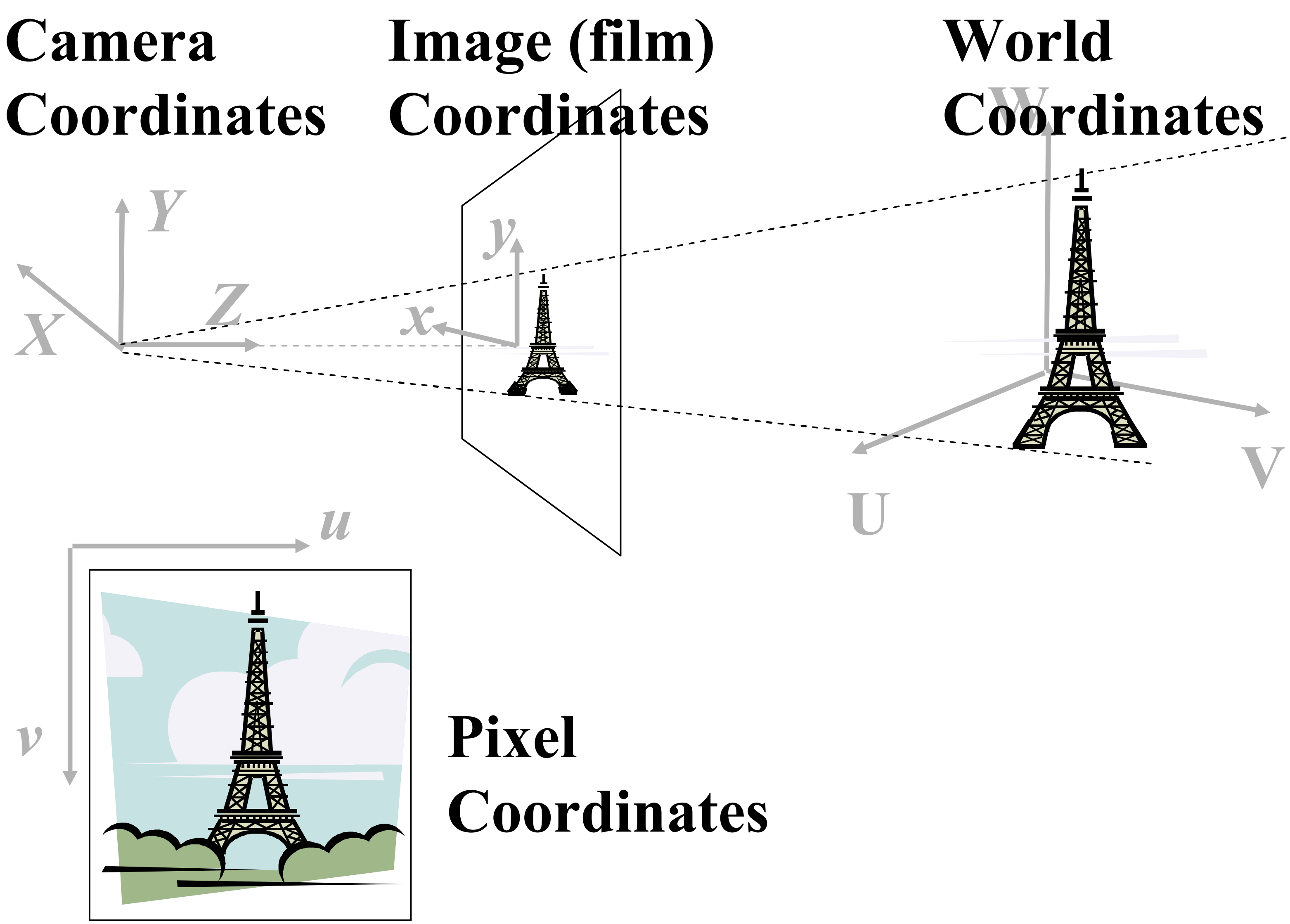
Imaging Geometry



Forward Projection

World Coords		Camera Coords		Film Coords		Pixel Coords
U V W	→	X Y Z	→	x y	→	u v

We want a mathematical model to describe how 3D World points get projected into 2D Pixel coordinates.

Our goal: describe this sequence of transformations by a big matrix equation!

Intrinsic Camera Parameters

World Coords U V W → **Camera Coords** X Y Z → **Film Coords** x y → **Pixel Coords** u v

Affine Transformation

Intrinsic parameters

- Describes coordinate transformation between film coordinates (projected image) and pixel array
- Film cameras: scanning/digitization
- CCD cameras: grid of photosensors

still in T&V section 2.4

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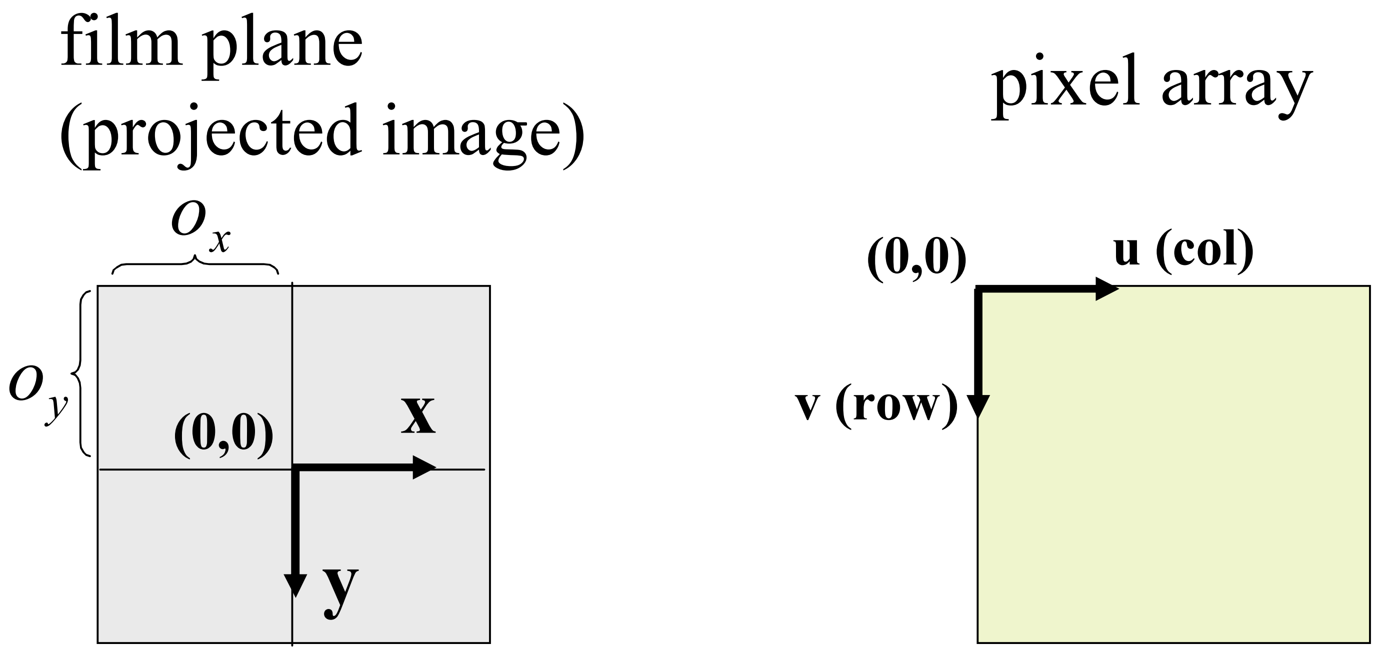
Intrinsic parameters (offsets)



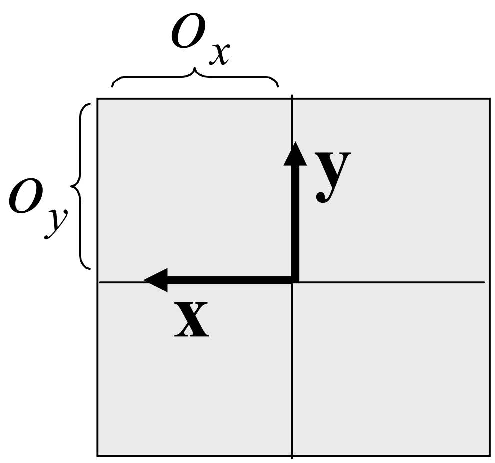
$$u = f\frac{X}{Z} + o_x \qquad v = f\frac{Y}{Z} + o_y$$

o_x and o_y called image center or principle point

Intrinsic parameters

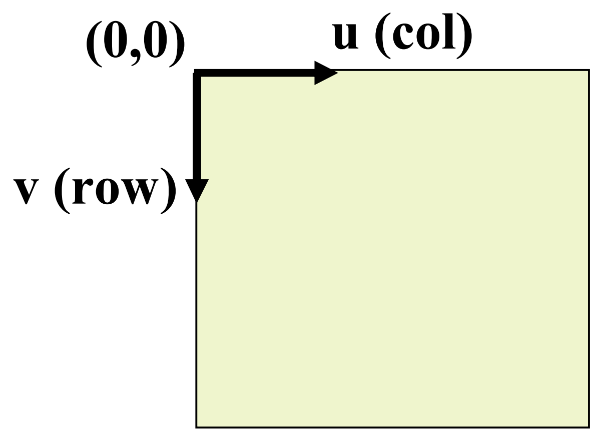
sometimes one or more coordinate axes are flipped (e.g. T&V section 2.4)

