From: http://www.devx.com/projectcool/Article/19987/0/page/2
The small green squares are the same color. Hold your hand to the screen and block out the adjacent blocks, showing only the two green square, and you'll see how dramatic the chromatic induction effect is.

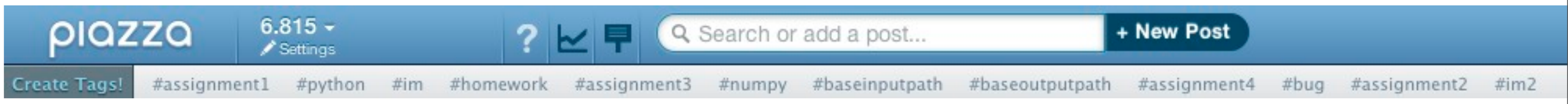
From: http://www.devx.com/projectcool/Article/19987/0/page/2
These two brown shades are different colors—yet the square blocks appear to be the same shade of brown. It is only when your eye follows the line down that you see how different the shades are. Cover the bottom part of the illustration with your hand and look only at the brown boxes to see the way the chromatic induction effect impacts the way you see color.

Image Processing 101
Fredo Durand
MIT EECS
6.815/6.865

Domain Transforms, Warping & Morphing

Fredo Durand
MIT EECS
6.815/6.865

Piazza 101



- Do not email us technical question
  - But do email us about stuff such as extensions
- Ask one question per post
- Do not use the response field to say you have the same problem
- Write answers in the response field

Pset question ?

Pset 2

- is out
- is hard
- some answers are in these slides

Domain

operations

Domain transform

- Apply a function *f* from R^2 to R^2 to the image domain
- if *(y, x)* had color *c* in the input,
  f(y, x) has color *c* in the output

Transformation

- Simple parametric transformations
  - linear, affine, perspective, etc

translatio
n

rotation

aspect

affine

perspective

cylindrical

illustration by Rick Szeliski

Warping

- Imagine your image is made of rubber
- warp the rubber

No prairie dogs were armed when creating this image

Application of warping: weight loss

- **Liquify in photoshop**

figure 9.35

figure 9.36

figure 9.37

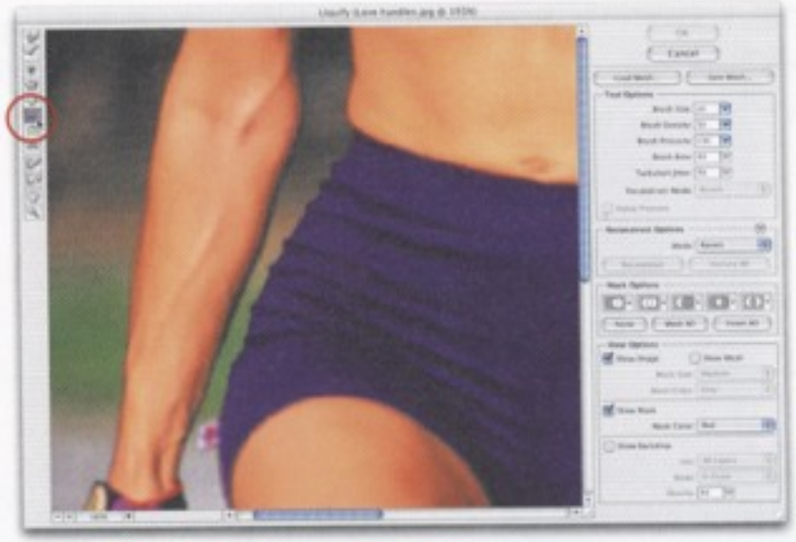
Selecting the entire left side of the image avoids potential artifacts.

figure 9.38

Dragging a Free Transform handle to narrow the selected area.

figure 9.39

The Liquify filter's Warp tool pushes pixels forward as you drag.

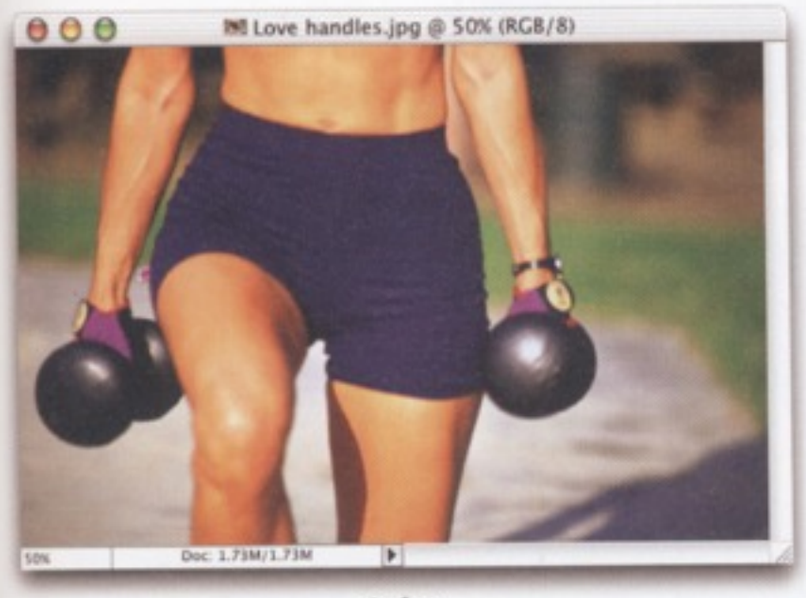


Step Three:

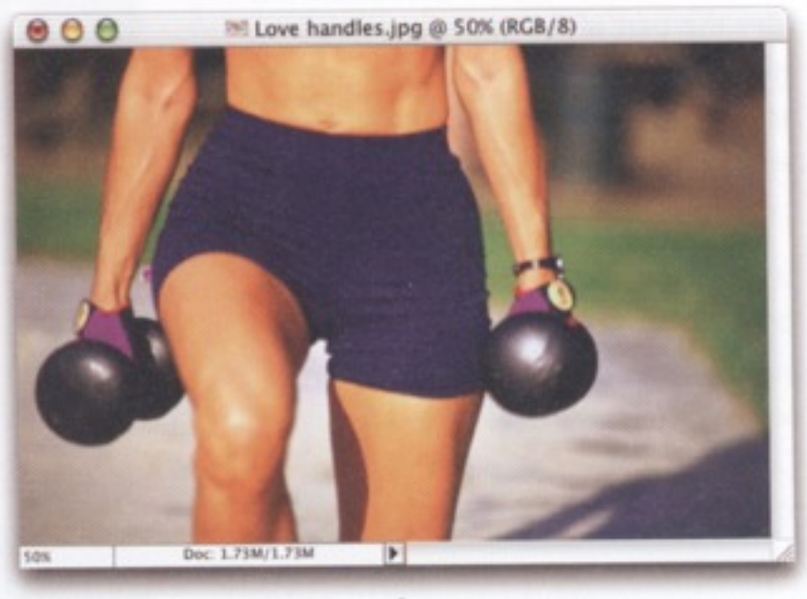
Get the Push Left tool from the Toolbar (as shown here). It was called the Shift Pixels tool in Photoshop 6 and 7, but Adobe realized that you were getting used to the name, so they changed it, just to keep you off balance.

Step Four:

Choose a relatively small brush size (like the one shown here) using the Brush Size field near the top-right of the Liquify dialog. With it, paint a downward stroke starting just above and outside the love handle and continuing downward. The pixels shifts back in toward the body, removing the love handle as you paint. (Note: If you need to remove love handles on the left side of the body, paint upward rather than downward. Why? That's just the way it works.) When you click OK, the love handle repair is complete.



Before.



After.

Domain transform issues

- Apply a function *f* from R2 to R2 to the image domain
- looks easy enough

- **But two big issues:**
  - which direction do we transform
  - how do we deal with non-integer coordinates?

  - And for warping: how do we specify *f*?

Questions?

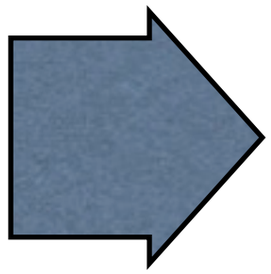
Basic

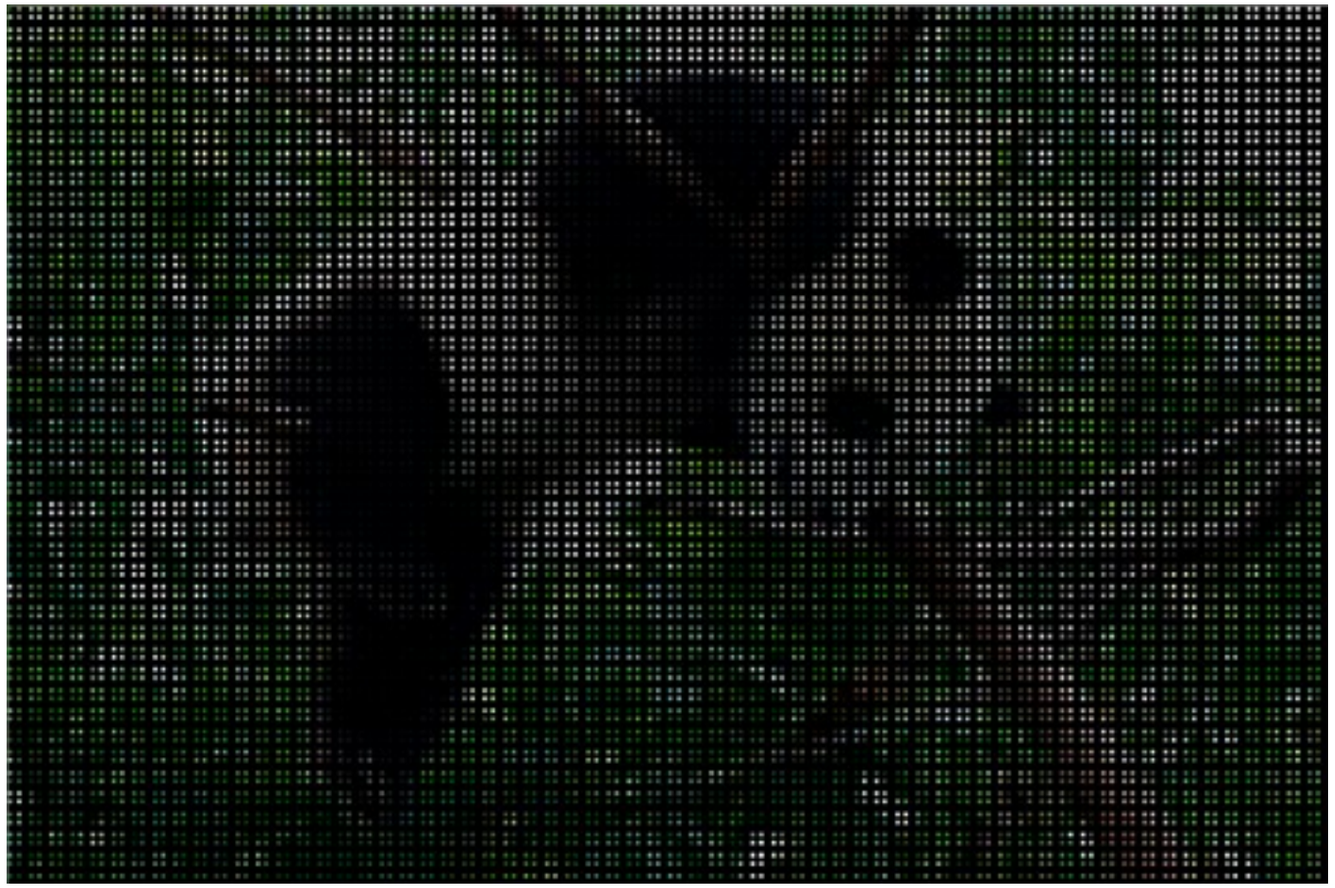
resampling

Naive scaling

- Take all the pixels in input and transform them to their output location
  - $\text{im}[y, x] => \text{out}[k*y, k*x]$

```
def scaleBAD(im, k):
    out = constantIm(im.shape[0]*k, im.shape[1]*k, 0)
    for y, x in imIter(im):
        out[k*y, k*x]= im[y, x]
return out
```

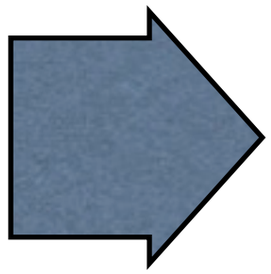




Use the inverse transform!!!!!

- Main loop on **output** pixels
  - $\text{out}[y, x] <= \text{im}[y/k, x/k]$

```
def scaleWithInverse(im, k):
    out = constantIm(im.shape[0]*k, im.shape[1]*k, 0.0)
    for y, x in imIter(out):
        out[y,x]=im[y/k, x/k]
return out
```



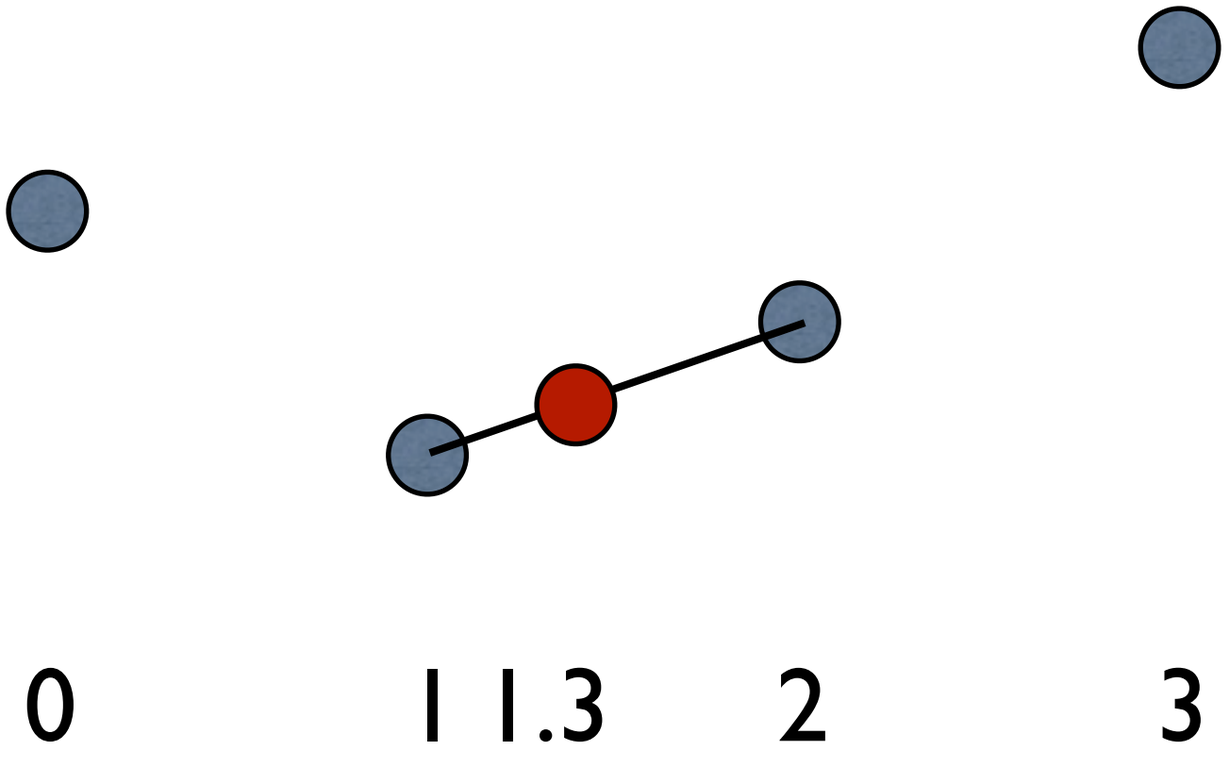
Questions?