film plane



(0,0)

pixel array



$$u = -f\frac{X}{Z} + o_x \qquad v = -f\frac{Y}{Z} + o_y$$

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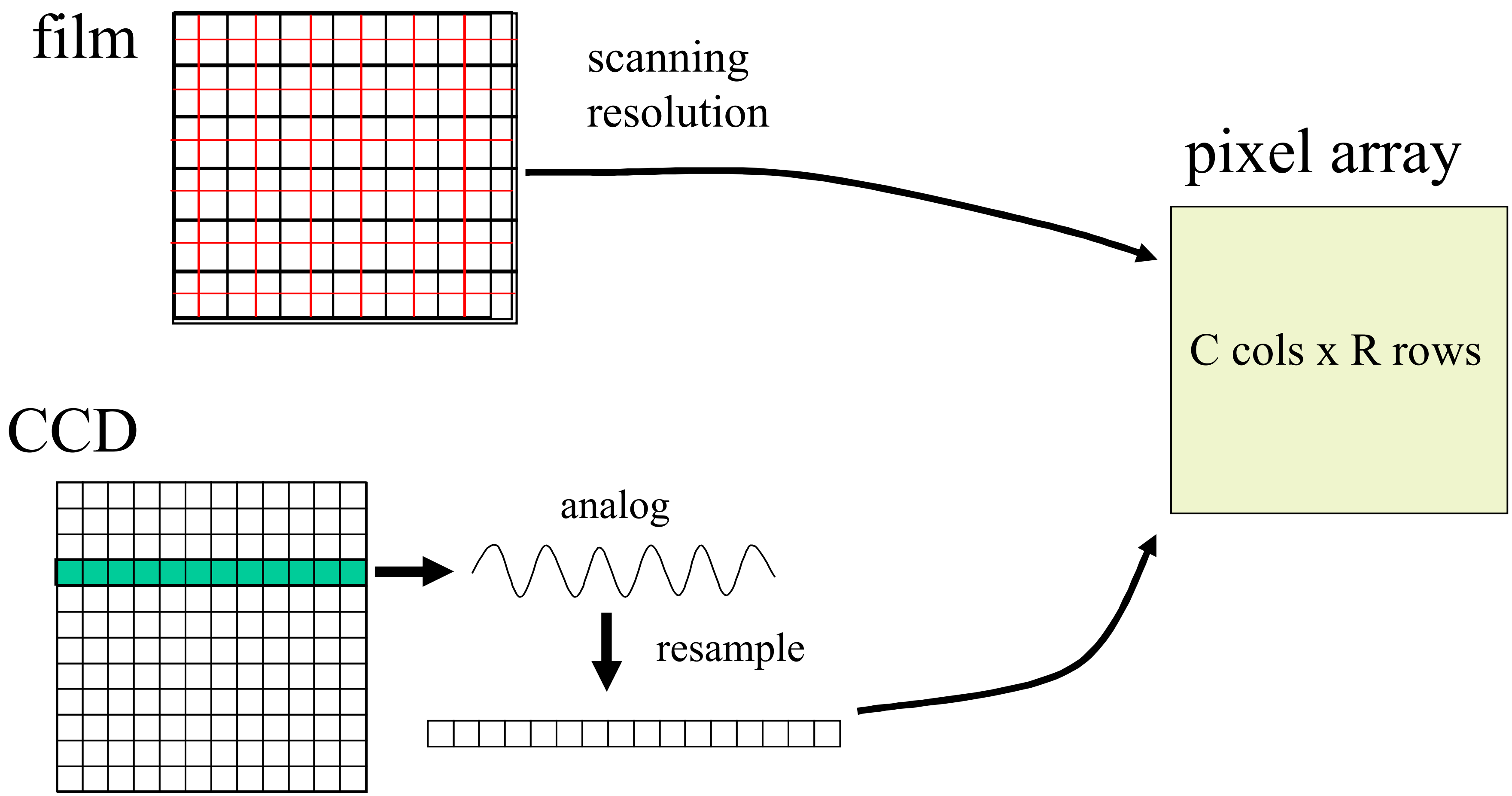
Intrinsic parameters (scales)

sampling determines how many rows/cols in the image



Effective Scales: s_x and s_y

$$u = \frac{1}{s_x} f \frac{X}{Z} + o_x \qquad v = \frac{1}{s_y} f \frac{Y}{Z} + o_y$$

Note, since we have different scale factors in x and y, we don't necessarily have square pixels!

Aspect ratio is s_y / s_x

Perspective projection matrix

Adding the intrinsic parameters into the perspective projection matrix:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} f/s_x & 0 & o_x & 0 \\ 0 & f/s_y & o_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

To verify:

$$u = \frac{x'}{z'} \qquad v = \frac{y'}{z'}$$

$$\Longrightarrow \quad u = \frac{1}{s_x} f \frac{X}{Z} + o_x \qquad v = \frac{1}{s_y} f \frac{Y}{Z} + o_y$$

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Note:

Sometimes, the image and the camera coordinate systems have opposite orientations: [the book does it this way]

$$f\frac{X}{Z} = -(u - o_x)s_x$$

$$f\frac{Y}{Z} = -(v - o_y)s_y$$

$$\Rightarrow$$

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} -f/s_x & 0 & +o_x & 0 \\ 0 & -f/s_y & +o_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

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Note 2

In general, I like to think of the conversion as a separate 2D affine transformation from film coords (x,y) to pixel coordinates (u,v):

$$\begin{pmatrix} u' \\ v' \\ w' \end{pmatrix} = \underbrace{\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{M_{aff}}} \underbrace{\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}_{\mathbf{M_{proj}}} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\mathbf{u = M_{int}\, P_C = M_{aff}\, M_{proj}\, P_C}$$

Huh?

Did he just say it was "a fine" transformation?

No, it was "affine" transformation, a type of 2D to 2D mapping defined by 6 parameters.

More on this in a moment...

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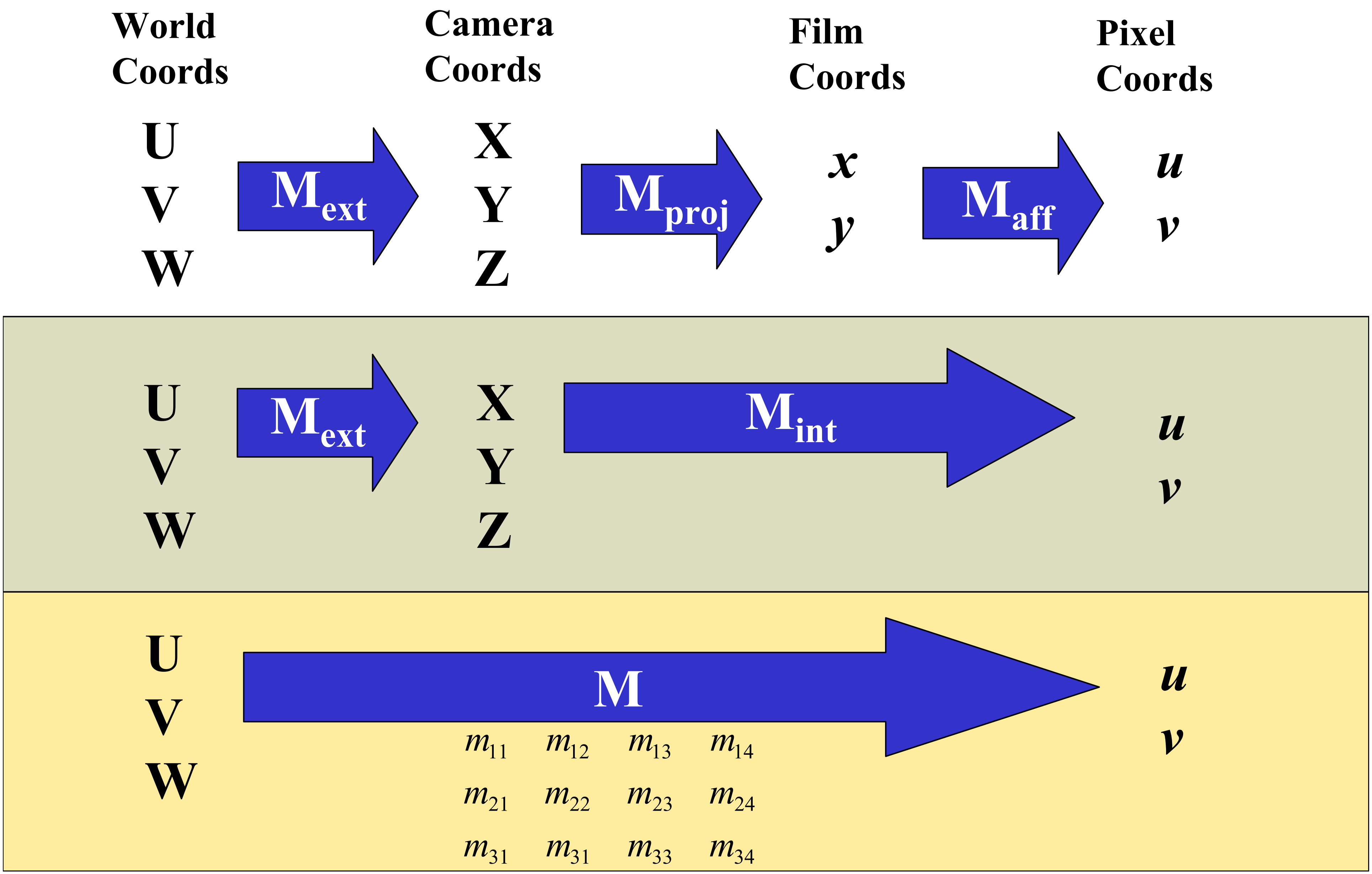
Summary : Forward Projection