Remaining problem

- A little too “blocky”
- Because we round to the nearest integer pixel coordinates
  - called nearest neighbor reconstruction

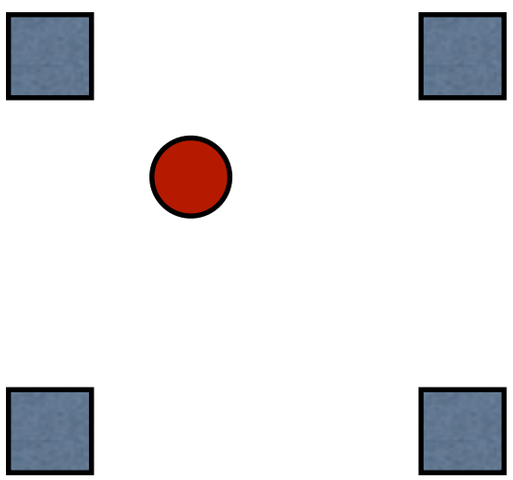
Linear reconstruction

- im is now a 1D array along x
- reconstruct im[1.3]
- =0.7*im[1]+0.3*im[2]

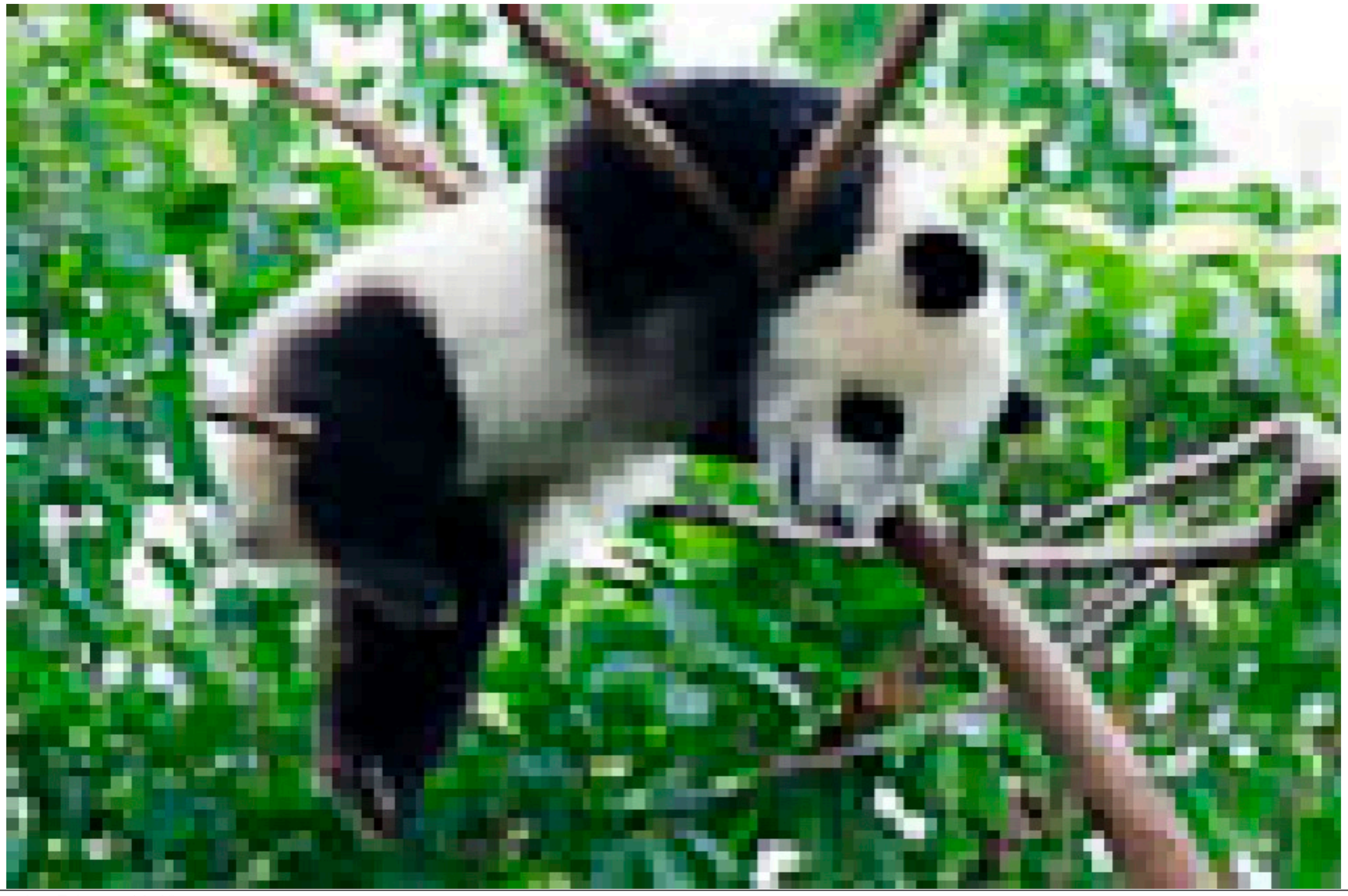


Bilinear reconstruction

- Take 4 nearest neighbors
- Weight according to x & y fractional coordinates
- Can be done using two 1D ;inear reconstructions along x then y (or y then x)



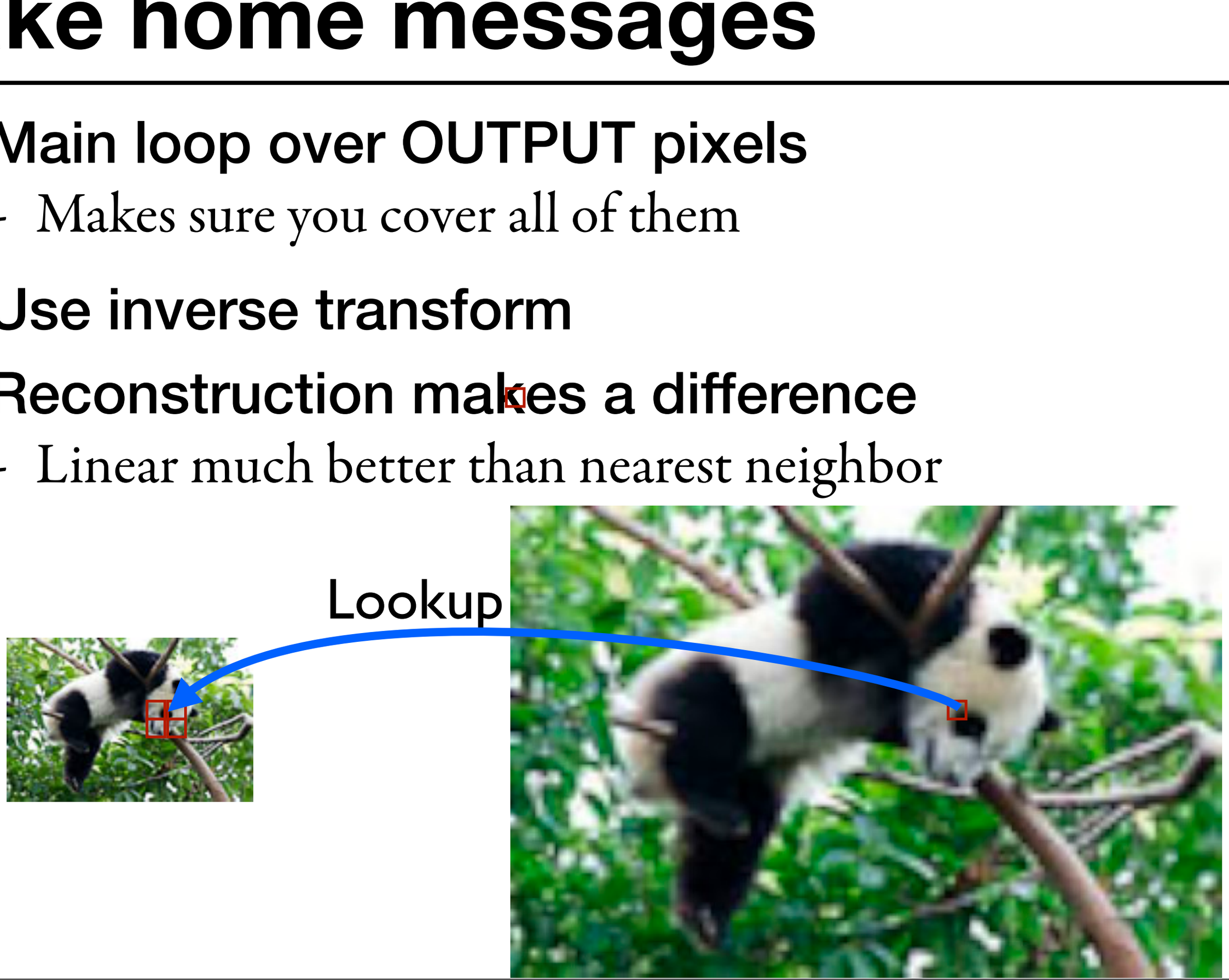
Recall nearest neighbor



Bilinear

Take home messages

- Main loop over OUTPUT pixels
  - Makes sure you cover all of them
- Use inverse transform
- Reconstruction makes a difference
  - Linear much better than nearest neighbor



Questions?

Better reconstruction

- Consider more than 4 pixels:
  - bicubic, Lanczos, etc.
- Try to sharpen edges
- Use training database of low-res/high-res pairs
  - http://people.csail.mit.edu/billf/superres/index.html

Bilinear

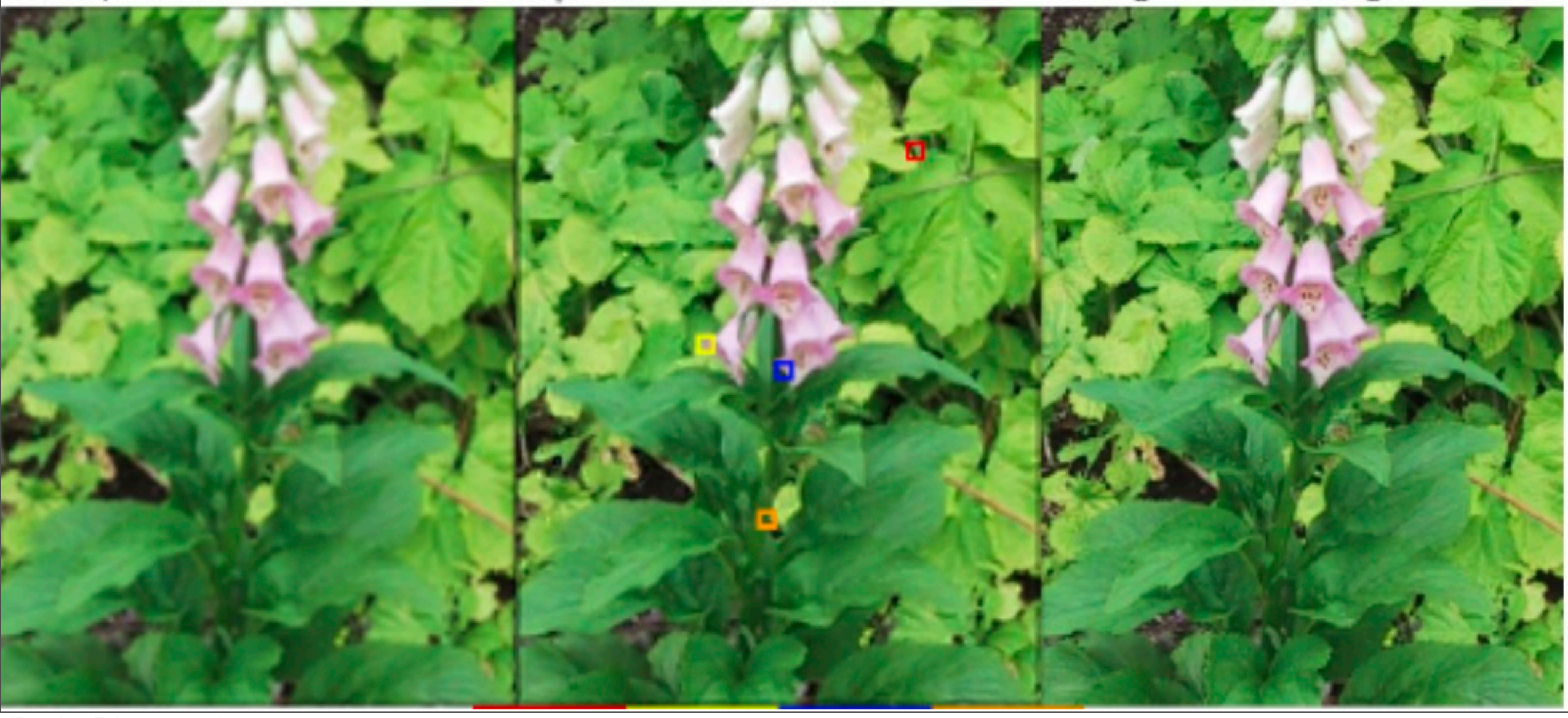
Bicubic (Photoshop)

Bill Freeman's super-resolution

Cubic spline zoom

Super-resolution zoom

True high-resolution image



Questions?

Basic programming tools

Loops & iterators

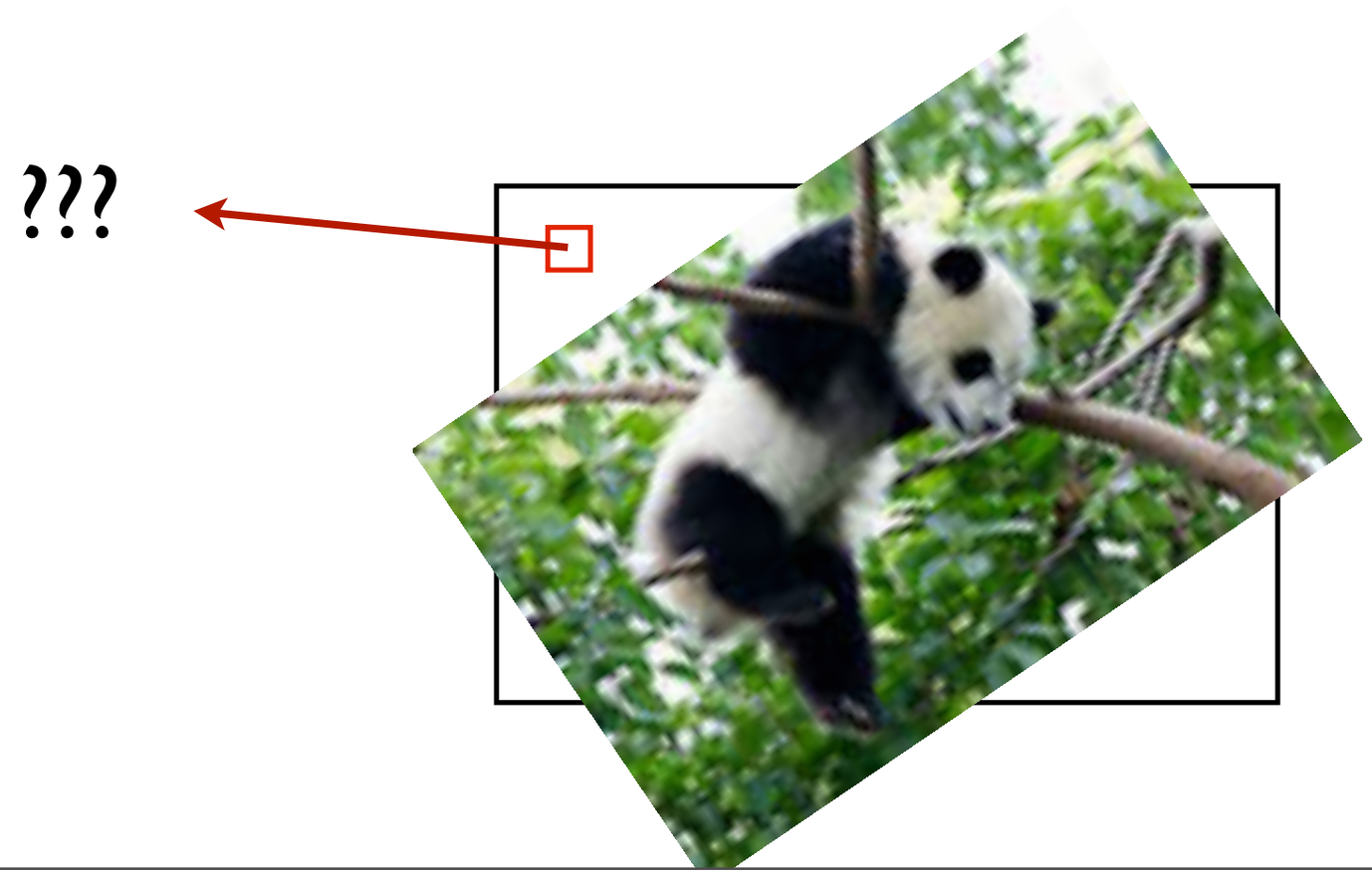
- Bad news: we'll need some for loop for resampling
- iterators

```
def imIter(im):
    for y in xrange(im.shape[0]):
        for x in xrange(im.shape[1]): yield y, x
```

Debug?

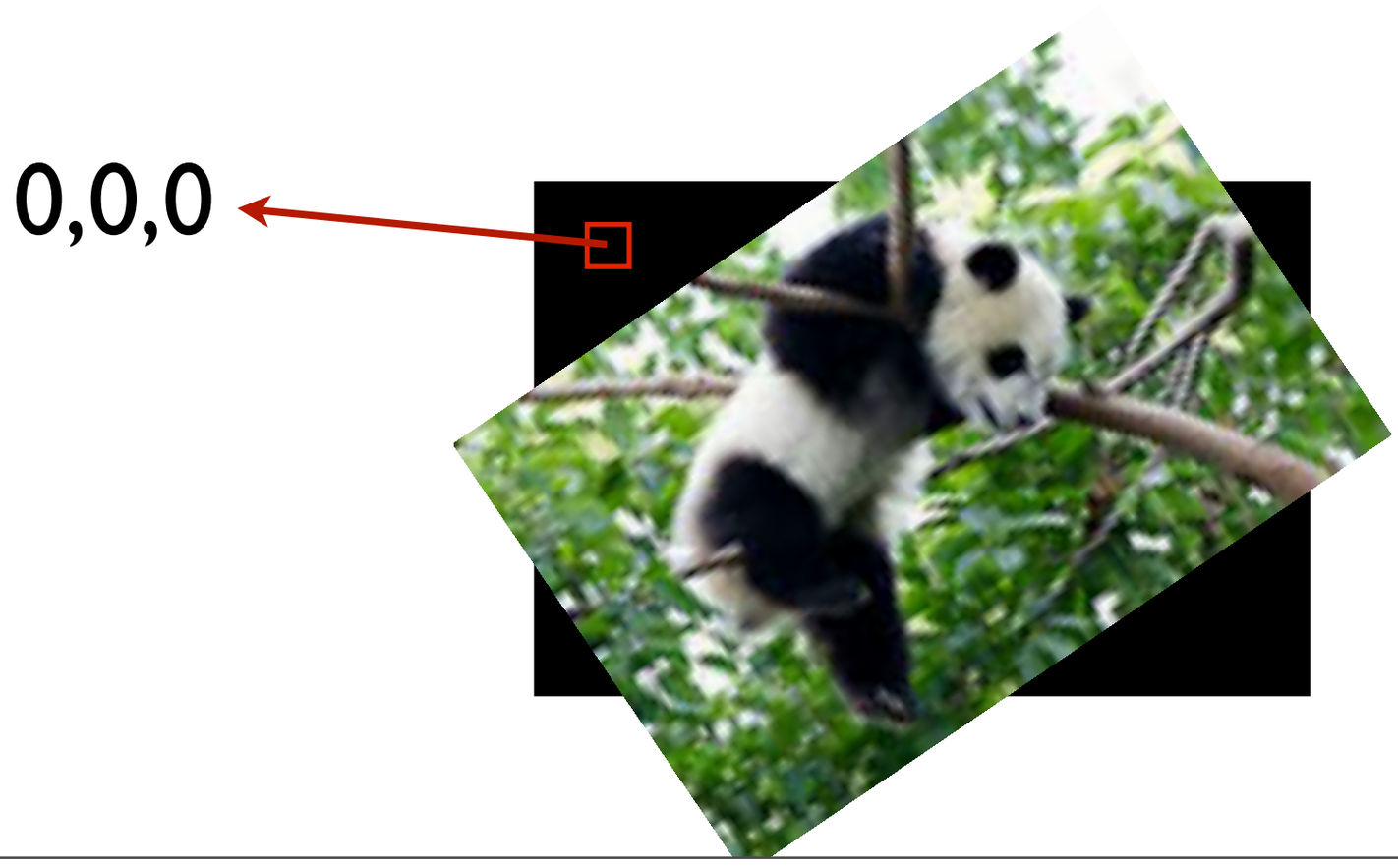
Padding problems

- **Sometimes, we try to read outside the image**
  - e.g. y, x are negative
  - For example, we try to rotate an image