Summary: Projection Equation

$$
\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \sim
\underbrace{\underbrace{\overbrace{\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & 1 \end{bmatrix}}^{\text{Film plane to pixels}}}_{\mathbf{M_{aff}}}
\underbrace{\overbrace{\begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}}^{\text{Perspective projection}}}_{\mathbf{M_{proj}}}}_{\mathbf{M_{int}}}
\underbrace{\overbrace{\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}}^{\text{World to camera}}}_{\mathbf{M_{ext}}}
\begin{bmatrix} U \\ V \\ W \\ 1 \end{bmatrix}
$$

$$\mathbf{M} = \mathbf{M_{int}}\,\mathbf{M_{ext}}$$

Lecture 13/14: Intro to Image Mappings

Image Mappings Overview

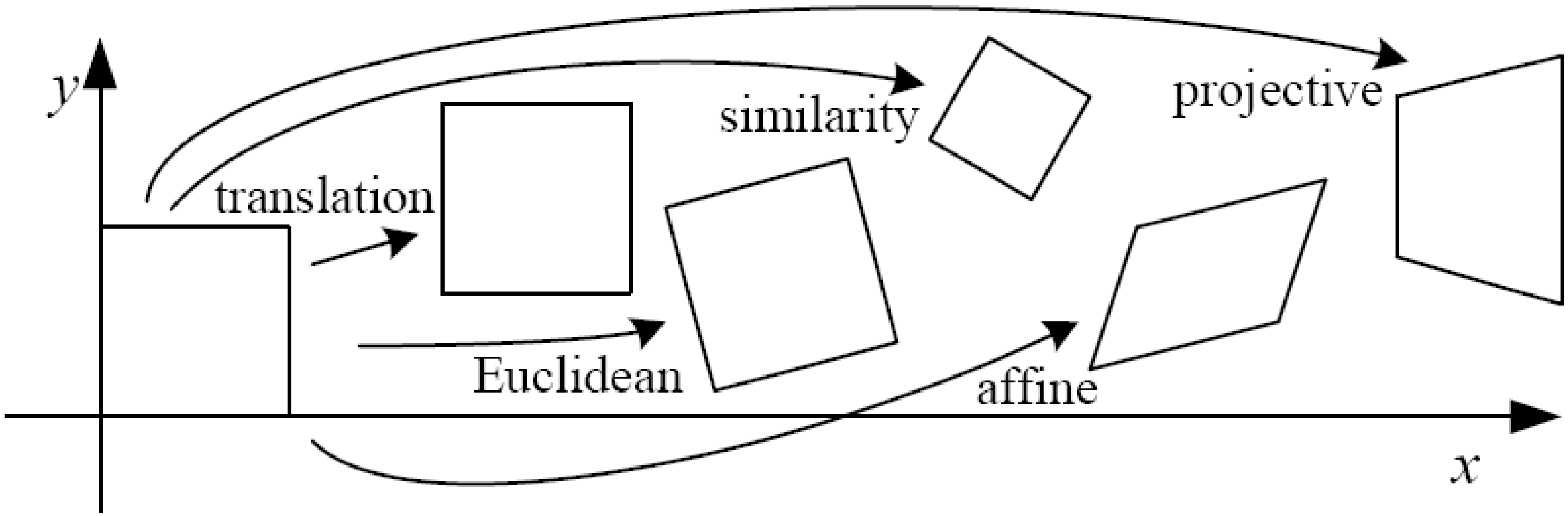


FIGURE 1. Basic set of 2D planar transformations

from R.Szeliski

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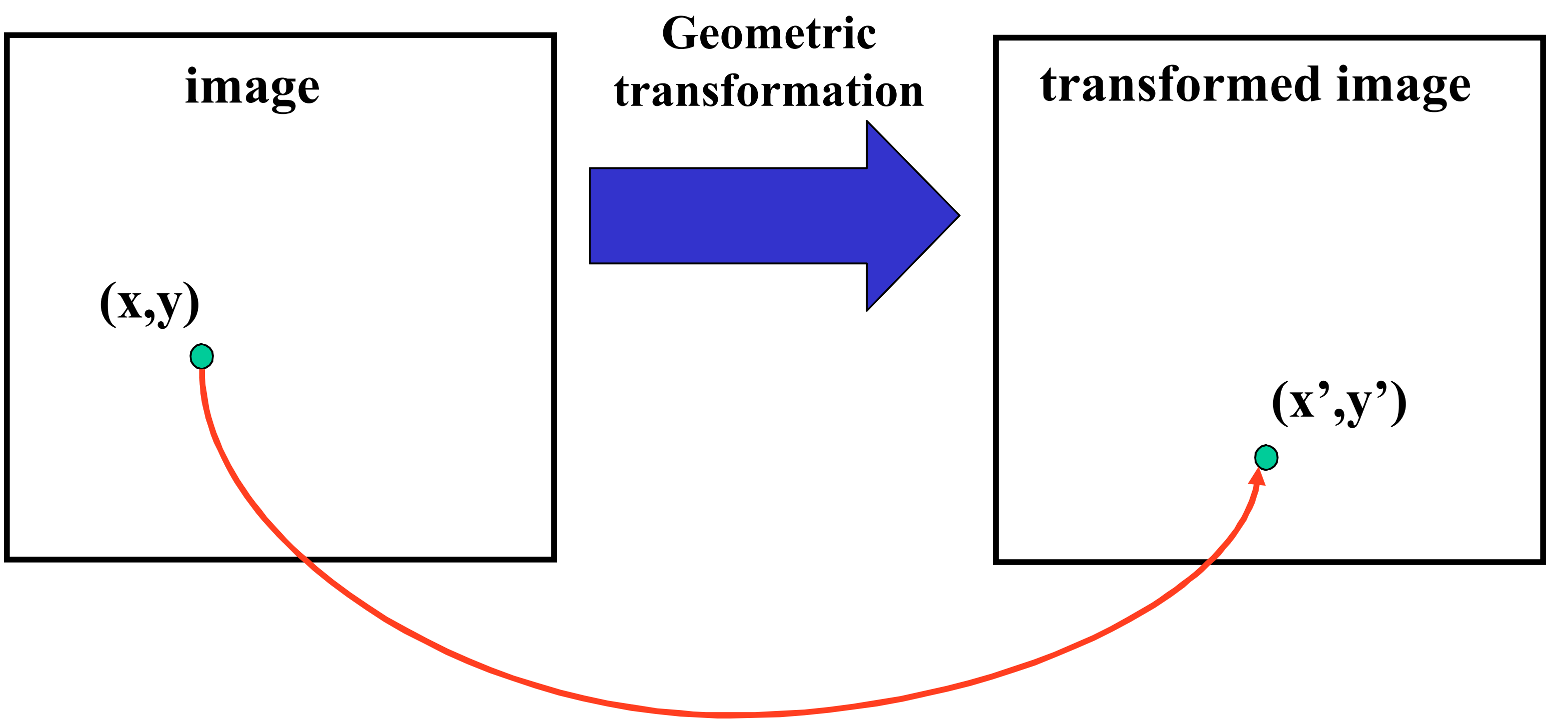
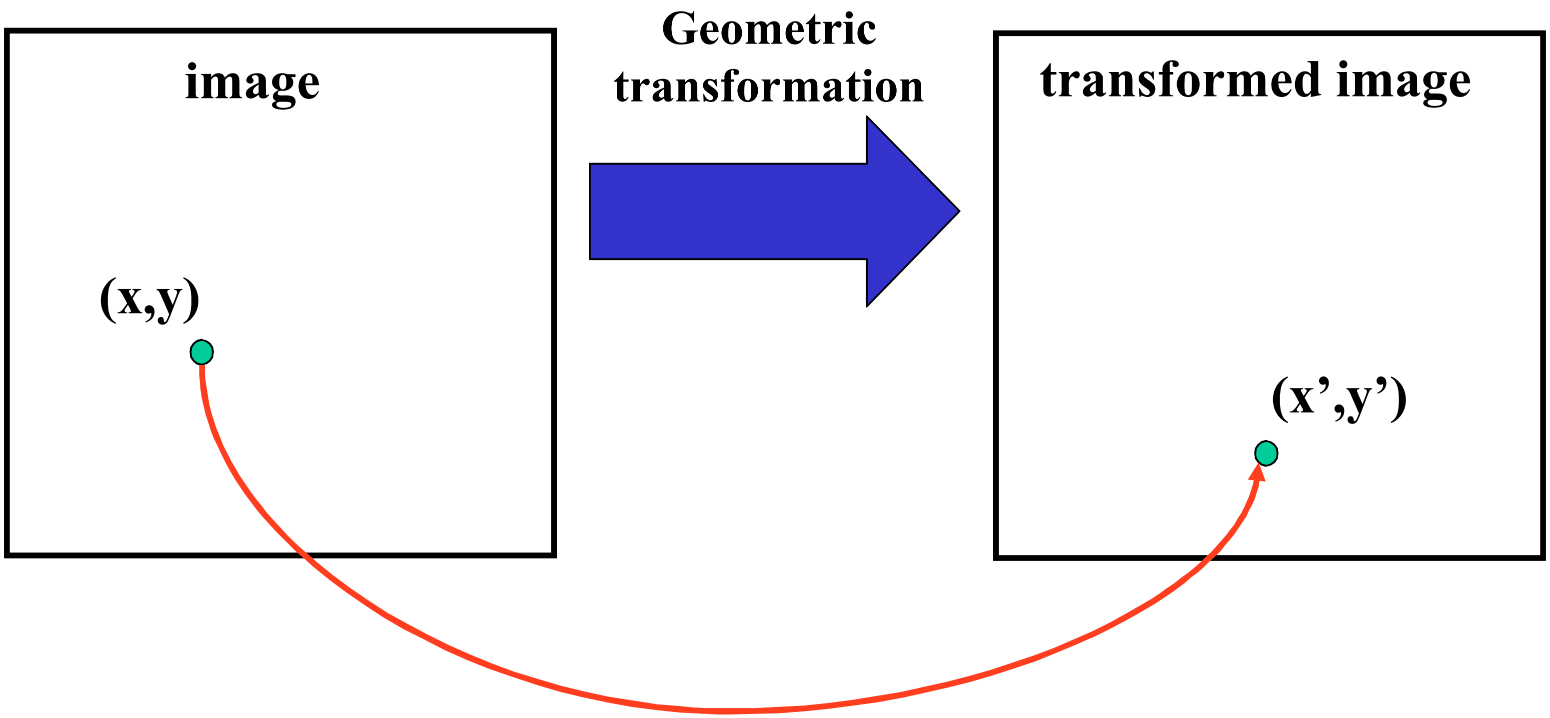
Geometric Image Mappings



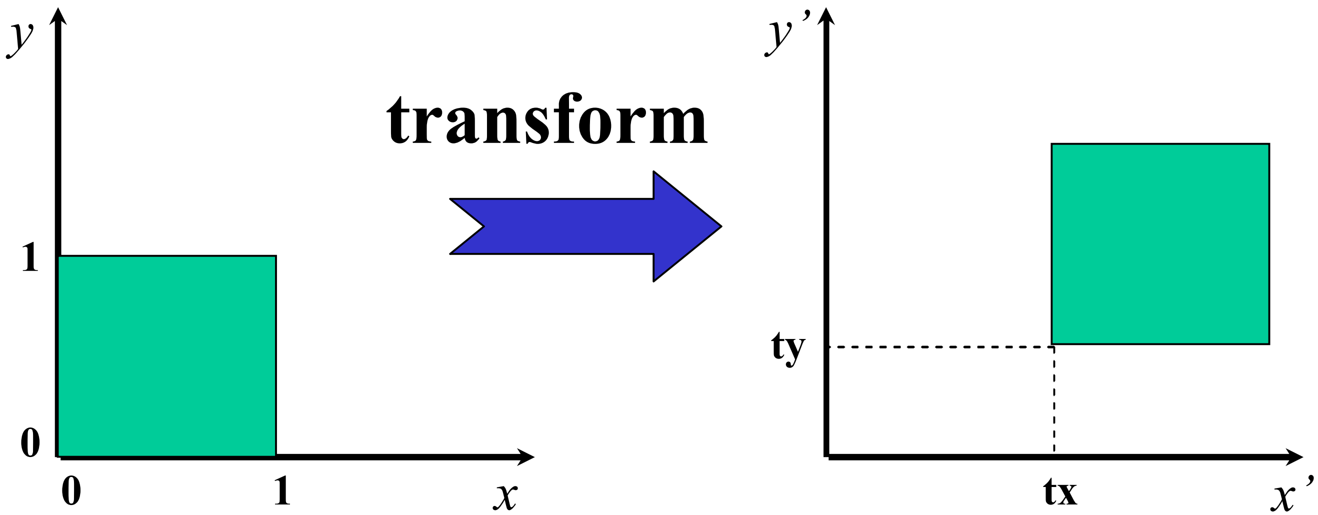
$$x' = f(x, y, \{\text{parameters}\})$$
$$y' = g(x, y, \{\text{parameters}\})$$

Linear Transformations
(Can be written as matrices)



$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{pmatrix} \quad M(\text{params}) \quad \end{pmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Translation