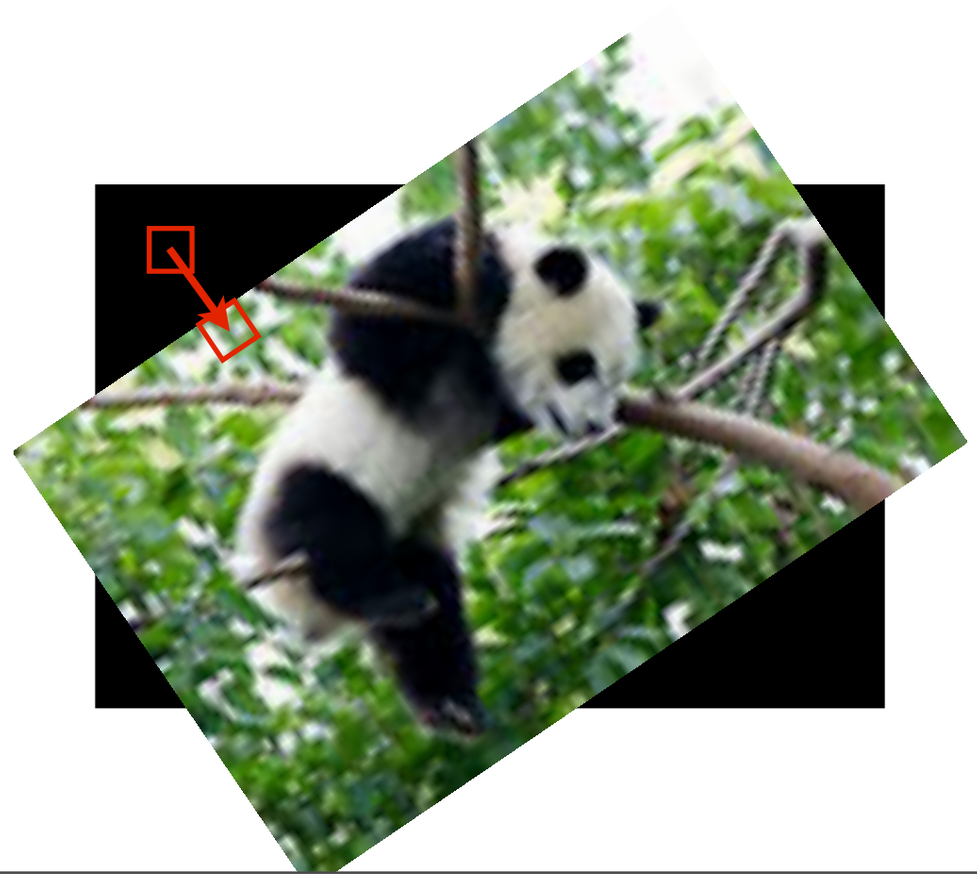
Black Padding

```
def getBlackPadded(im, y, x):
    if (x<0) or (x>=im.shape[1]) or (y<0)
        or (y>= im.shape[0]):
        return numpy.array([0, 0, 0])
    else: return im[y, x]
```



Edge Padding

```
def clipX(im, x): return min(width(im)-1, max(x, 0))
def clipY(im, y): return min(height(im)-1, max(y, 0)
def getSafePix(im, y, x):
    return im[clipY(im, y), clipX(im, x)]
```



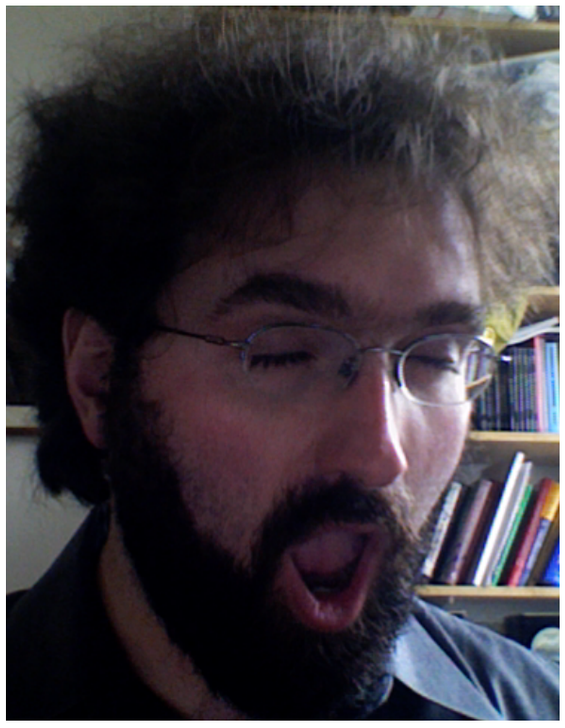
Questions?

Warping & Morphing

Important scientific question

- **How to turn Dr. Jekyll into Mr. Hyde?**
- **How to turn a man into a werewolf?**

- **Powerpoint cross-fading?**



Important scientific question

- **How to turn Dr. Jekyll into Mr. Hyde?**
- **How to turn a man into a werewolf?**

- **Powerpoint cross-fading?**

From An American Werewolf in London

- **or**
- **Image Warping and Morphing?**

Digression: old metamorphoses

- http://en.wikipedia.org/wiki/The_Strange_Case_of_Dr._Jekyll_and_Mr._Hyde
- http://www.eatmybrains.com/showtopten.php?id=15
- http://www.horror-wood.com/next_gen_jekyll.htm
- **Unless I'm mistaken, both employ the trick of making already-applied makeup turn visible via changes in the color of the lighting, something that works only in black-and-white cinematography. It's an interesting alternative to the more familiar Wolf Man time-lapse dissolves. This technique was used to great effect on Fredric March in Rouben Mamoulian's 1932 film of *Dr. Jekyll and Mr. Hyde*, although Spencer Tracy eschewed extreme makeup for his 1941 portrayal.**

Dr. Jekyll and Mr. Hyde, 1932

Dr. Jekyll and Mr. Hyde, 1932

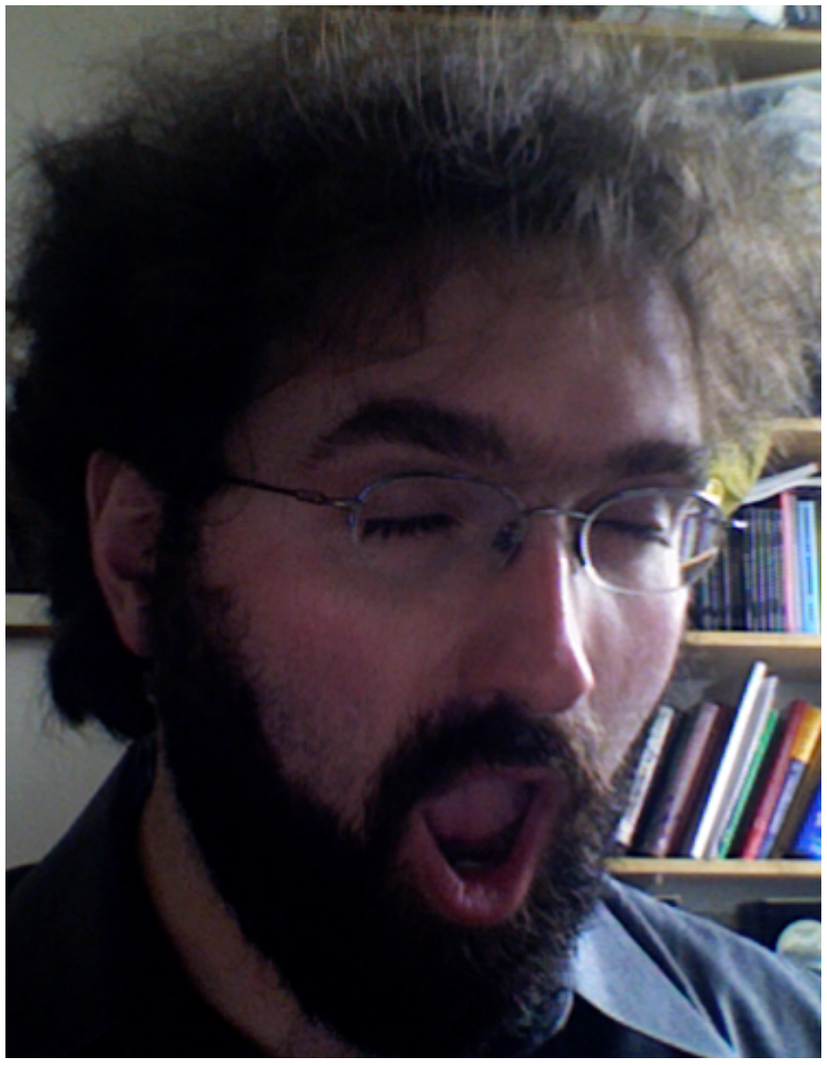
Dr. Jekyll and Mr. Hyde, 1932

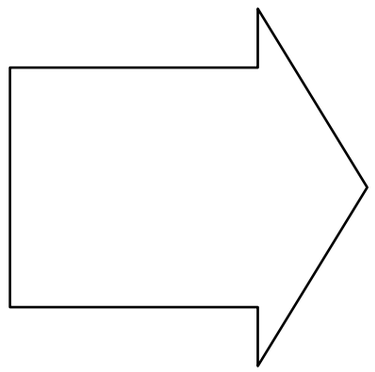
Dr. Jekyll and Mr. Hyde, 1941

- **Jekyll & Hide 1932:**
  - 35:13
  - ch18 1:06:45
  - ch19 1:17:50
- **Jekyll & Hide 1941:**
  - ch20 1:25:13

Challenge

- **“Smoothly” transform a face into another**
- **Related: slow motion interpolation**
  interpolate between key frames

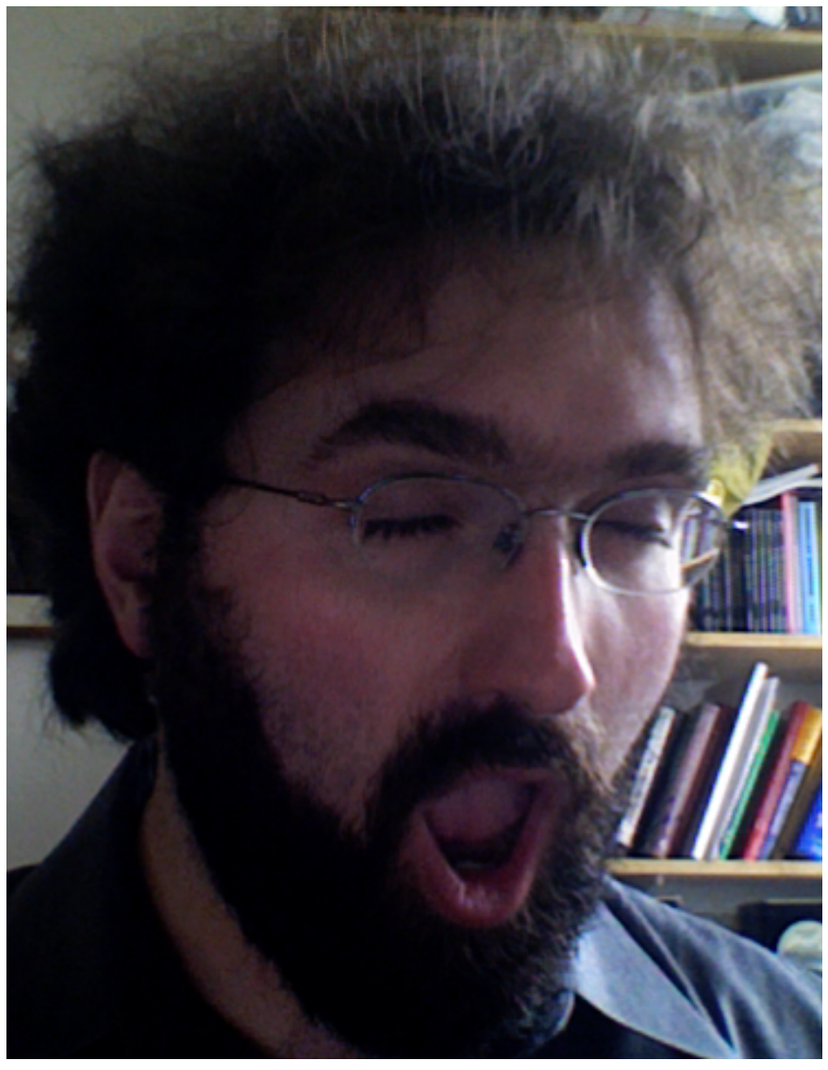
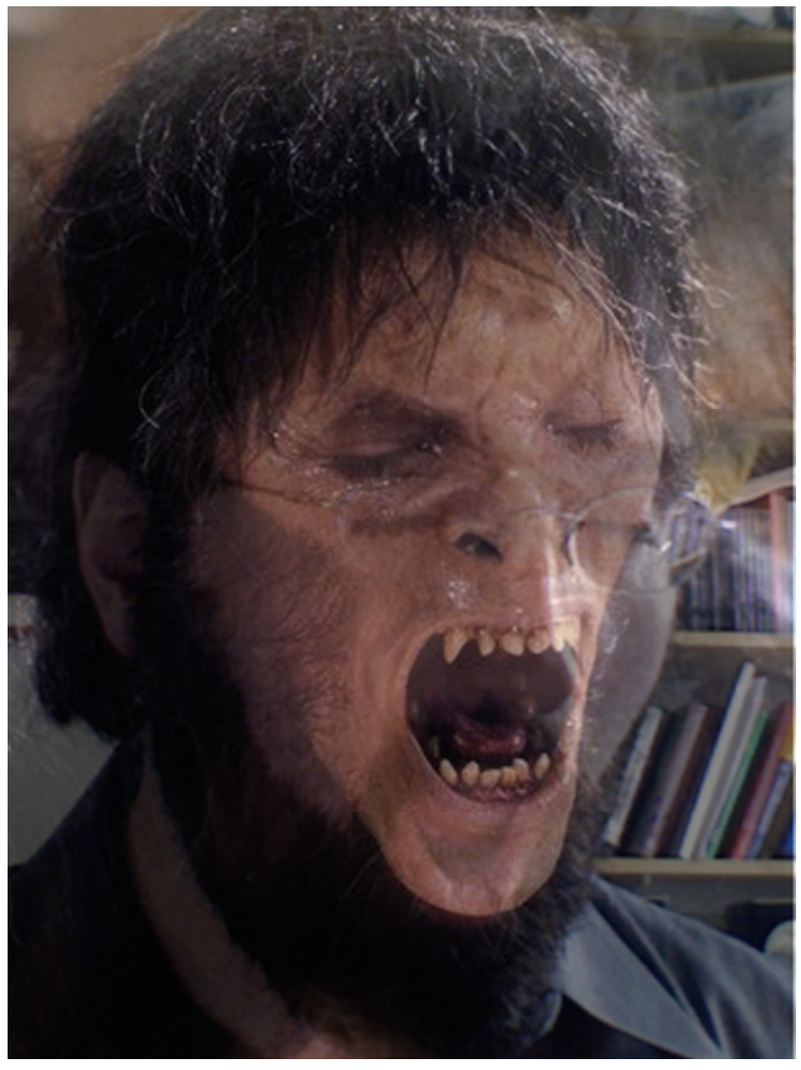




Averaging images

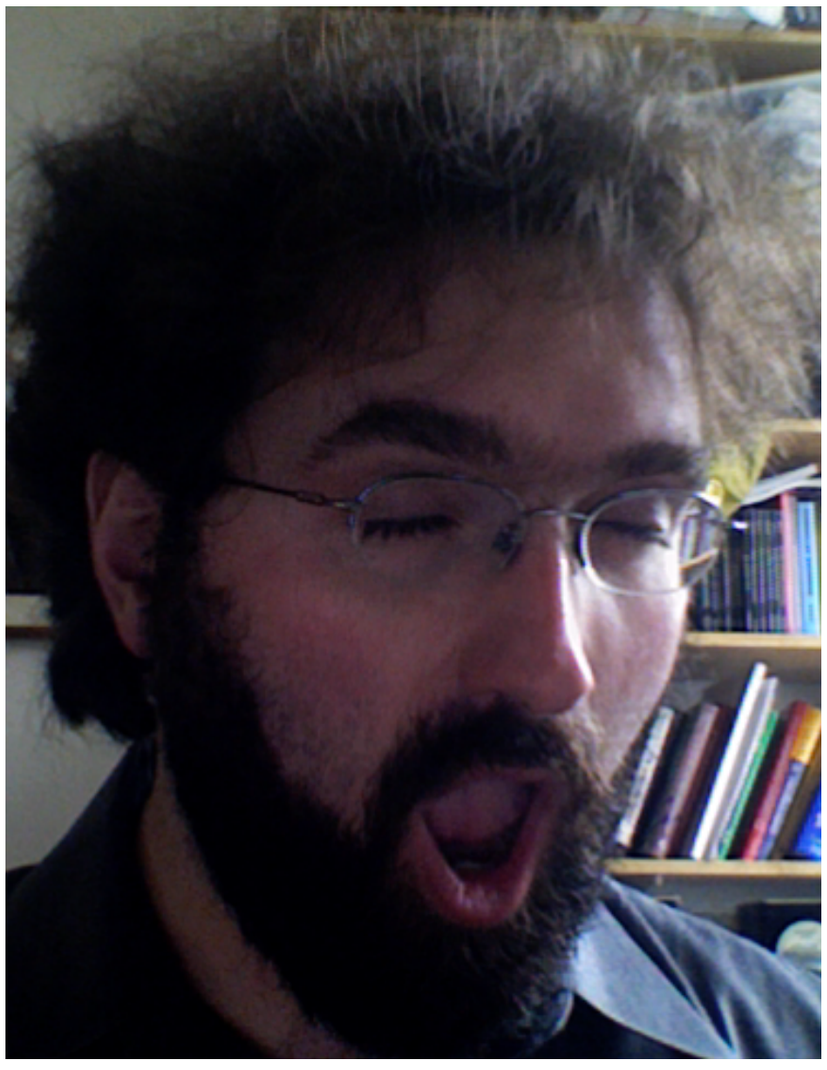
- **Cross-fading**

output[y, x]=t * im1[y, x] +(1-t) * im2[y, x]

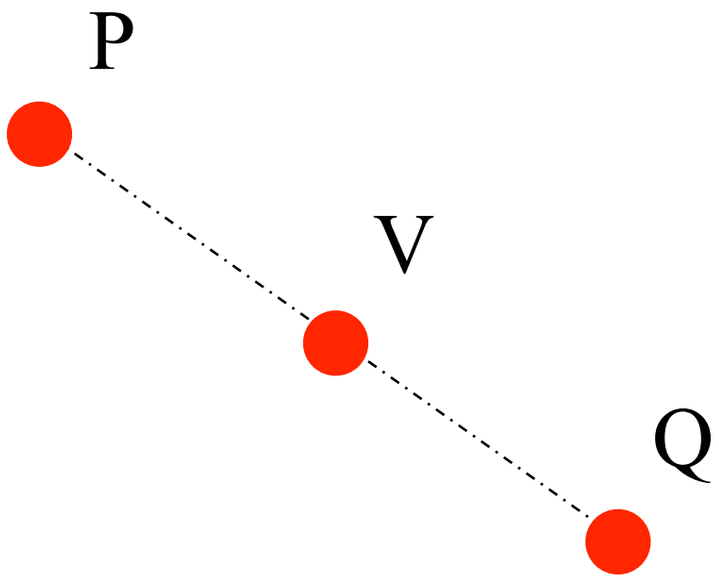

Problem with cross fading

- **Features (eyes, mouth, etc) are not aligned**
- **It is probably not possible to get a global alignment**
- **We need to interpolate the LOCATION of features**
  - domain transform!