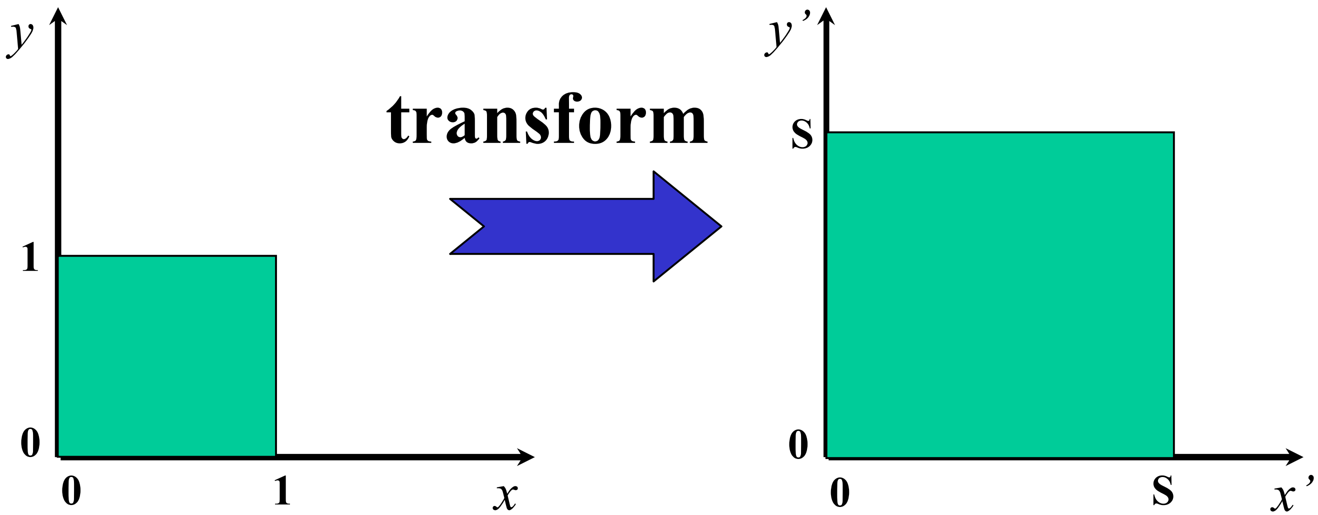
$$x' = x + t_x$$
$$y' = y + t_y$$

equations

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

matrix form

Scale



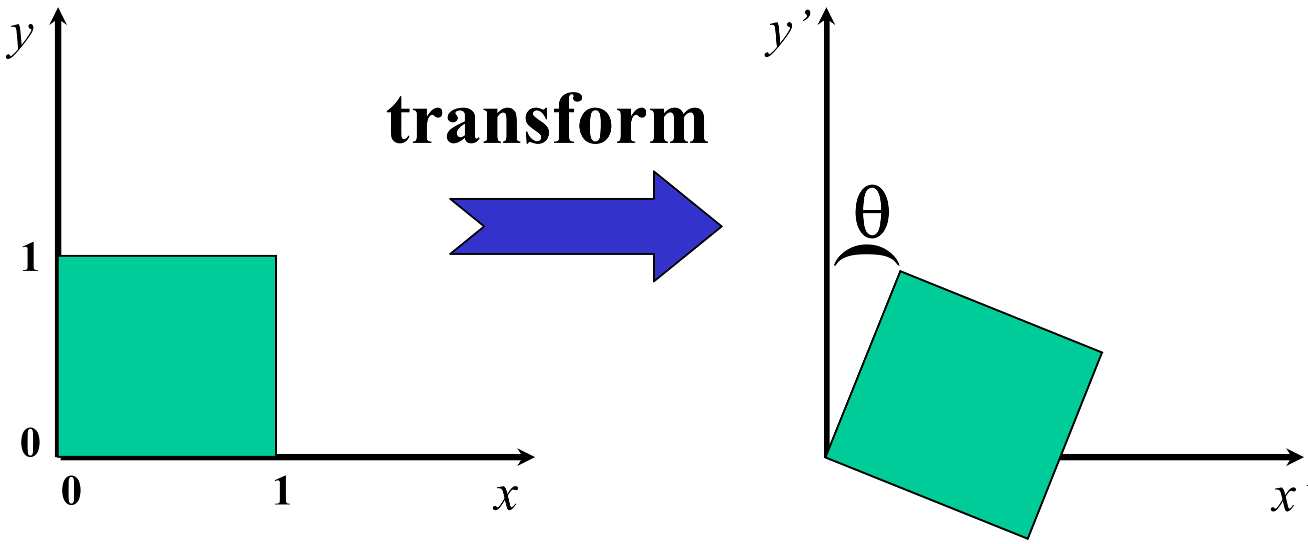
$$x' = s\,x_i$$
$$y' = s\,y_i$$

equations

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

matrix form

Rotation



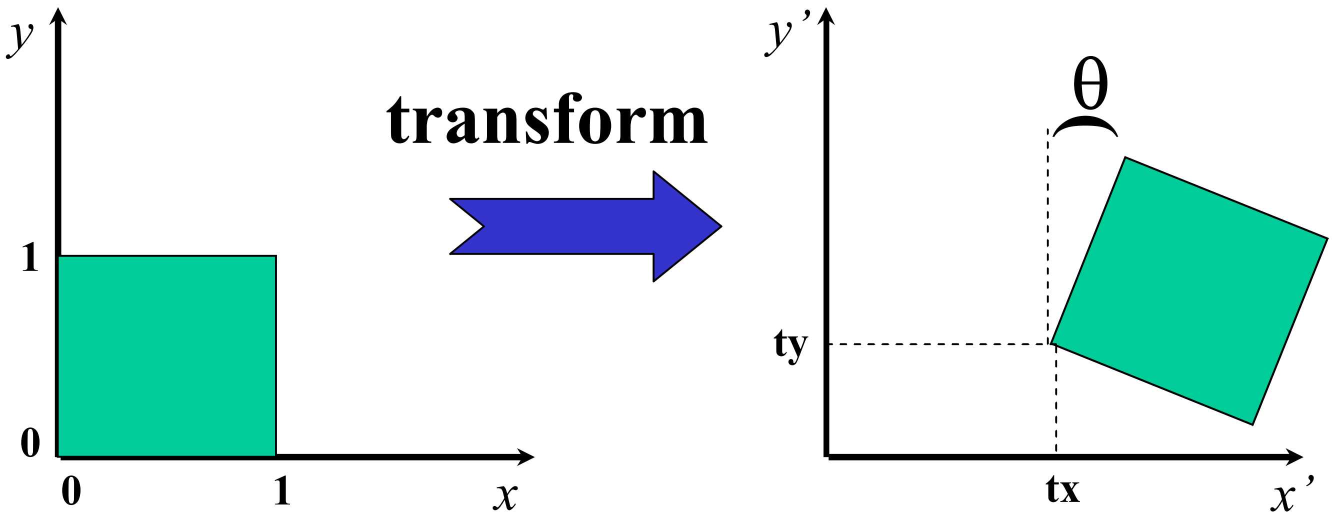
$$x' = x_i \cos\theta - y_i \sin\theta$$
$$y' = x_i \sin\theta + y_i \cos\theta$$

equations

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

matrix form

Euclidean (Rigid)



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

equations

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

matrix form

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Partitioned Matrices

A *partitioned matrix*, or a *block matrix*, is a matrix M that has been constructed from other smaller matrices. These smaller matrices are called *blocks* or *sub-matrices* of M.

For instance, if we partition the below 5×5 matrix as follows

$$L = \left(\begin{array}{cc|ccc} 1 & 0 & 1 & 2 & 3 \\ 0 & 1 & 1 & 2 & 3 \\ \hline 2 & 3 & 9 & 9 & 9 \\ 2 & 3 & 9 & 9 & 9 \\ 2 & 3 & 9 & 9 & 9 \end{array}\right),$$

then we can define the matrices

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, B = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix}, C = \begin{pmatrix} 2 & 3 \\ 2 & 3 \\ 2 & 3 \end{pmatrix}, D = \begin{pmatrix} 9 & 9 & 9 \\ 9 & 9 & 9 \\ 9 & 9 & 9 \end{pmatrix}$$

and write L as

$$L = \begin{pmatrix} A & B \\ C & D \end{pmatrix}, \quad \text{or} \quad L = \left(\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right).$$

http://planetmath.org/encyclopedia/PartitionedMatrix.html

Partitioned Matrices

$$\begin{bmatrix} x' \\ y' \\ \hline 1 \end{bmatrix} = \left[\begin{array}{cc|c} \cos\theta & -\sin\theta & t_x \\ \sin\theta & \cos\theta & t_y \\ \hline 0 & 0 & 1 \end{array}\right] \begin{bmatrix} x \\ y \\ \hline 1 \end{bmatrix}$$

$$\begin{bmatrix} \overset{\text{2x1}}{p'} \\ \overset{\text{1x1}}{1} \end{bmatrix} = \begin{bmatrix} \overset{\text{2x2}}{R} & \overset{\text{2x1}}{t} \\ \overset{\text{1x2}}{0} & \overset{\text{1x1}}{1} \end{bmatrix} \begin{bmatrix} \overset{\text{2x1}}{p} \\ \overset{\text{1x1}}{1} \end{bmatrix}$$

matrix form

$$p' = Rp + t$$

equation form

Another Example (from last time)

$$\begin{pmatrix} X \\ Y \\ Z \\ \hline 1 \end{pmatrix} = \left(\begin{array}{ccc|c} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ \hline 0 & 0 & 0 & 1 \end{array}\right) \begin{pmatrix} U \\ V \\ W \\ \hline 1 \end{pmatrix}$$

$$\begin{pmatrix} \overset{3\text{x}1}{\mathbf{P}_{\mathbf{C}}} \\ \overset{1\text{x}1}{1} \end{pmatrix} = \begin{pmatrix} \overset{3\text{x}3}{\mathbf{R}} & \overset{3\text{x}1}{\mathbf{T}} \\ \overset{1\text{x}3}{0} & \overset{1\text{x}1}{1} \end{pmatrix} \begin{pmatrix} \overset{3\text{x}1}{\mathbf{P}_{\mathbf{W}}} \\ \overset{1\text{x}1}{1} \end{pmatrix}$$

$$\mathbf{P}_{\mathbf{C}} = \mathbf{R}\,\mathbf{P}_{\mathbf{W}} + \mathbf{T}$$

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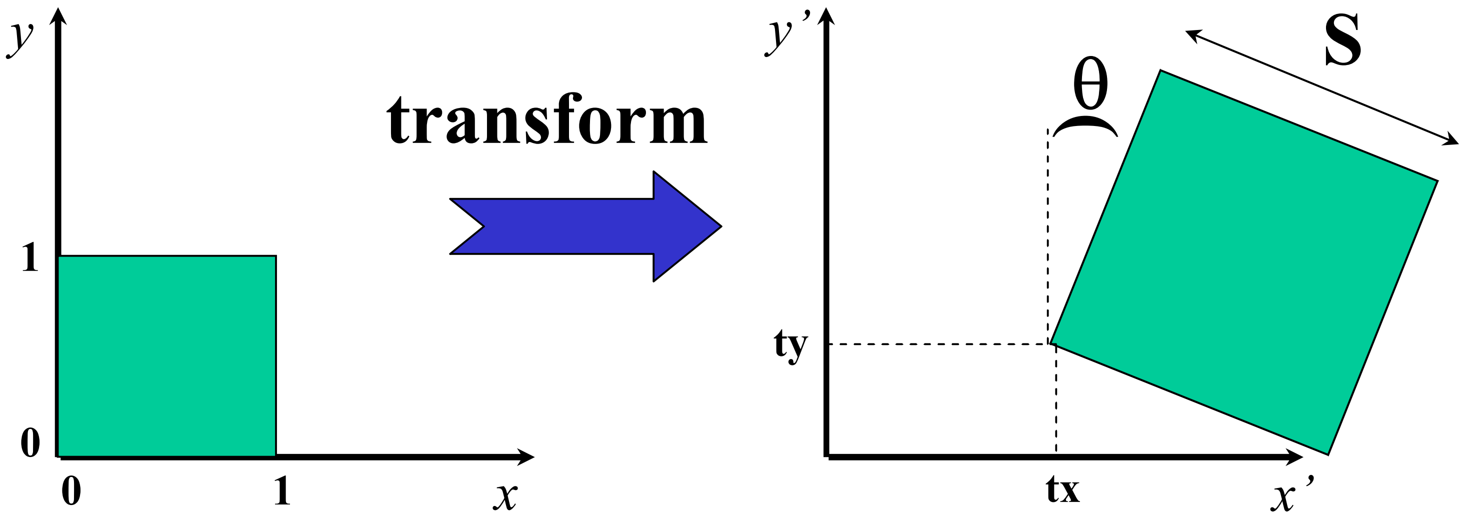
Similarity (scaled Euclidean)



$$p' = sRp + t$$

equations

$$\begin{bmatrix} p' \\ 1 \end{bmatrix} = \begin{bmatrix} sR & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p \\ 1 \end{bmatrix}$$

matrix form

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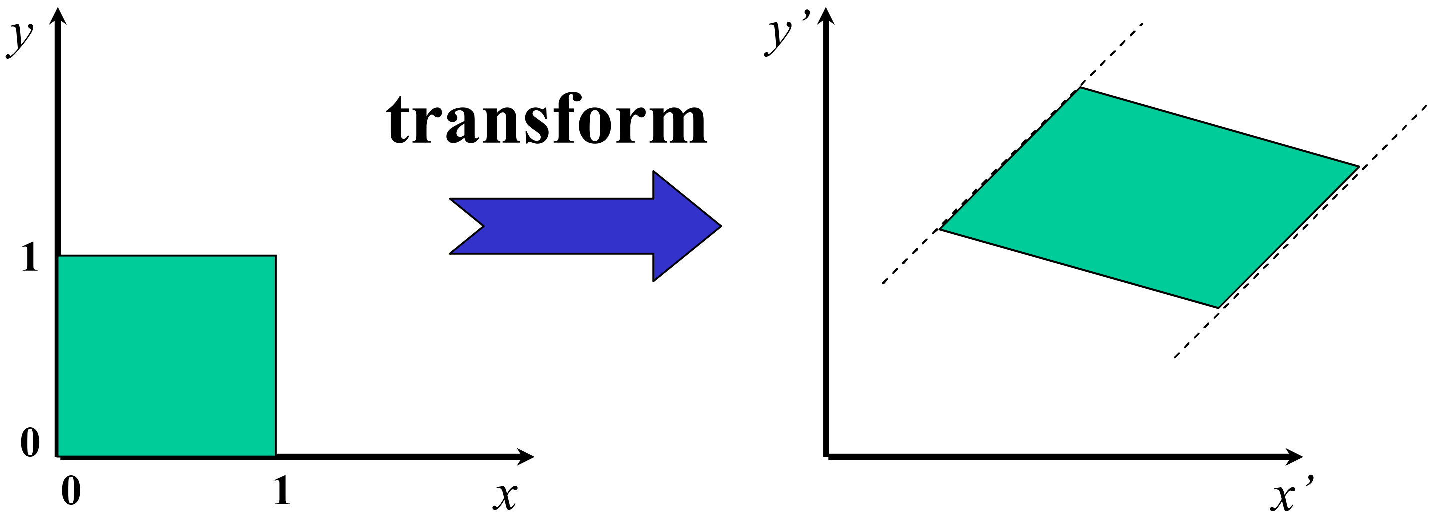
Affine



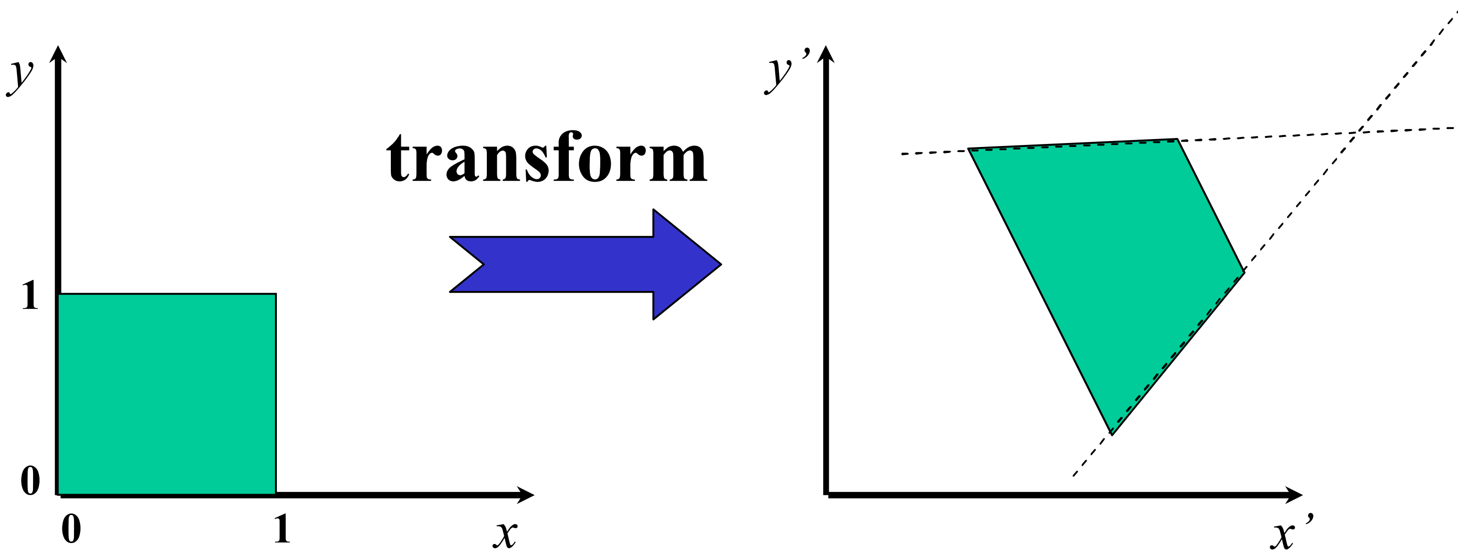
$$p' = Ap + b$$

equations

$$\begin{bmatrix} p' \\ 1 \end{bmatrix} = \begin{bmatrix} A & b \\ 0 & 1 \end{bmatrix} \begin{bmatrix} p \\ 1 \end{bmatrix}$$

matrix form

Projective



$$p' = \frac{Ap + b}{c^T p + 1}$$

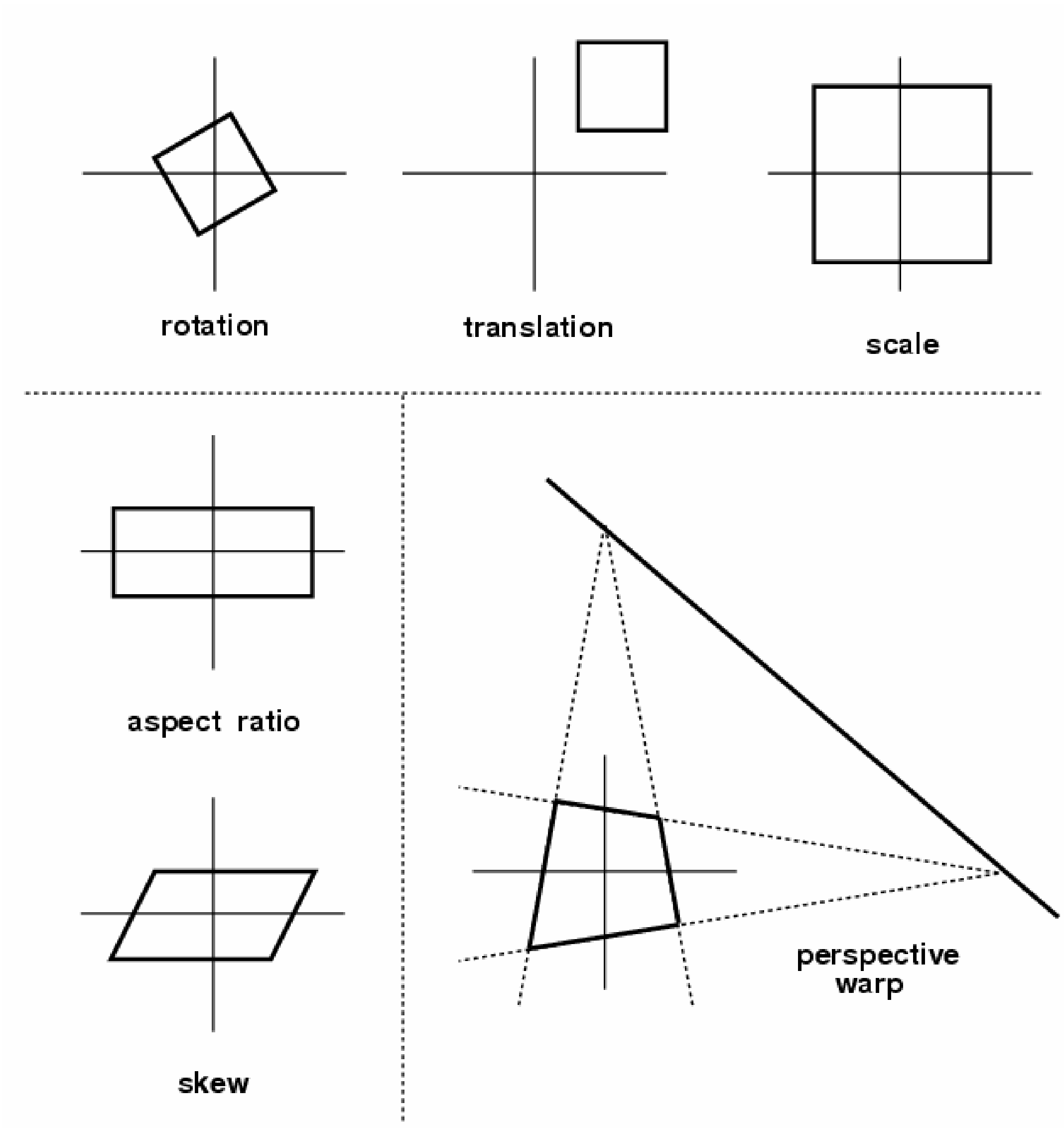
equations

Note!