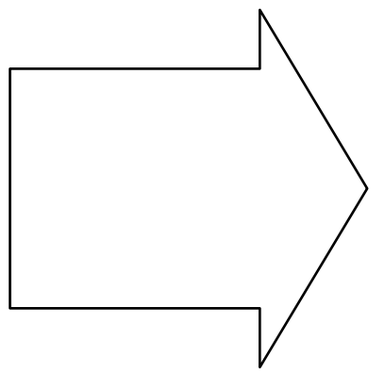
Averaging points (location)

- **P & Q are two 2D points (in the “domain”)**
- **V= t P + (1-t) Q**



Warping

- **Move pixel spatially: C’(x,y)=C(f(x,y))**
- **Leave colors unchanged**



Warping

- **Deform the domain of images (not range)**
- **Central to morphing**
- **Also useful for**
  - Optical aberration correction
  - Video stabilization
  - Slimming people down

original image

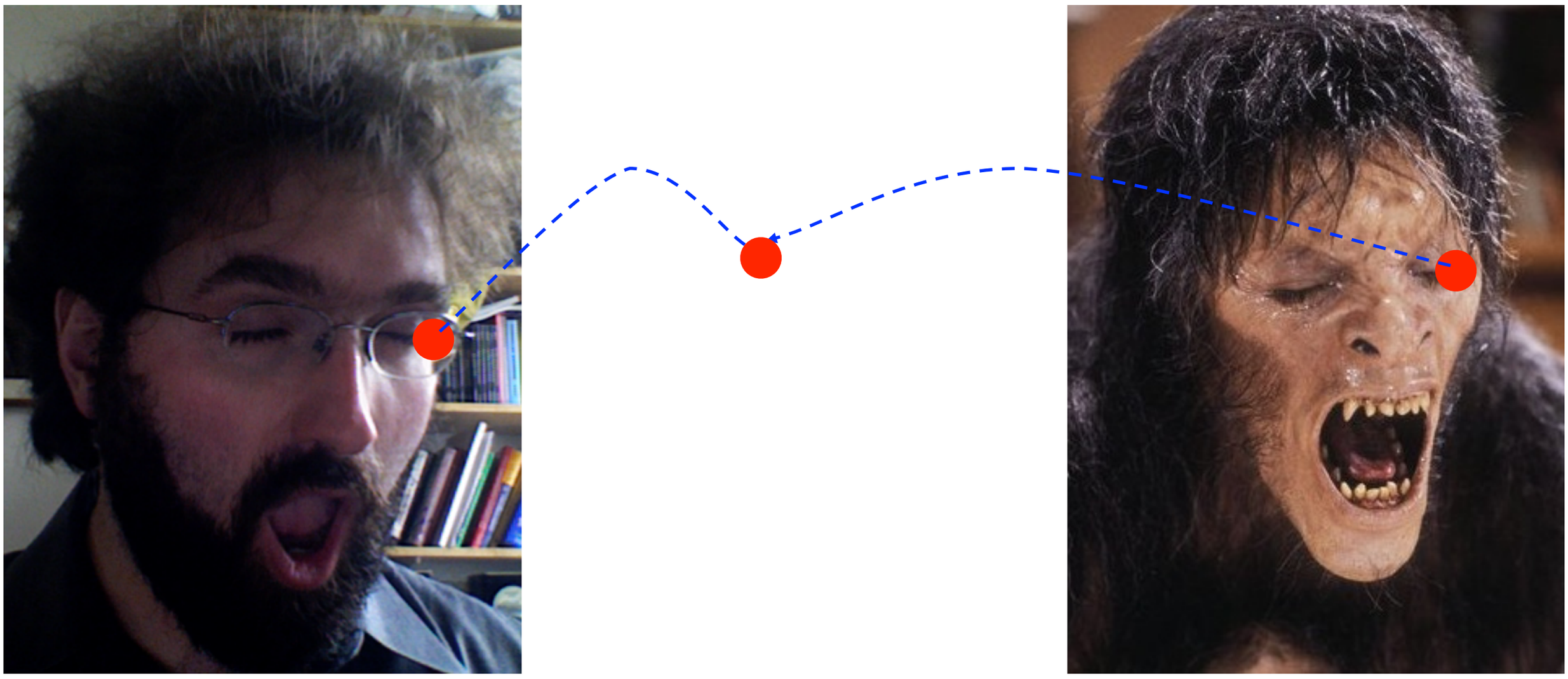
DxO Optics Pro correction

Recap & questions

- **Color (range) interpolation:**
  output[y, x]=t * im1[y, x] +(1-t) * im2[y, x]
- **Location (domain) interpolation: V= t P + (1-t) Q**
- **Warping: domain transform out(x,y)=im(f^{-1}(x,y))**

Morphing: combine both

- **For each pixel**
  - Transform its location like a vector (domain)
  - Then linearly interpolate colors (range)

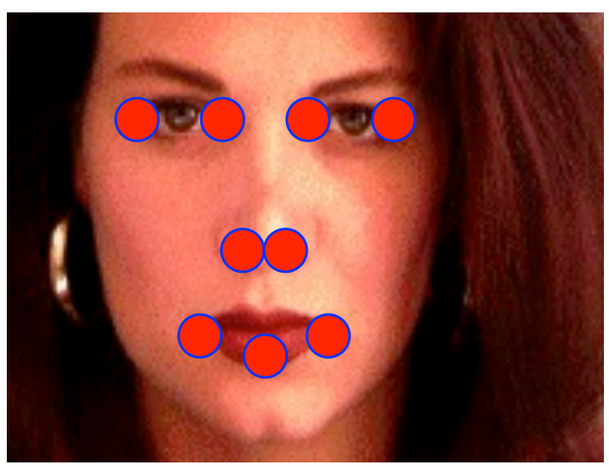


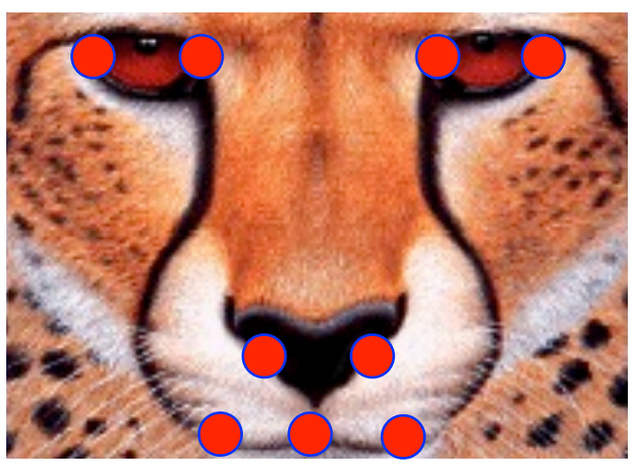
Morphing

- **Input: two images I_0 and I_{N+1}**

- **Expected output: image sequence I_i, with i∈ 1..N**

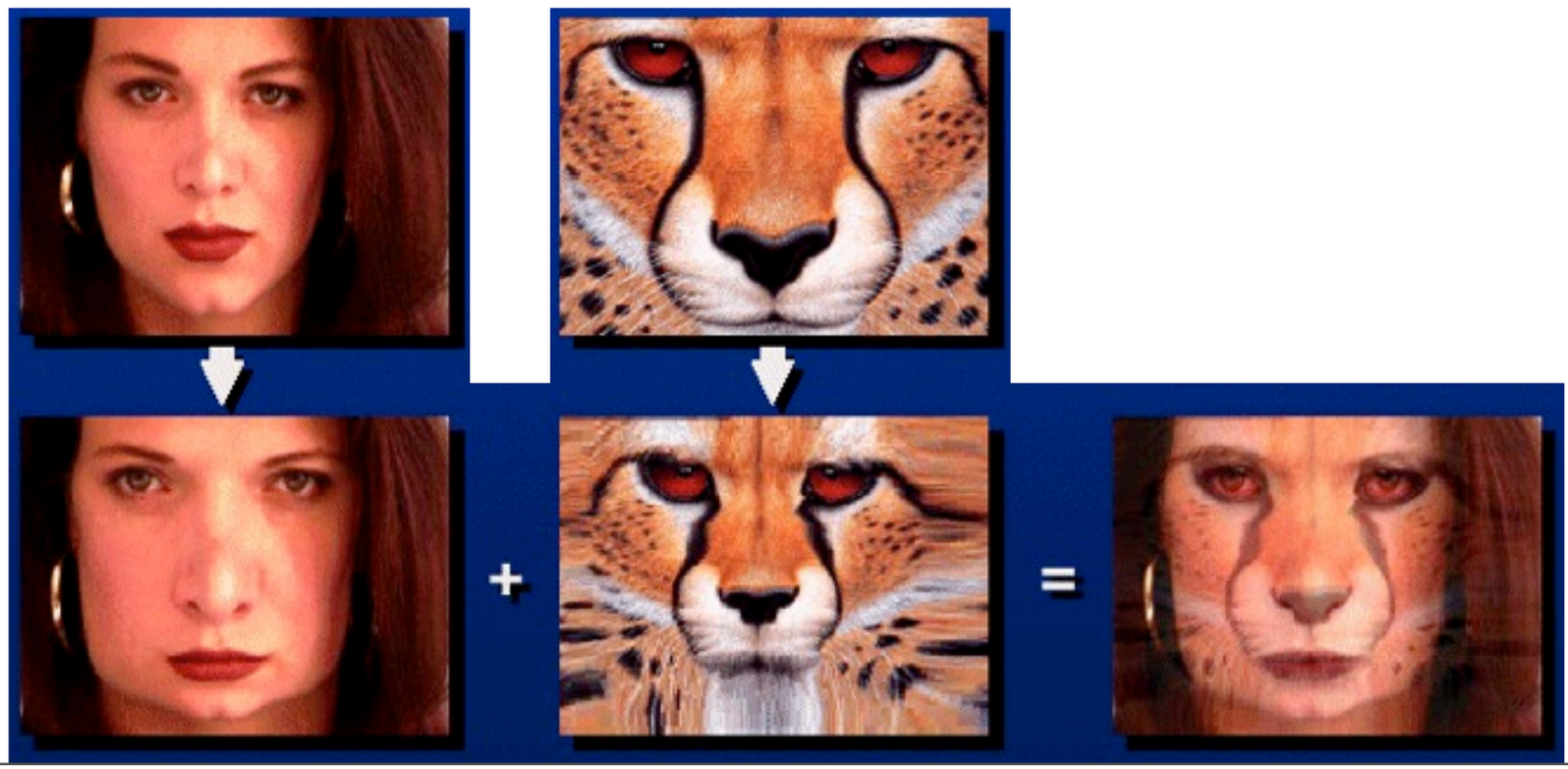
- **User specifies sparse correspondences on the images**





Morphing

- **For each intermediate frame I_t**
  - Interpolate feature locations $P^t_i = (1- t)\, P^0_i + t\, P^1_i$
  - Perform **two** warps: one for I_0, one for I_1
    - Deduce a dense warp field from the pairs of features
    - Warp the pixels
  - Linearly interpolate the two warped images



Warping

Warping

- **Imagine your image is made of rubber**
- **warp the rubber**

No prairie dogs were armed when creating this image

Warping

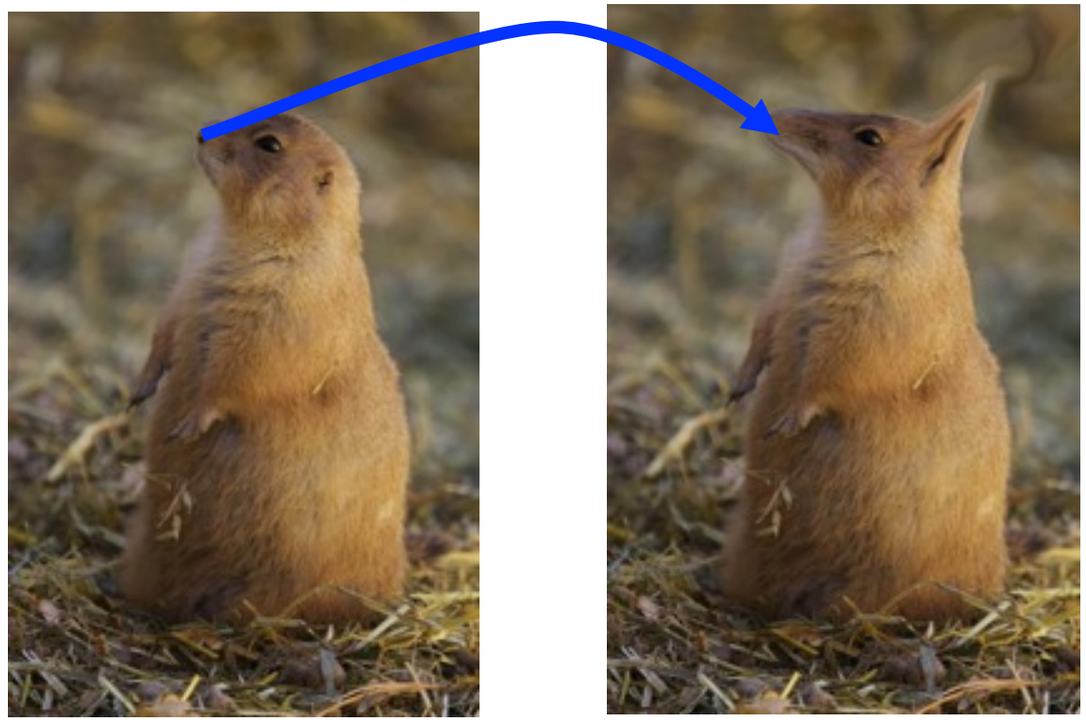
Assume we are given the spatial mapping

- How do we compute the warped image?

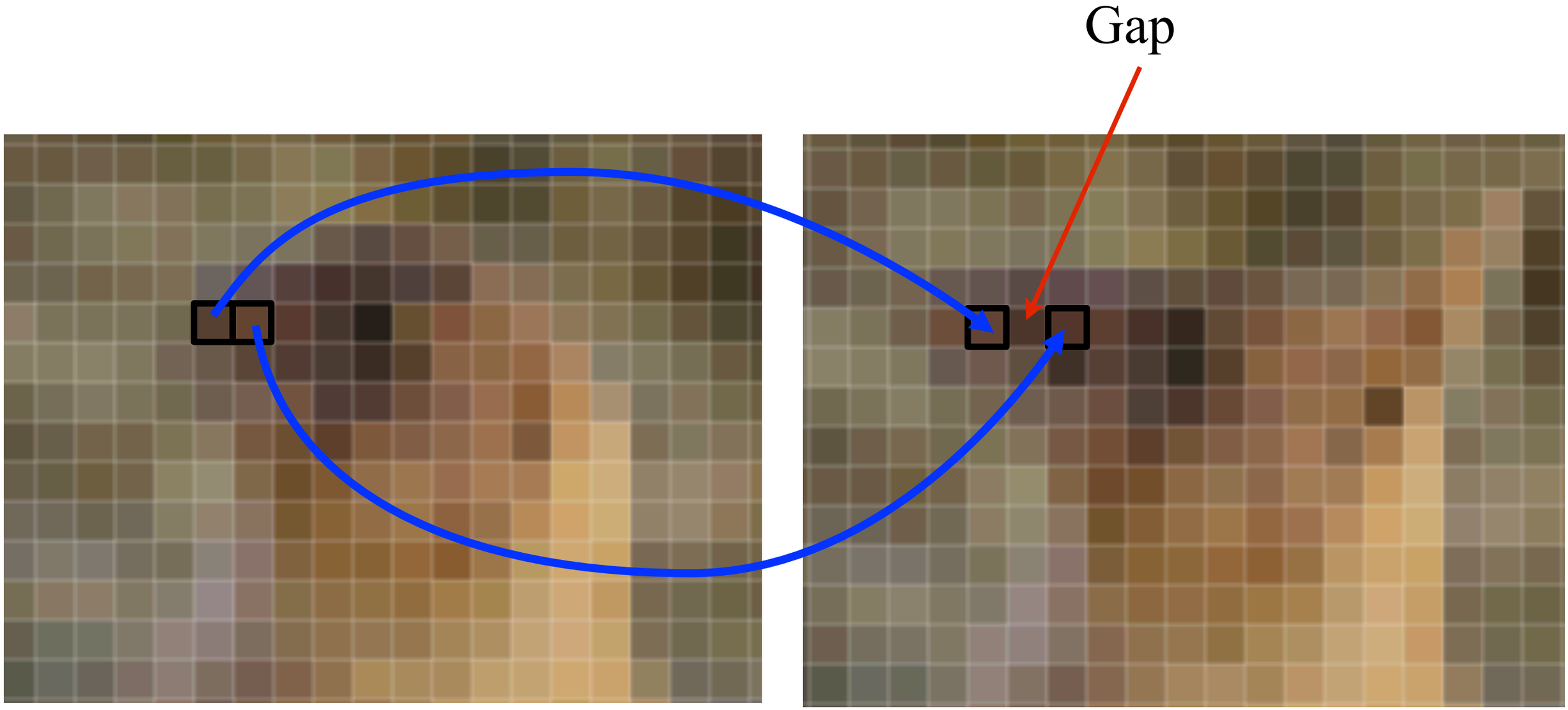
Careful: warp vs. inverse warp

How do you perform a given warp:

- **Forward warp**
  - For each input pixel, compute output location and copy color there



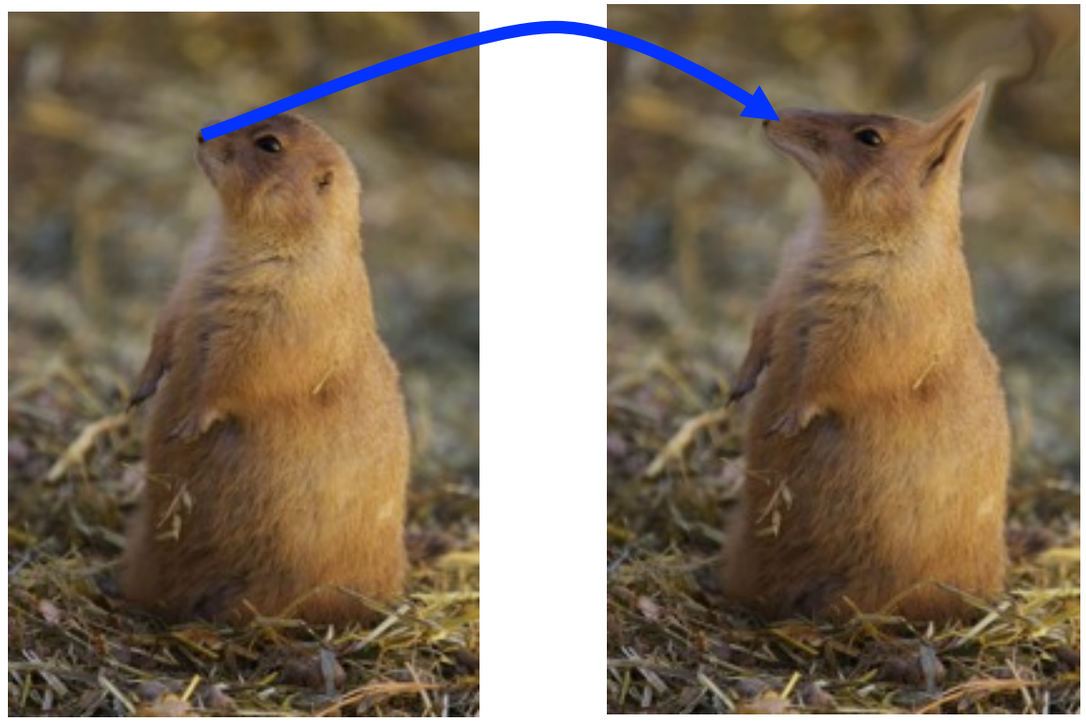
Forward warp and gaps



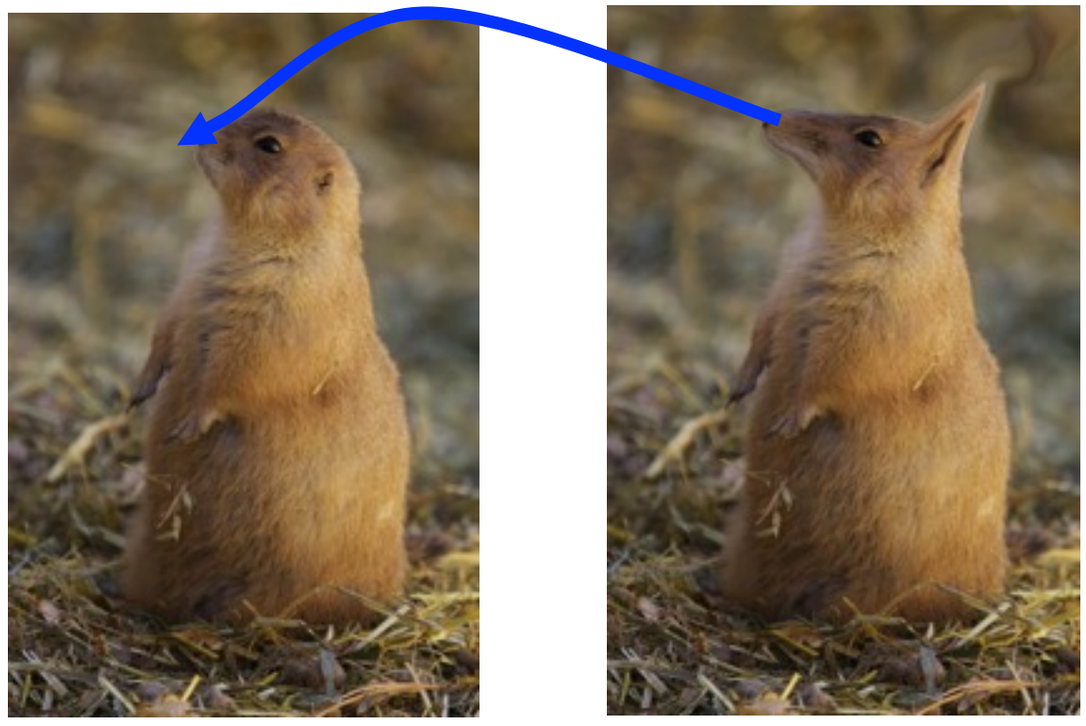
Careful: warp vs. inverse warp

How do you perform a given warp:

- **Forward warp**
  - –Potential gap problems



- **Inverse lookup the most useful**
  - –For each output pixel
    - Lookup color at inverse-warped location in input



Questions?

How do we specify the warp?

- **Before, we saw simple transformations**
  - linear, affine, perspective

translatio
n

rotation

aspect

affine

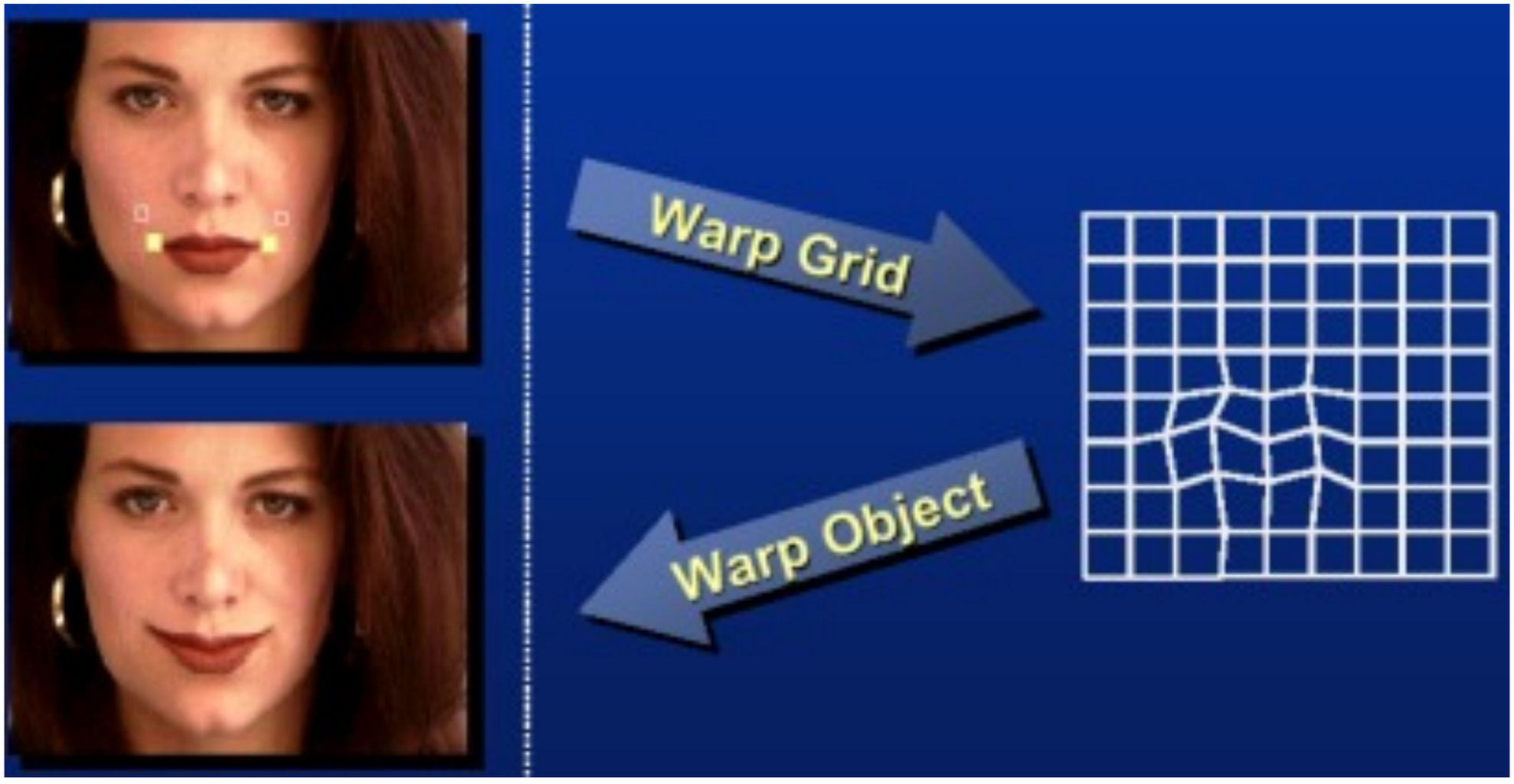
perspective

cylindrical

- **But we want more flexibility**

Image Warping – parametric

- **Move control points to specify a spline warp**
- **Spline produces a smooth vector field**



Slide Alyosha Efros

Warp specification - dense

- **How can we specify the warp?**

  Specify corresponding *spline control points*

  - *interpolate* to a complete warping function

But we want to specify only a few points, not a grid

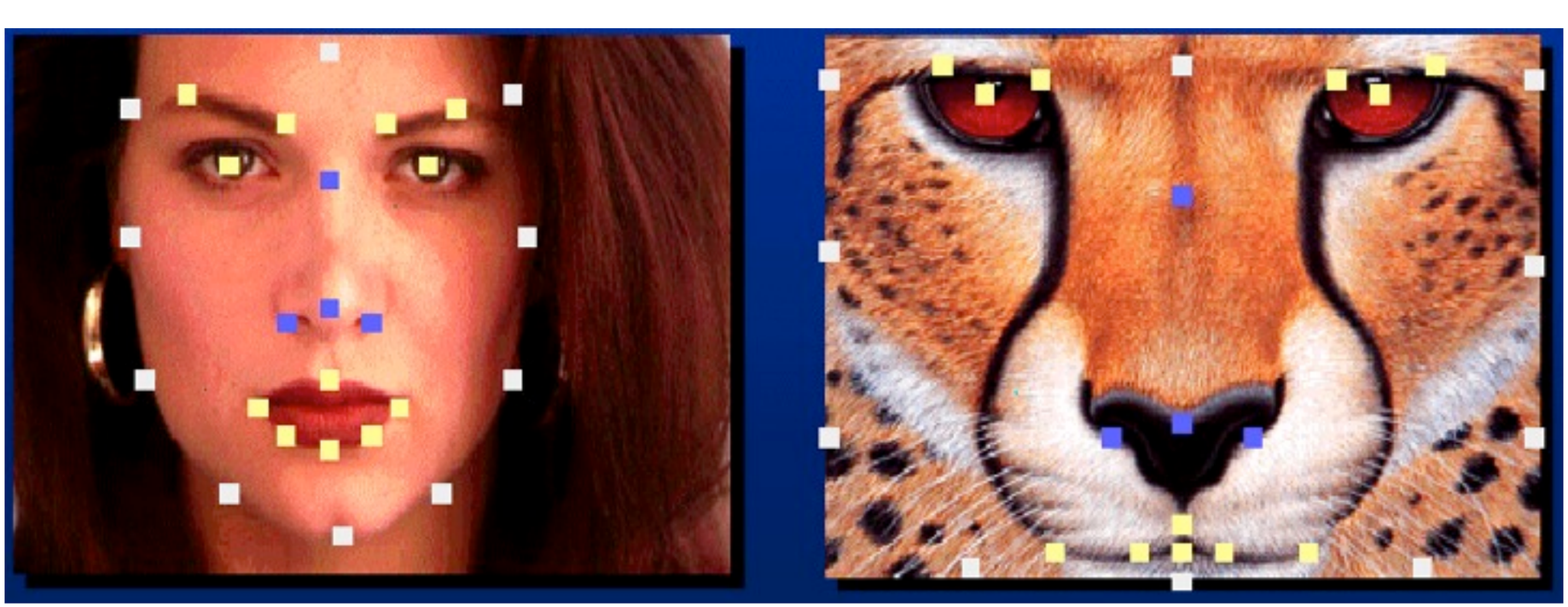
Slide Alyosha Efros

Warp specification - sparse

- **How can we specify the warp?**

  Specify corresponding *points*

  - *interpolate* to a complete warping function
  - How do we do it?

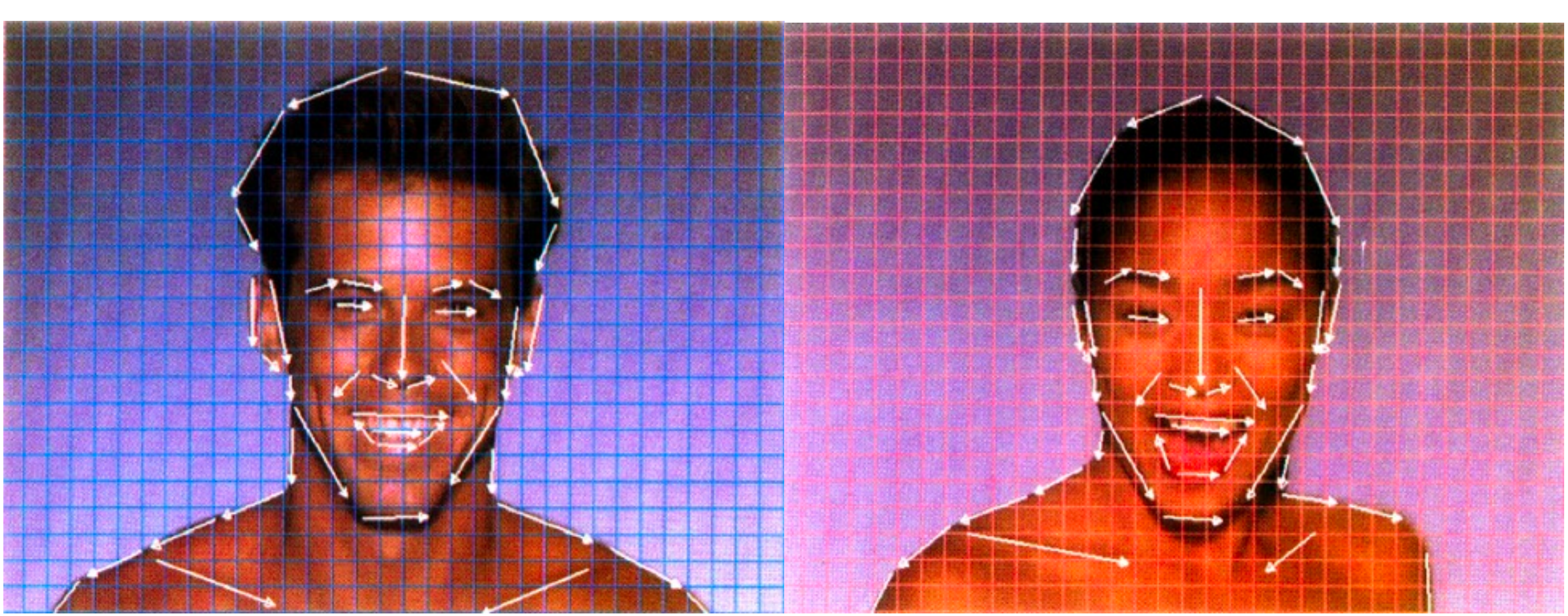


How do we go from feature points to pixels?

Slide Alyosha Efros

Beier and Neely

- **Specify warp based on pairs of segments**
  - http://dl.acm.org/citation.cfm?id=134003
  - Feature-Based Metamorphosis, SIGGRAPH 1992
  - Used in Michael Jackson' Black and White Music Video
  - Pset 2!!