$$\begin{bmatrix} p' \\ 1 \end{bmatrix} \sim \begin{bmatrix} A & b \\ c^T & 1 \end{bmatrix} \begin{bmatrix} p \\ 1 \end{bmatrix}$$

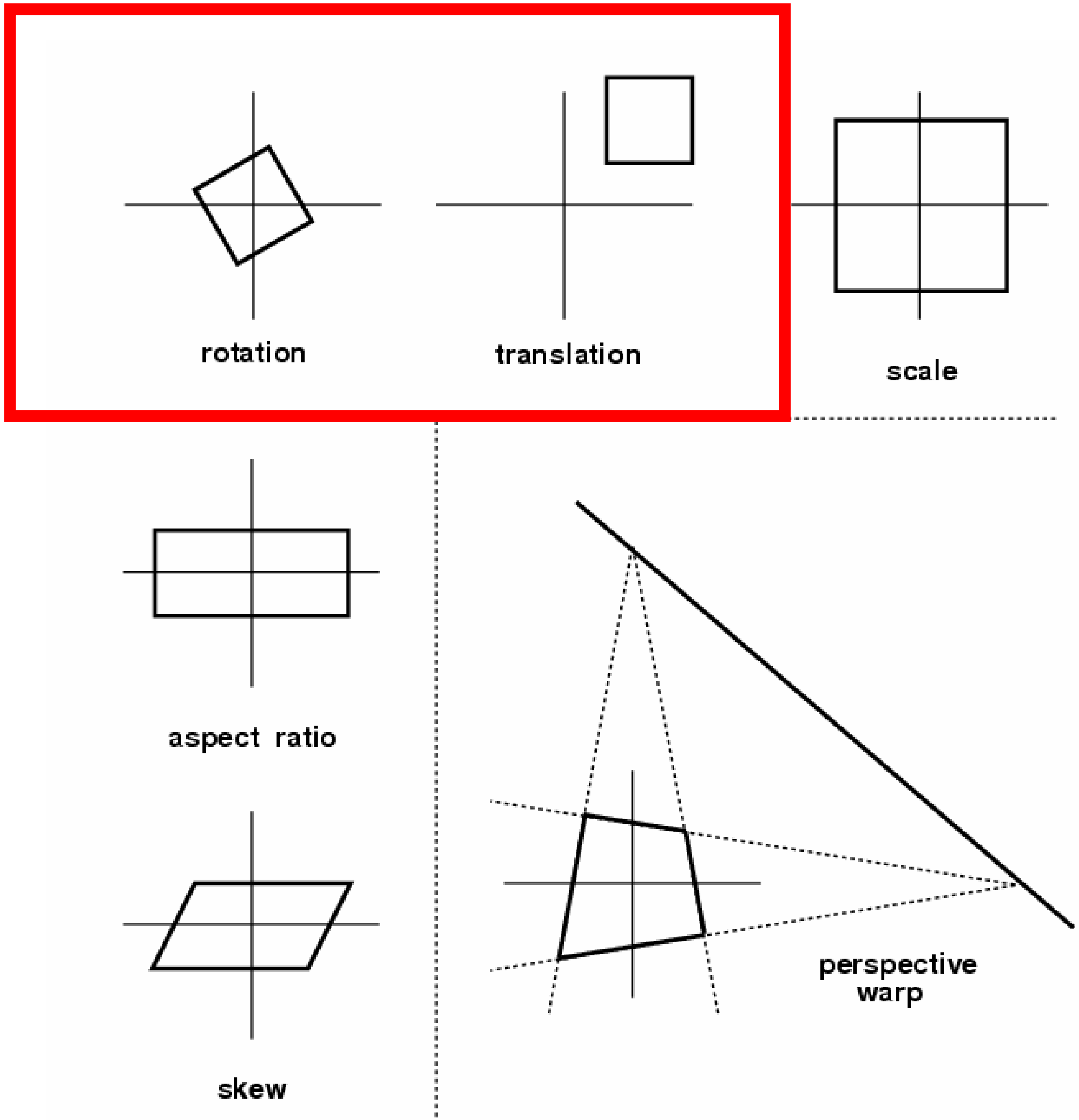
matrix form

Summary of 2D Transformations



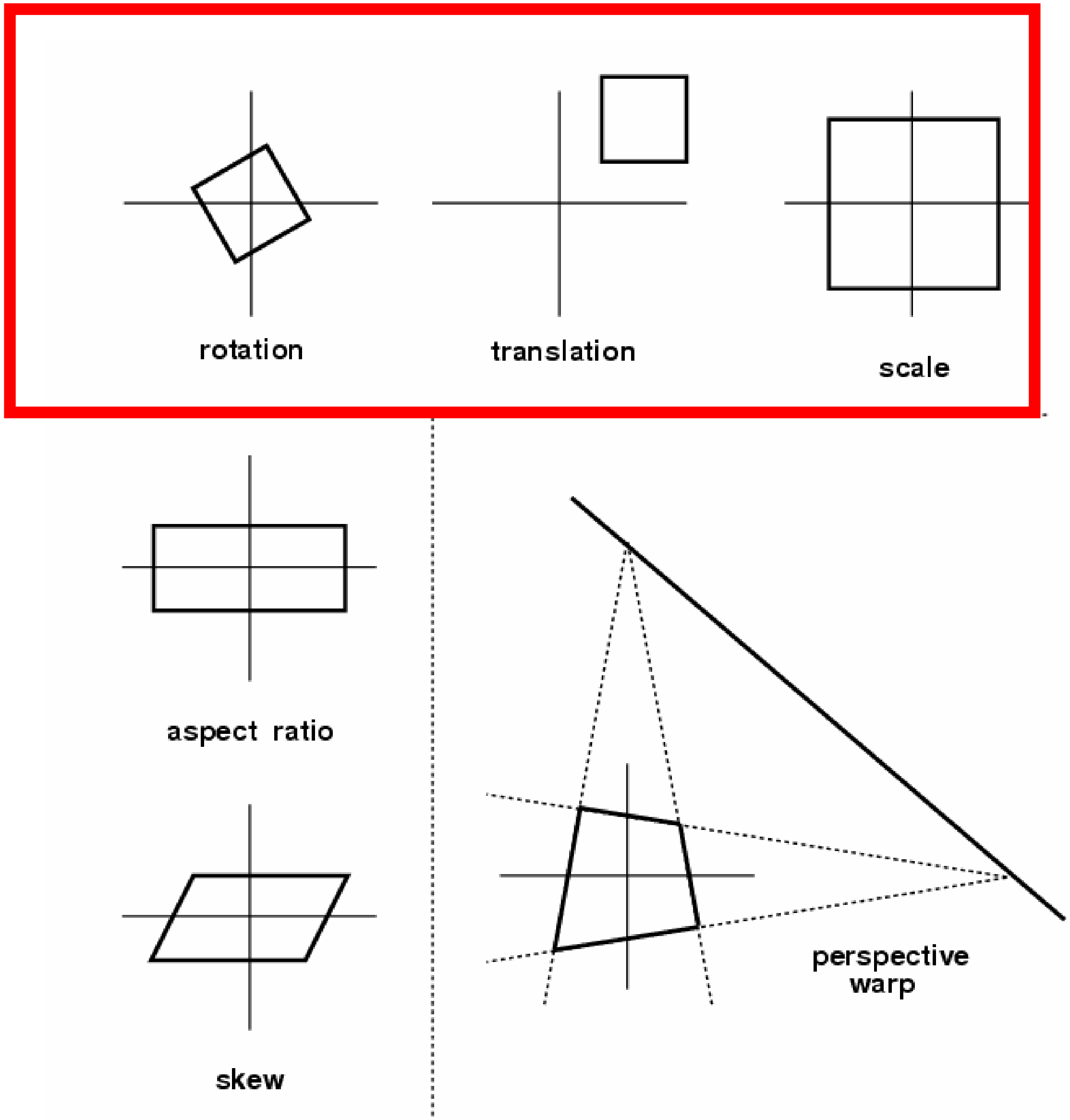
Summary of 2D Transformations

Euclidean



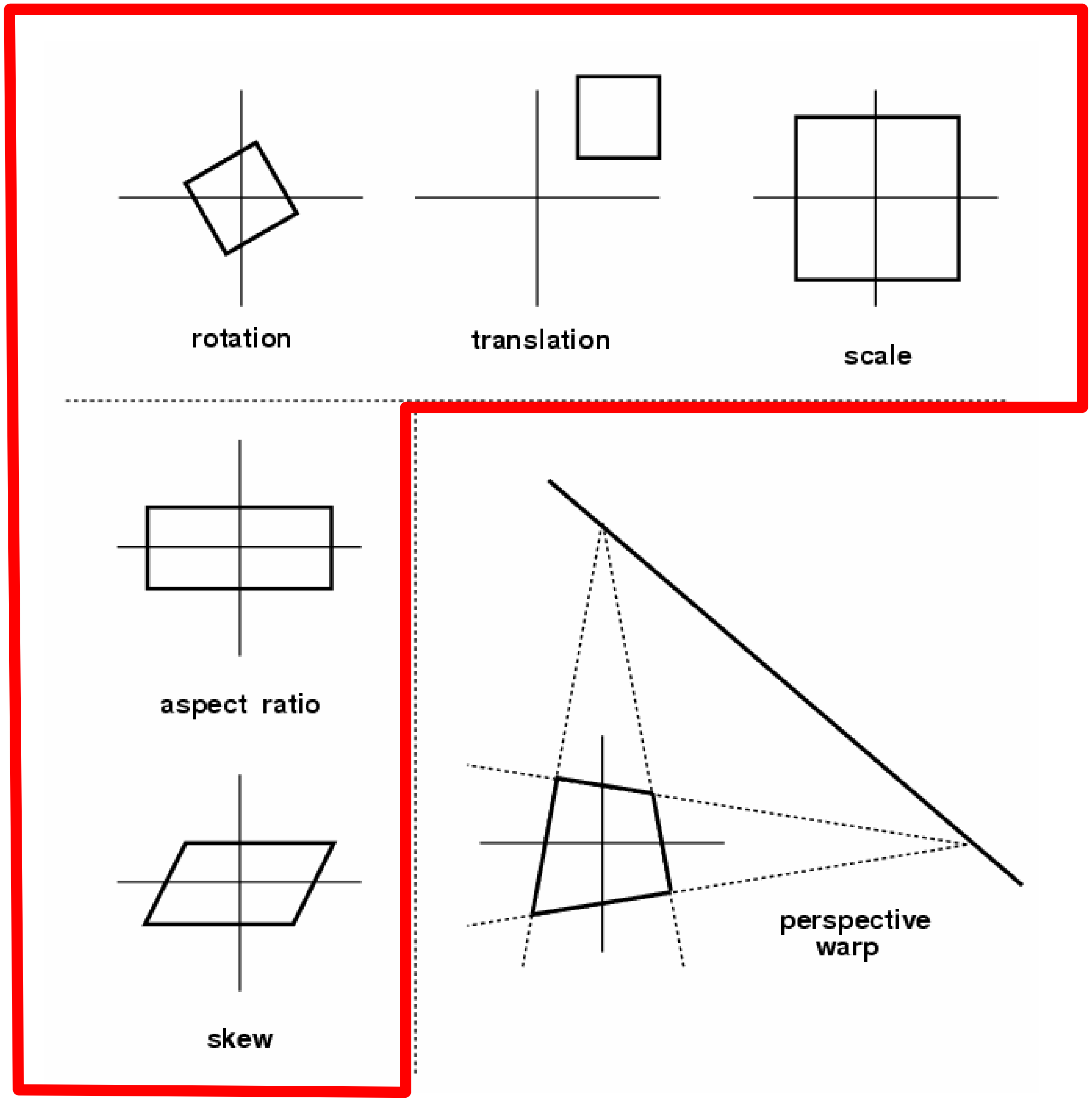
Summary of 2D Transformations

Similarity



Summary of 2D Transformations

Affine



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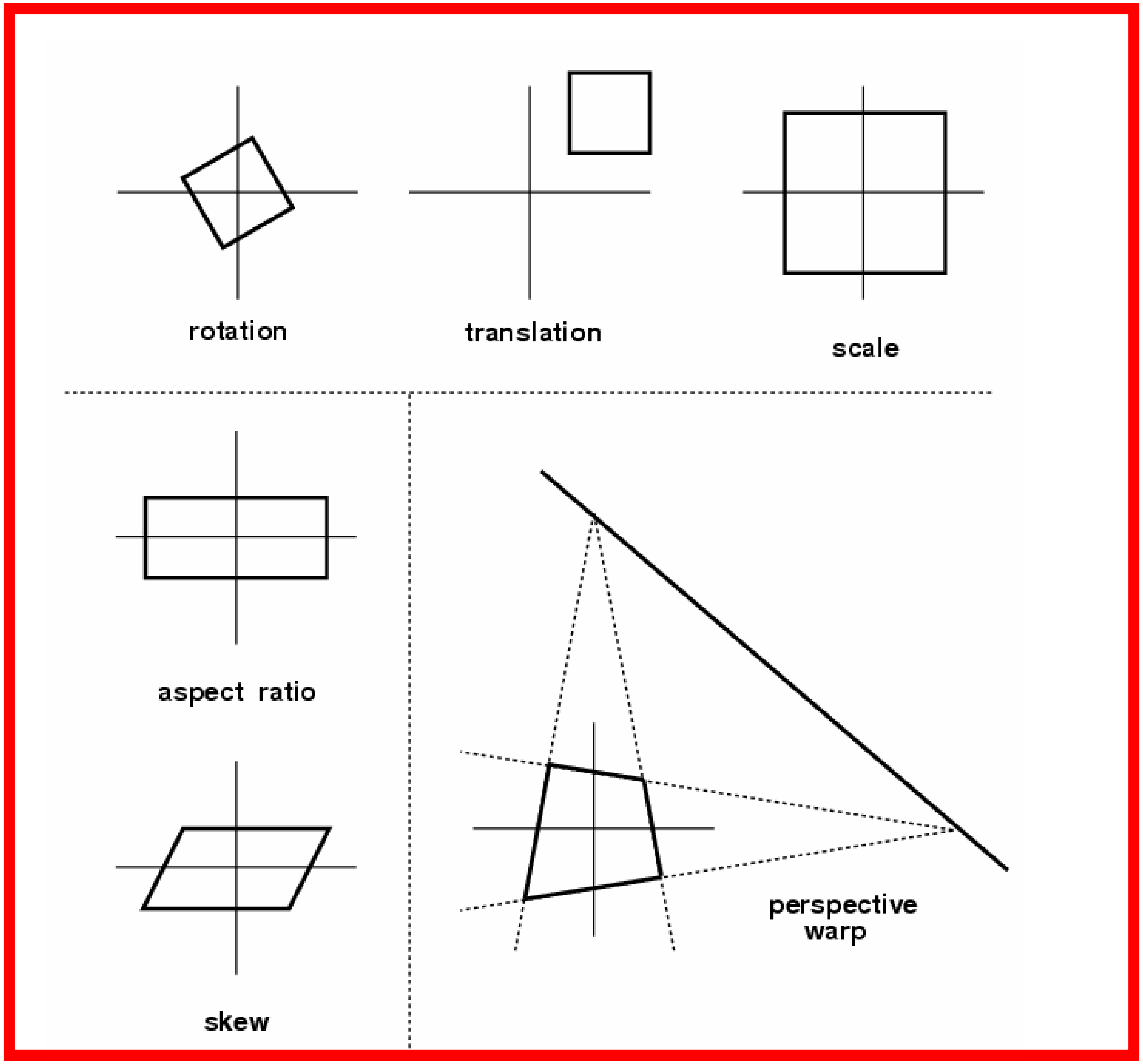
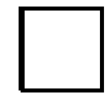
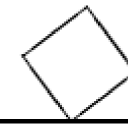
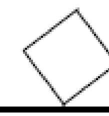
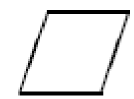
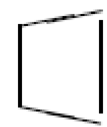
Summary of 2D Transformations

Projective



Summary of 2D Transformations

Name	Matrix	# D.O.F.	Preserves:	Icon
translation	$\left[\ \boldsymbol{I} \mid \boldsymbol{t}\ \right]_{2\times 3}$	2	orientation $+\cdots$	
rigid (Euclidean)	$\left[\ \boldsymbol{R} \mid \boldsymbol{t}\ \right]_{2\times 3}$	3	lengths $+\cdots$	
similarity	$\left[\ s\boldsymbol{R} \mid \boldsymbol{t}\ \right]_{2\times 3}$	4	angles $+\cdots$	
affine	$\left[\ \boldsymbol{A}\ \right]_{2\times 3}$	6	parallelism $+\cdots$	
projective	$\left[\ \boldsymbol{H}\ \right]_{3\times 3}$	8	straight lines	

from R.Szeliski