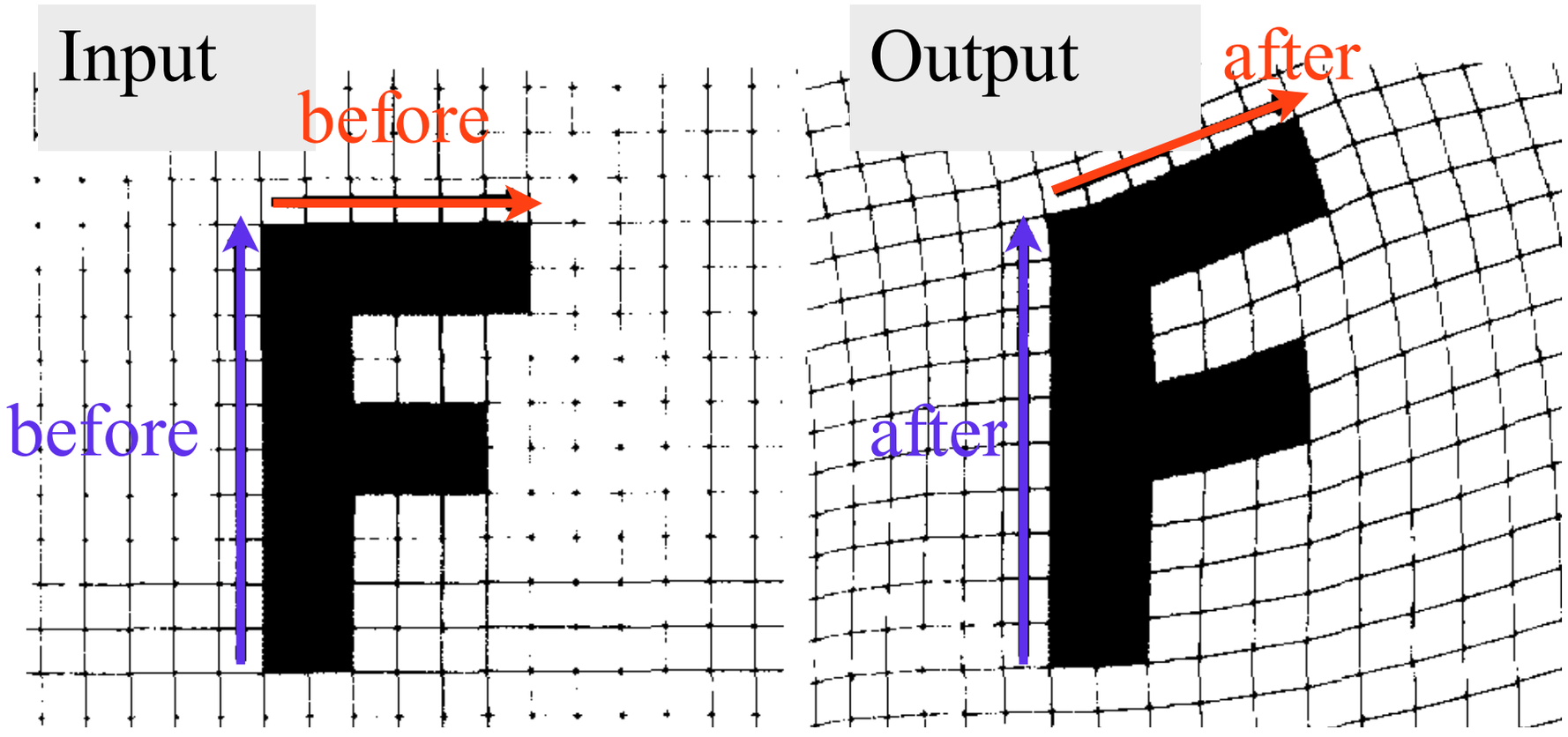


Questions?

Segment-based warping

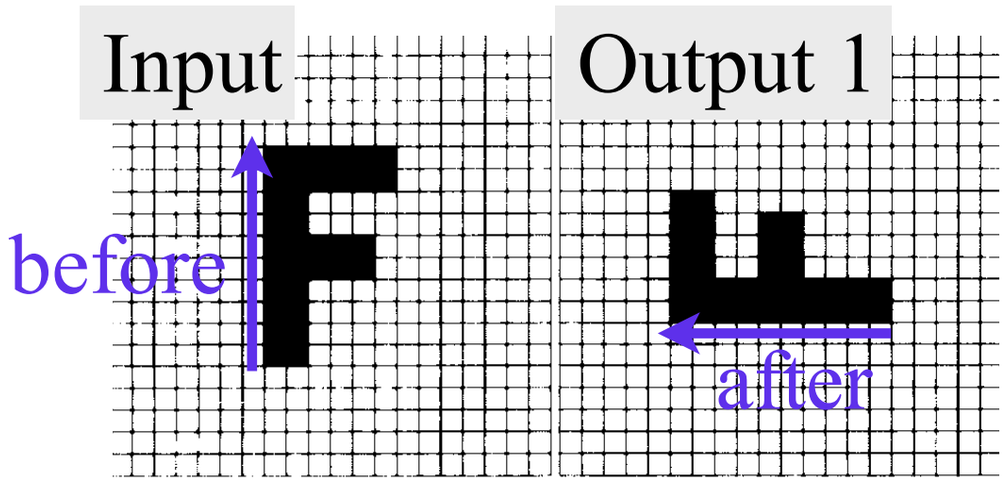
Problem statement

- **Inputs: One image, two lists of segments before and after, in the image domain**
- **Goal: warp the image "following" the displacement of the segments**



Idea

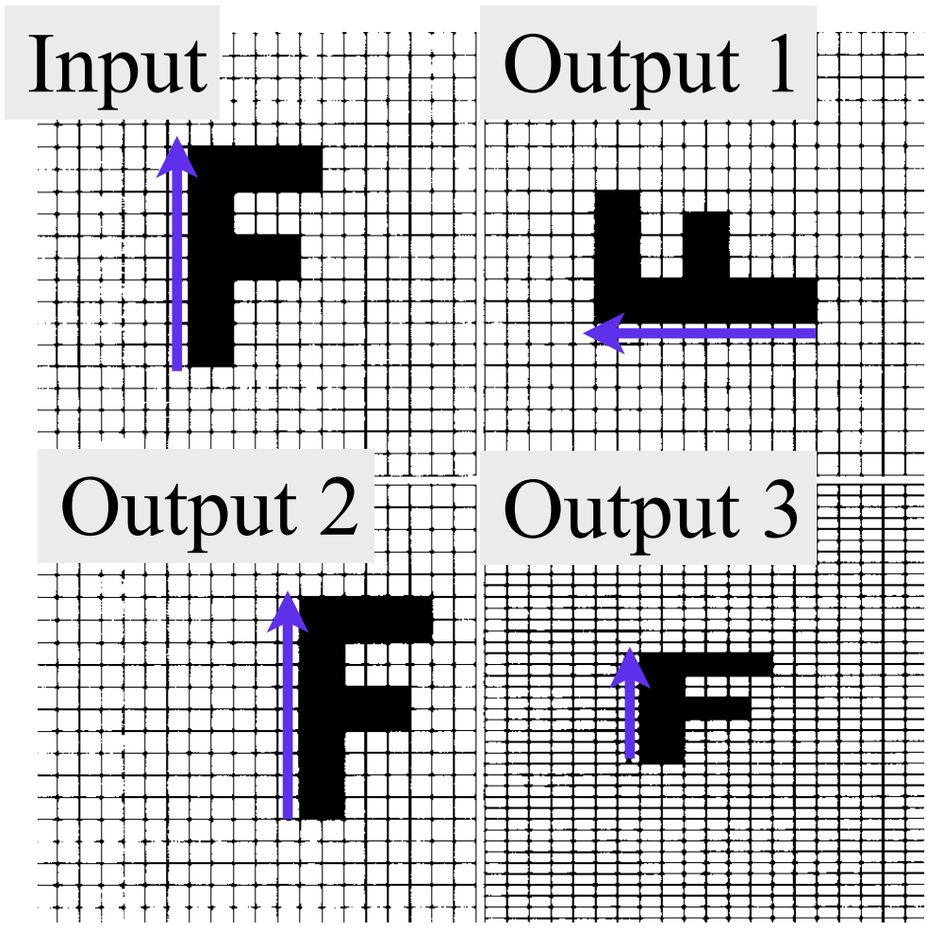
- **Each before/after pair of segment implies a planar transformation**
  - simple and linear



Single line transforms

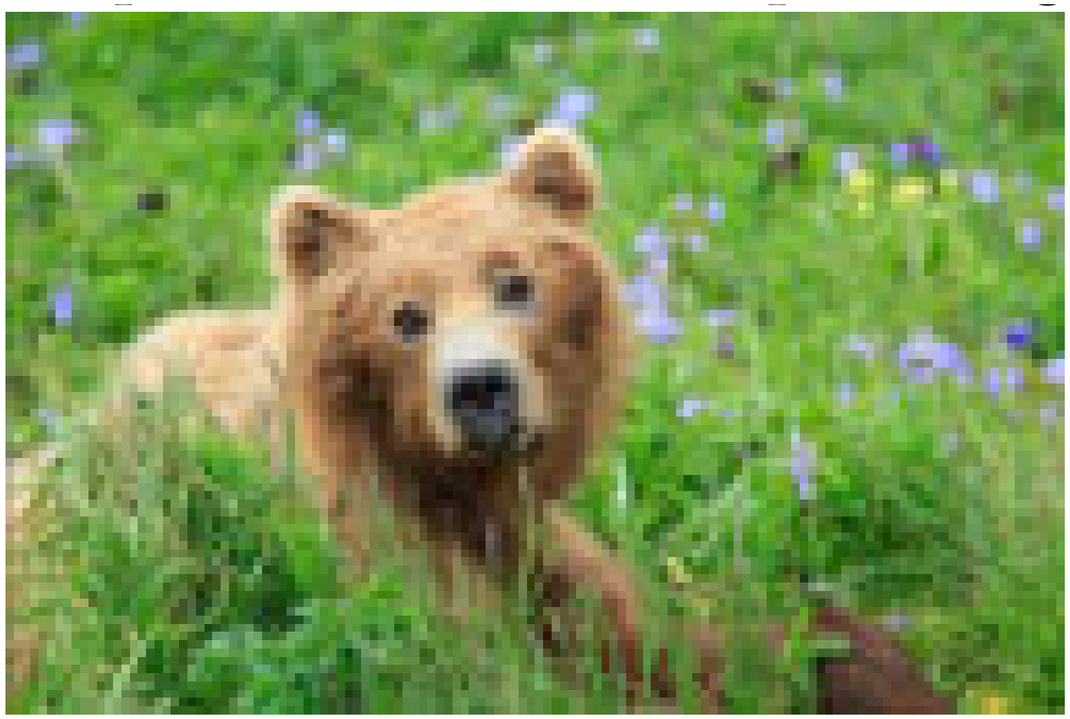
Idea

- **Each before/after pair of segment implies a planar transformation**
  - simple and linear

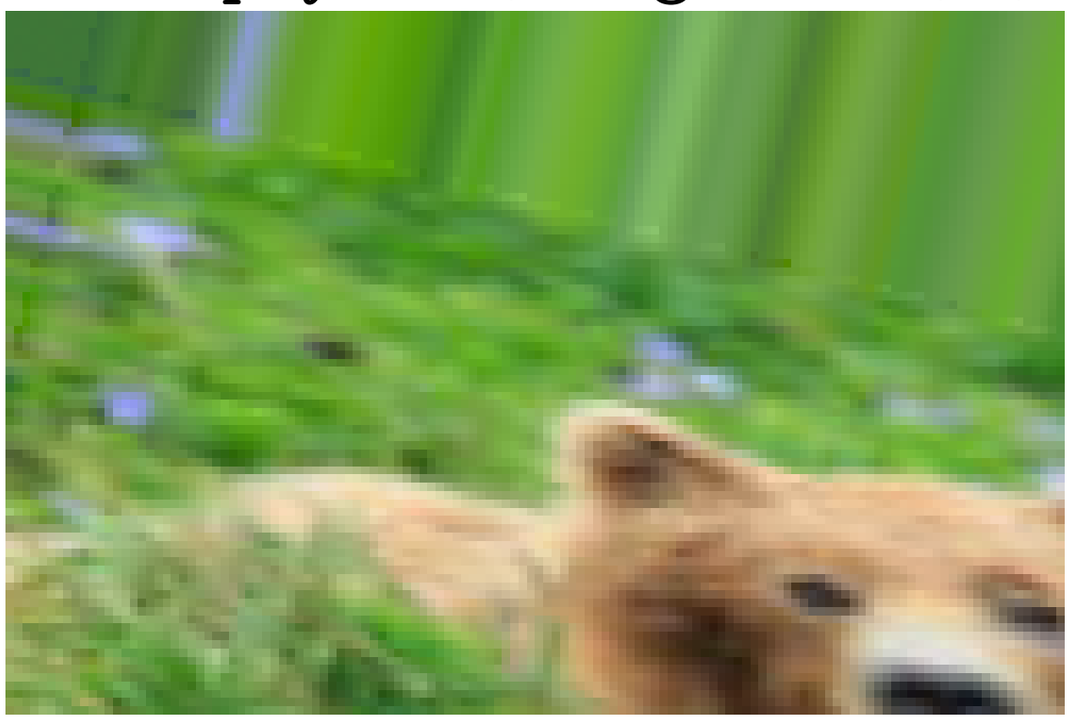


Single line transforms

Test

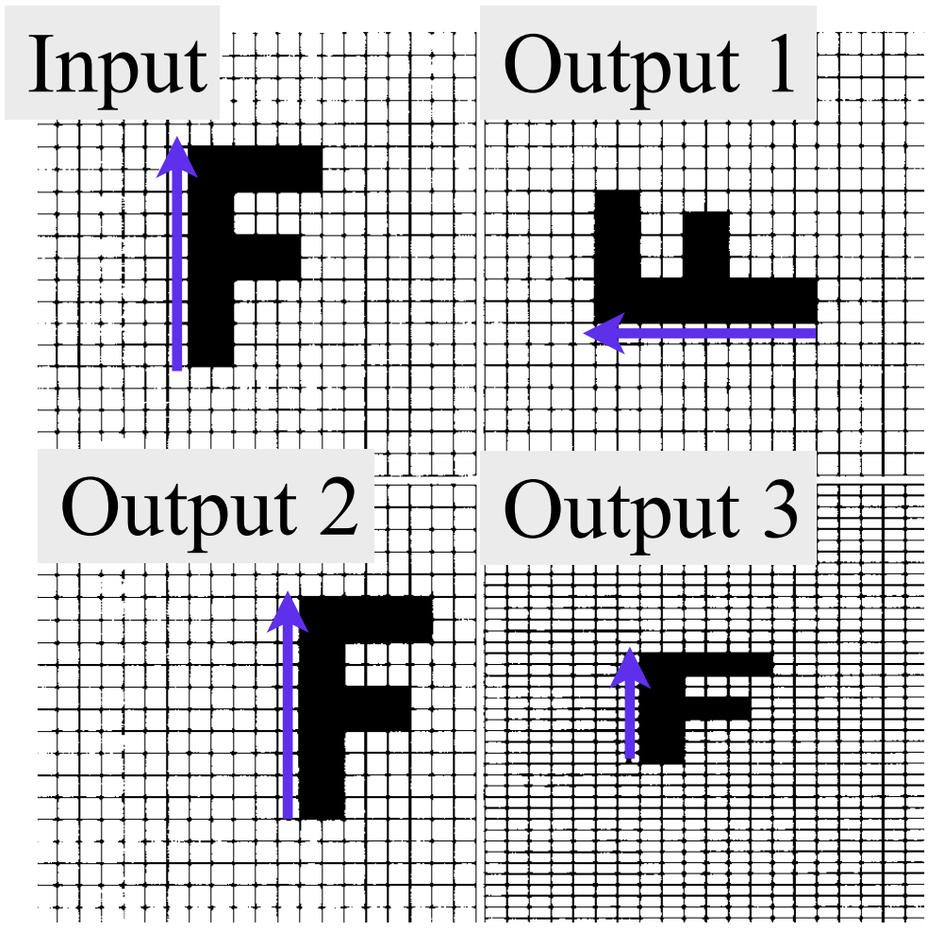


$\longrightarrow$ `warpBy1(im, segment(0,0, 10,0), segment(10, 10, 30, 15))` $\longrightarrow$

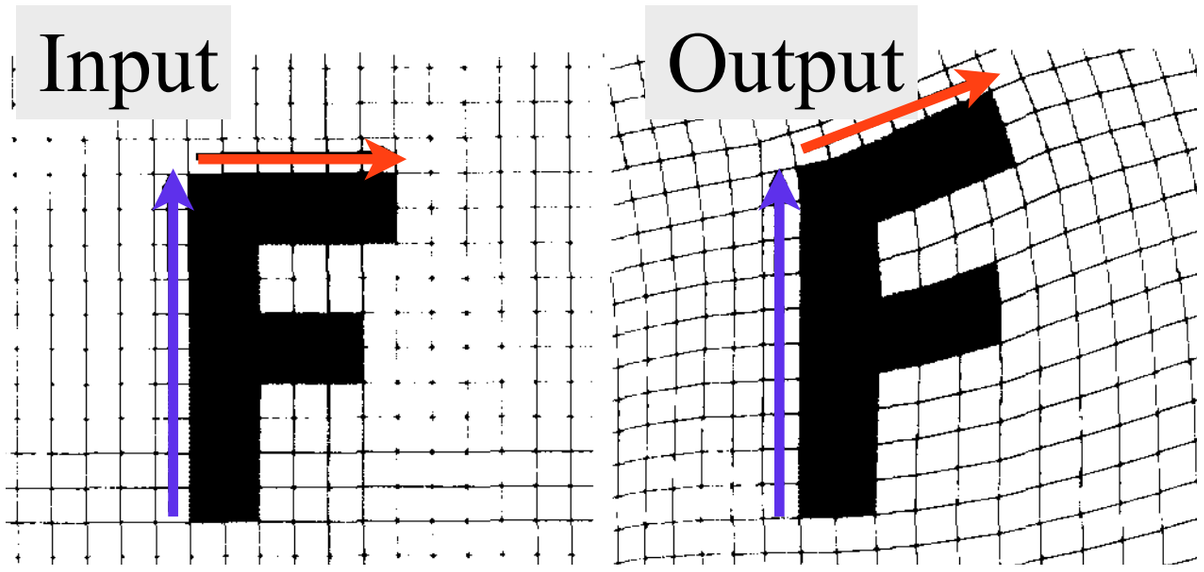


Idea

- **Each before/after pair of segment implies a planar transformation**
- **Then take weighted average of transformations**



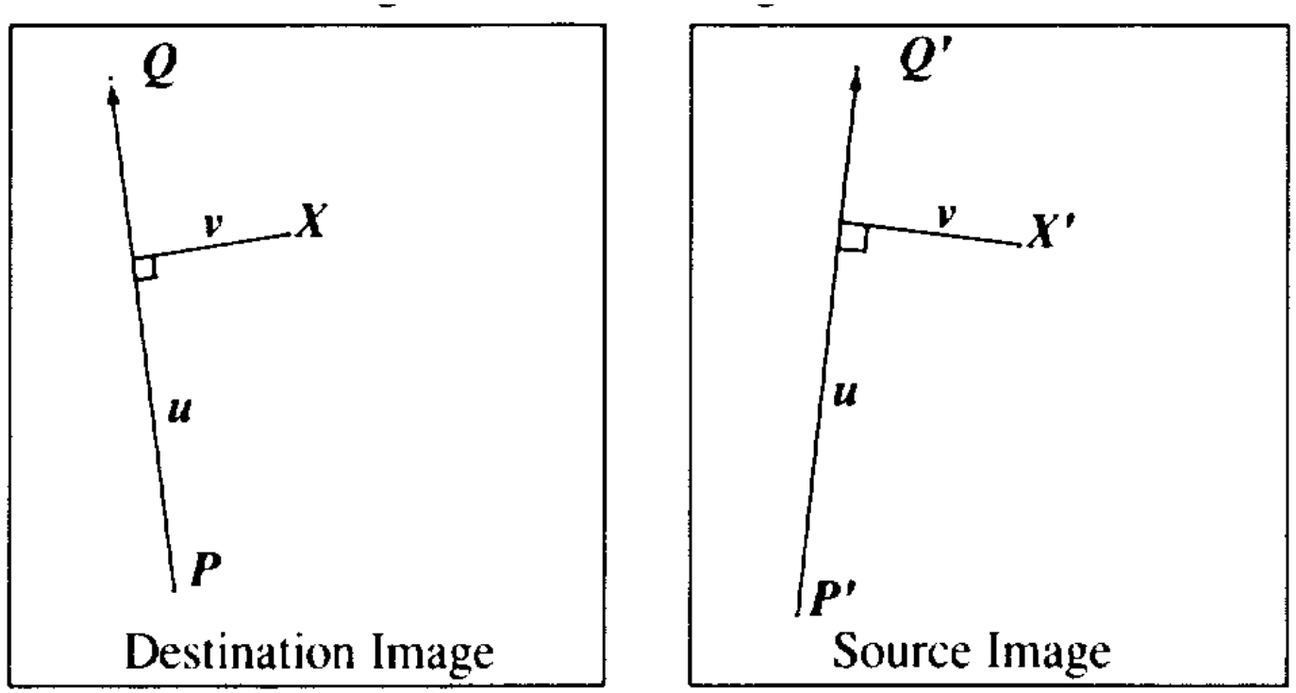
Single line transforms



Transform wrt 2 lines

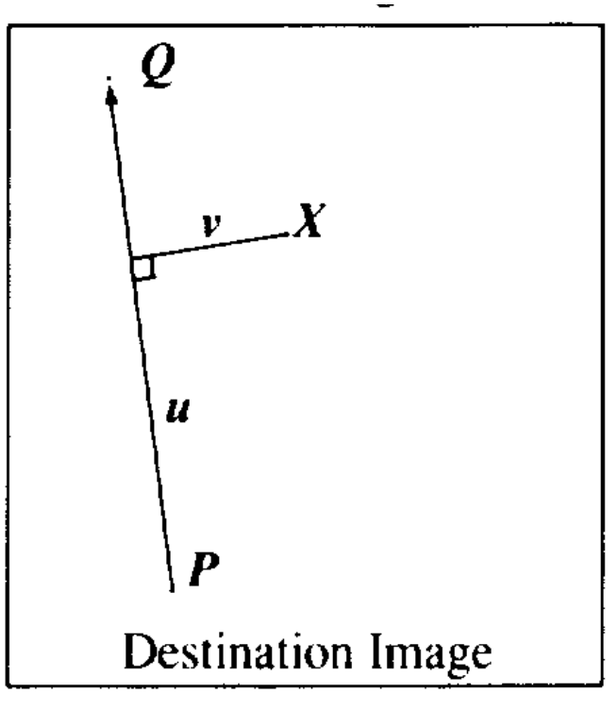
Transform wrt 1 segment

- **Define a coordinate system with respect to segment**
  - 1 dimension, *u*, along segment
  - 1 dimension, *v*, orthogonal to segment
- **Compute u, v in one image**
  - The after one, because we use the inverse transform
- **Compute point corresponding to u, v in second image**



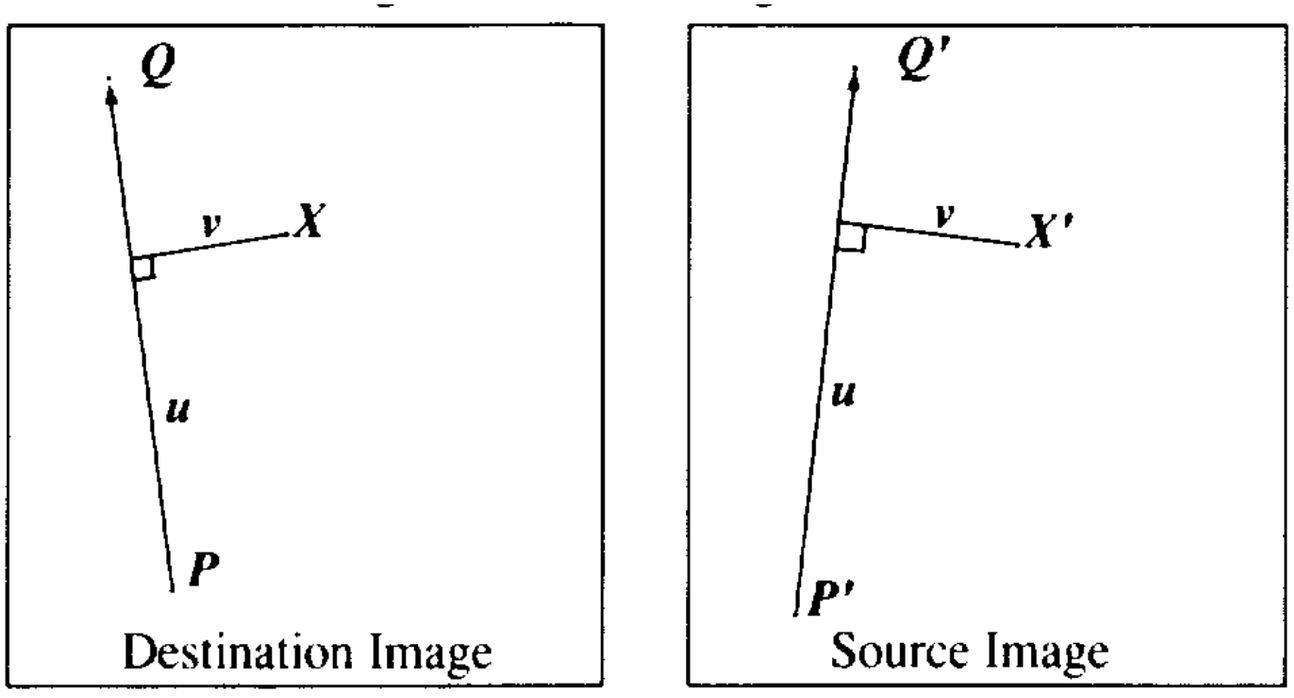
Computing u, v

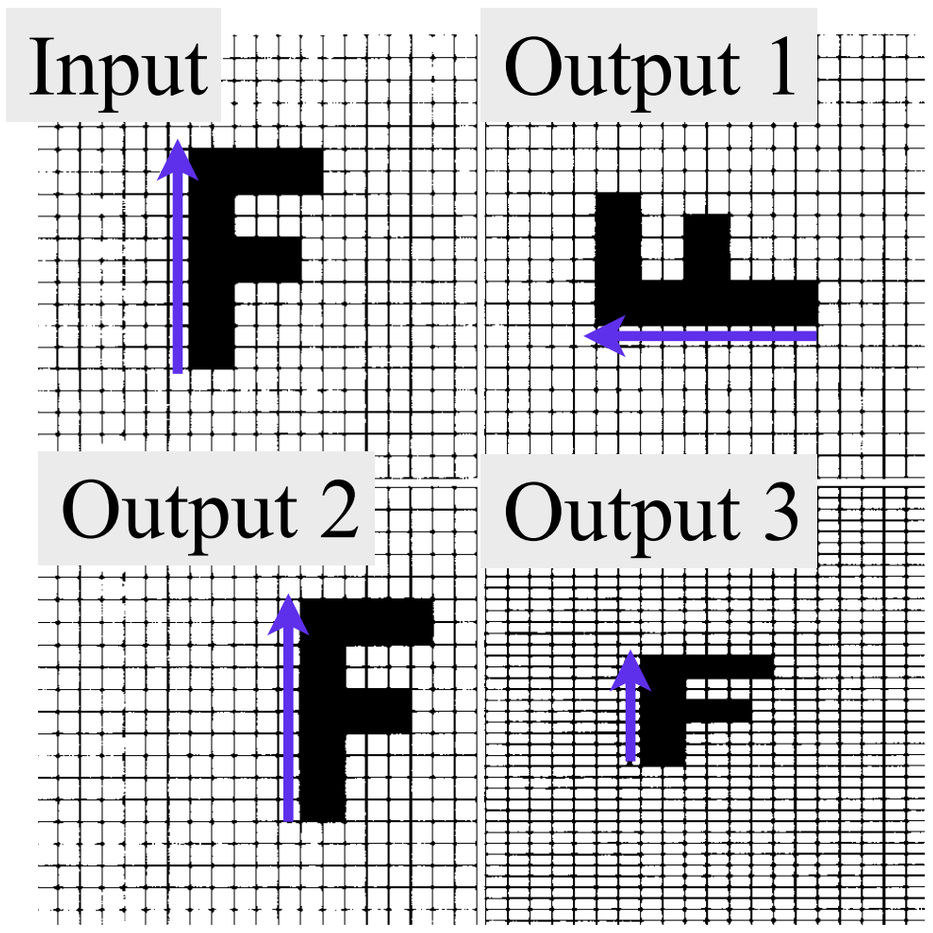
- **u = PX.PQ/||PQ||²**
  - this way u is 0 at P and 1 at Q
- **v=PX.perpendicular(PQ)/||PQ||**
  - where perpendicular(PQ) is PQ rotated by 90 degrees, and has length ||PQ||
  - unlike u which is normalized, v is in distance units



Transforming a point given u, v

- **X'=P'+uP'Q+v perpendicular(P'Q')/||P'Q'||**
- **The u component is scaled according to segment scaling**
- **But v is absolute (see output3)**
  - They say they tried to scale v as well but it didn't work as well





Single line transforms

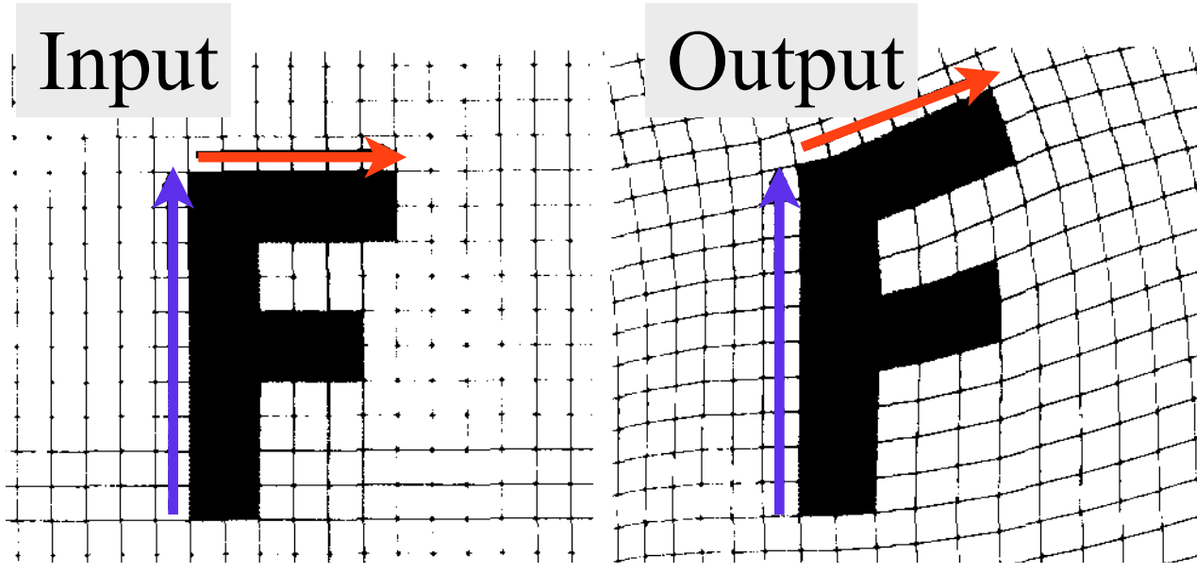
Questions?

Multiple segments

- **For each point X**
  - For each segment pair sbefore[i], safter[i]
    - Transform X into X'i
  - Compute weighted average of all transformed X'i
    - weight according to distance to segments

$$weight = \left(\frac{length^p}{a + dist} \right)^b$$

where a, b, p
control the influence



Transform wrt 2 lines

Debugging: example

- **Debugging my distance function**

Questions?

- **More debugging**

Morphing

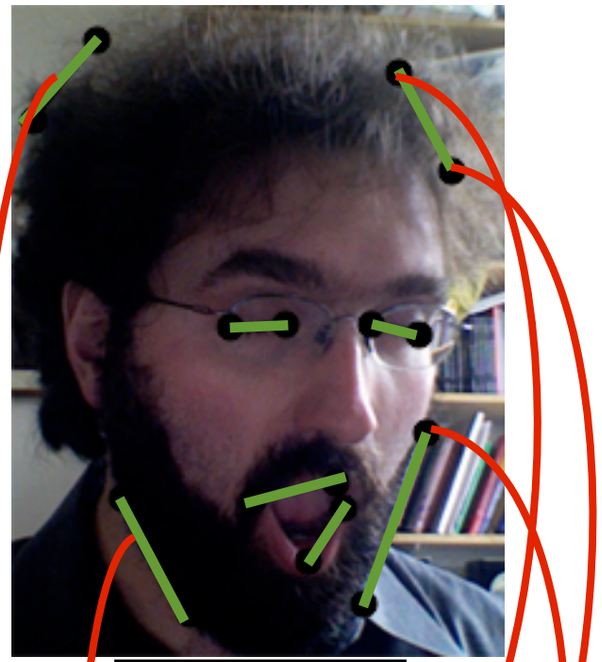
Input images

Segments

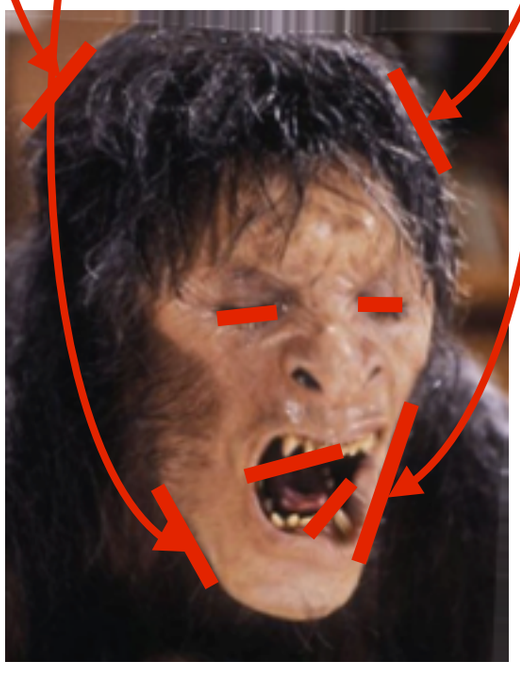
Interpolate segments

t=0.5

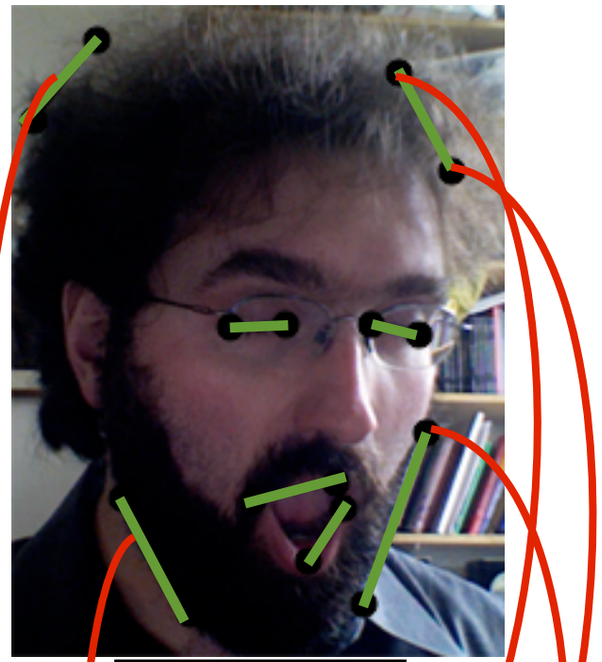
Warp images to segments[t]

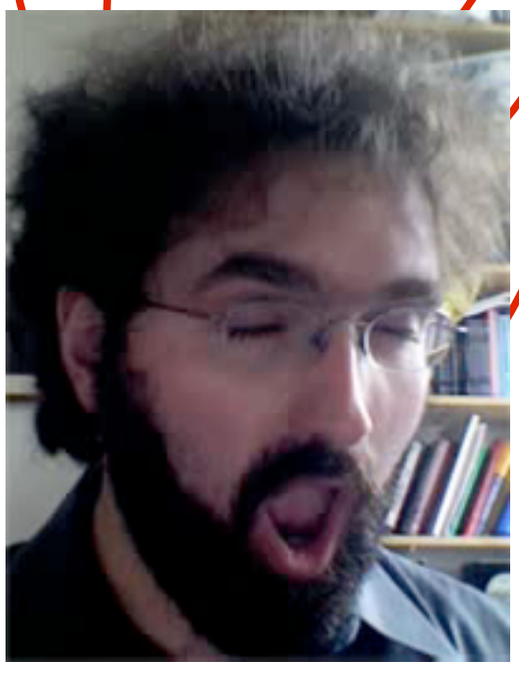


The red segments are at the same location in both images
Image features such as eyes are aligned

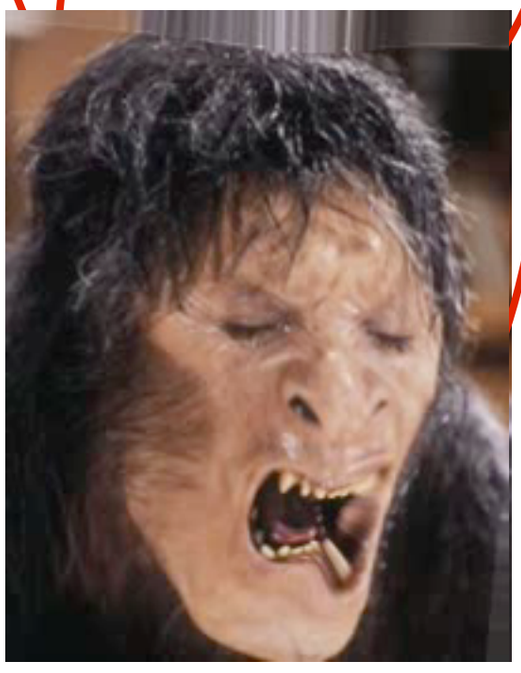


Warp images to segments[t]

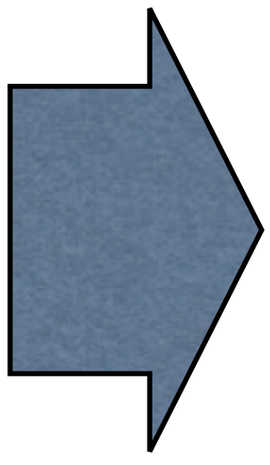


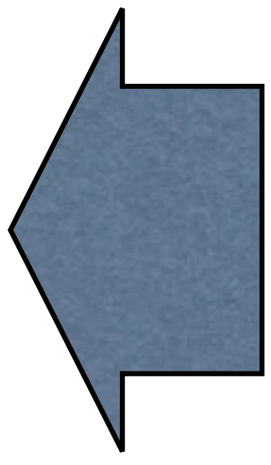


The red segments are at the same location in both images
Image features such as eyes are aligned

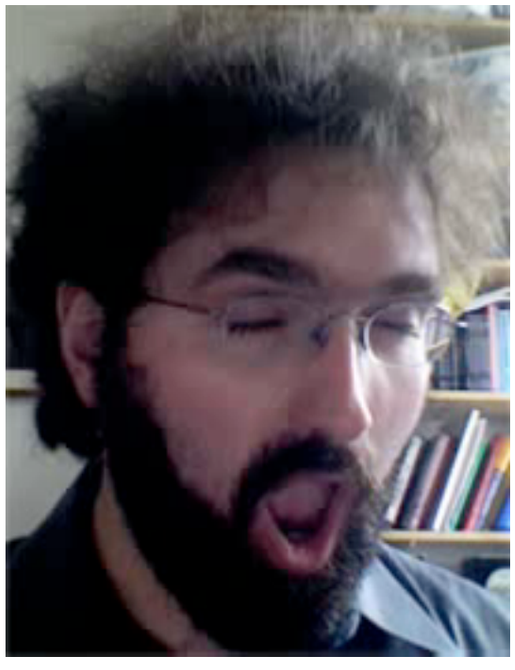


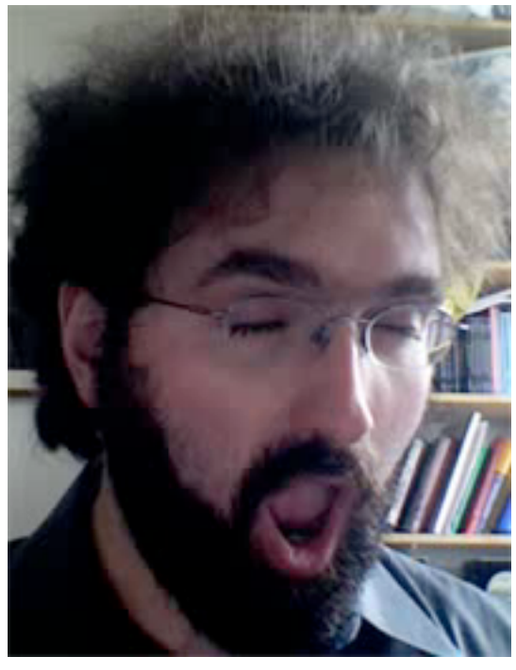
Interpolate color

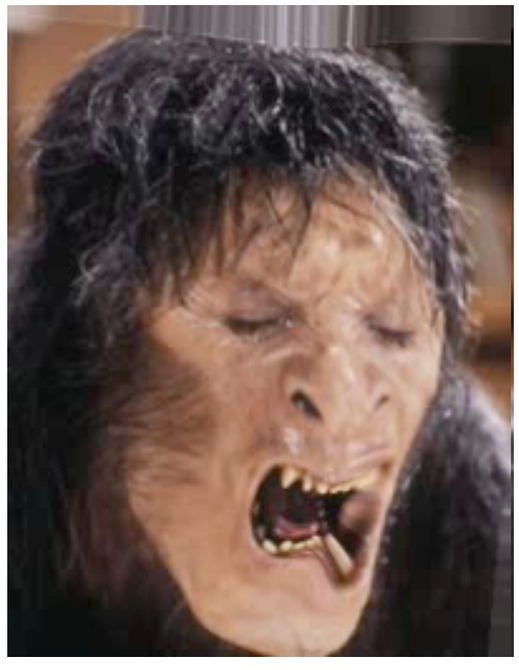




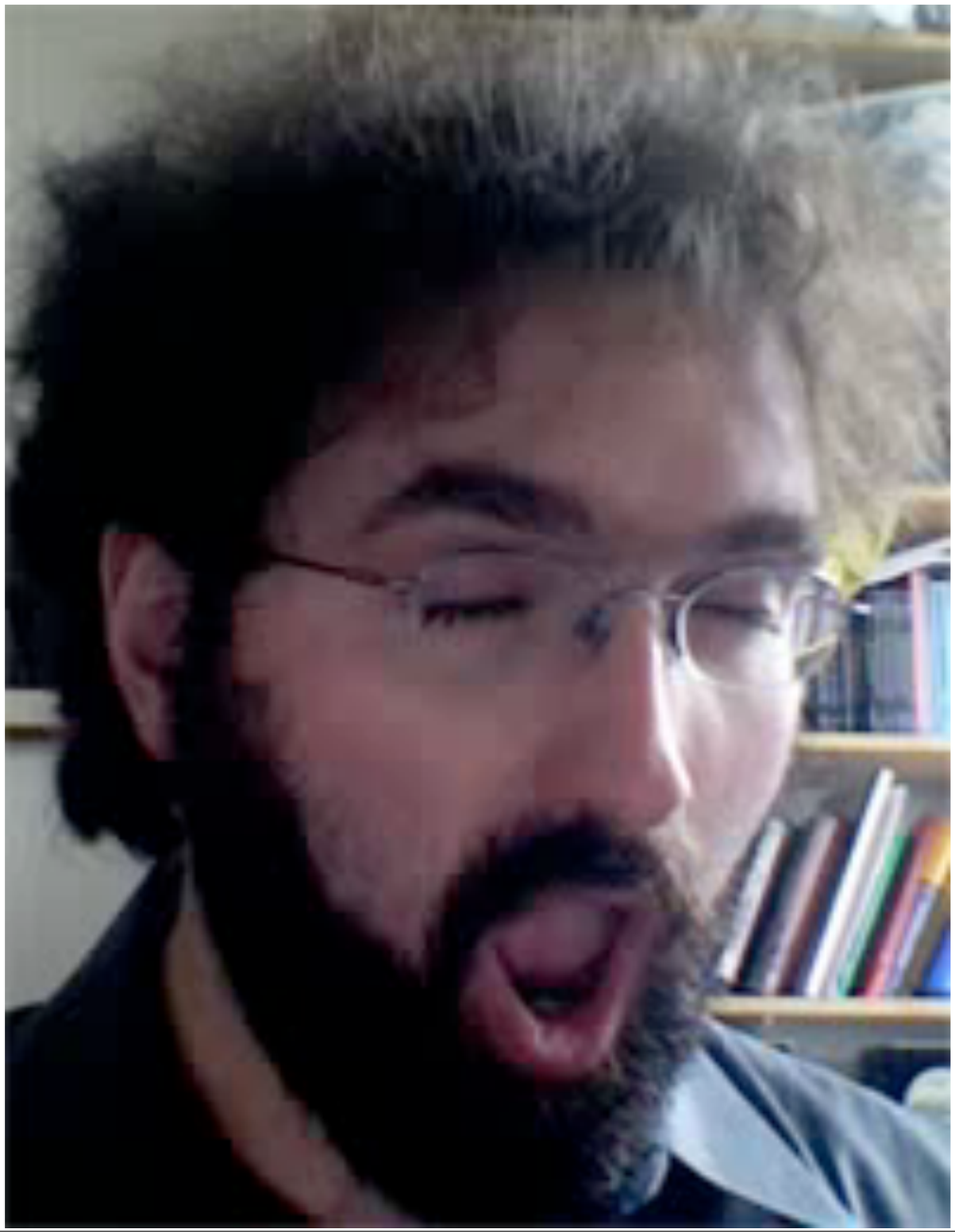
Interpolate color







Result



Recap

- For each intermediate frame I_t
  - Interpolate segment locations $y^t_i = (1- t)\, x^0_i + t\, x^1_i$
  - Perform **two** warps: one for I_0, one for I_1
    - Deduce a dense warp field from the pairs of features
    - Warp the pixels
  - Linearly interpolate the two warped images

Michael Jackson' BW

- Uses the very technique we just studied

Pset 2

Requirements

- Scaling using nearest-neighbor reconstruction
- Scaling with bi-linear reconstruction
- Rotation using linear reconstruction (6.865)
- Image warping according to one pair of segments
- Image warping according to two lists of segments, using weighted warping
- Image morphing
- Morph sequence between you and a peer (due on Wednesday).

The whacky UI

segmentsBefore=numpy.array([segment(87, 131, 109, 129), segment(142, 126, 165, 129)])

segmentsAfter=numpy.array([segment(81, 112, 107, 107), segment(140, 102, 163, 101)])

NB

- This is a hard Pset
- Code is going to be slow
- Start early
- Debug as you go

Photo session

- Wednesday afternoon at 1pm or 2pm or 3pm or 4pm.
- In 32-D424

Willow

- 1988, special effects by ILM
- First use of morphing

Women in Art video

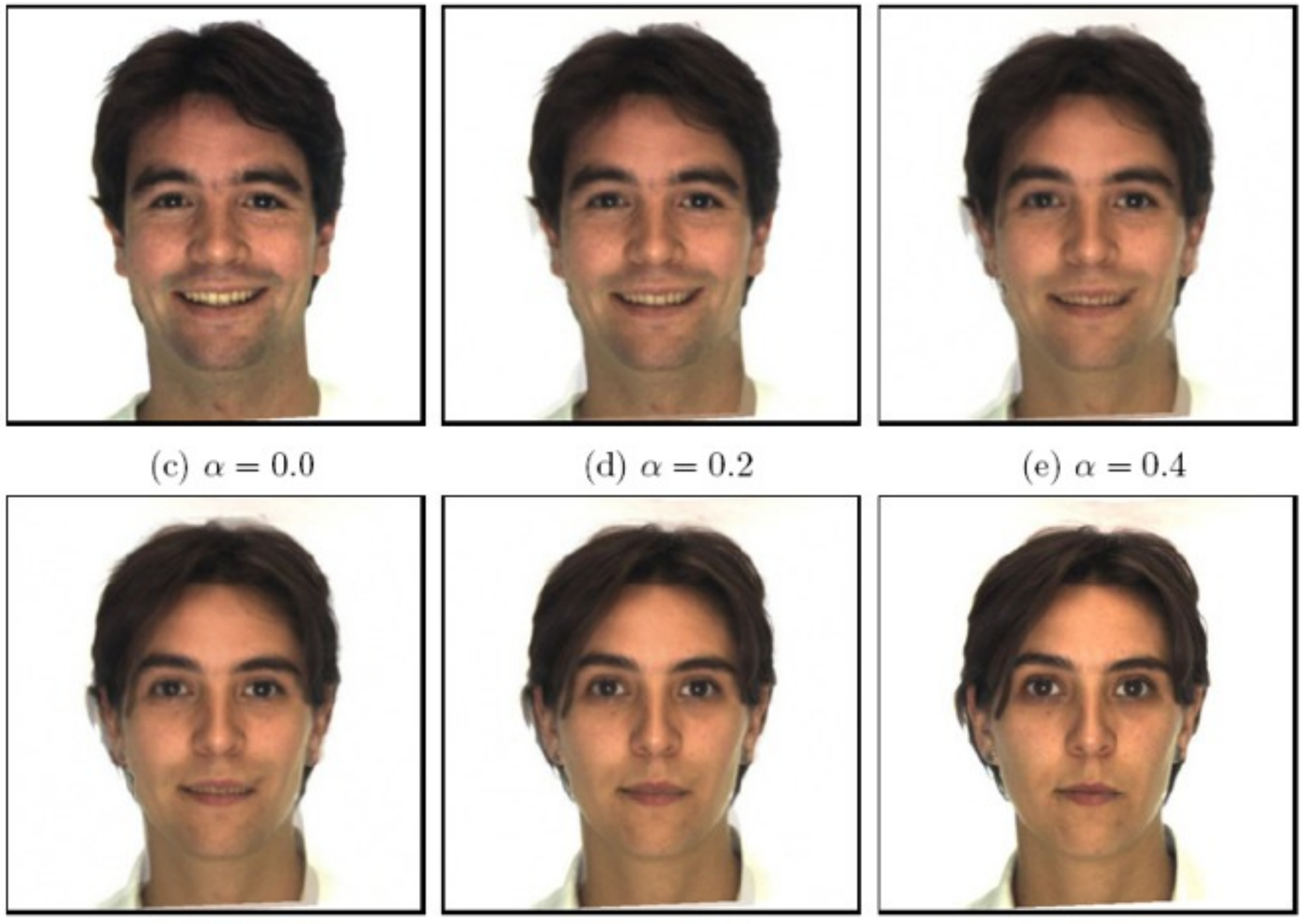
http://youtube.com/watch?v=nUDIoN-_Hxs

Slide Alyosha Efros

Bells and whistles

Morphing & matting

- **Extract foreground first to avoid artifacts in the background**



(c) $\alpha = 0.0$ (d) $\alpha = 0.2$ (e) $\alpha = 0.4$

(f) $\alpha = 0.6$ (g) $\alpha = 0.8$ (h) $\alpha = 1.0$

Uniform morphing

Figure 4. Uniform metamorphosis

Non-uniform morphing

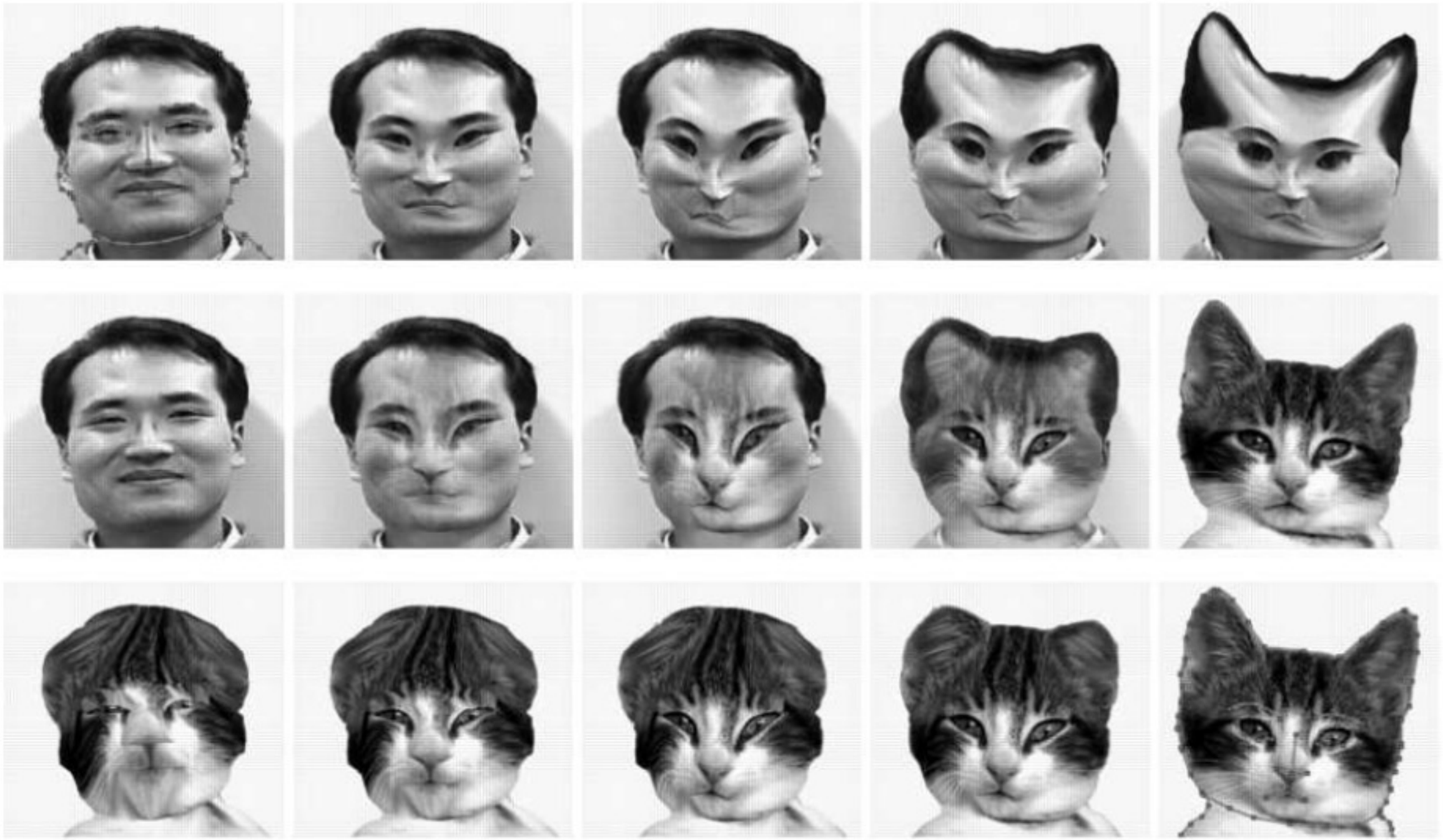
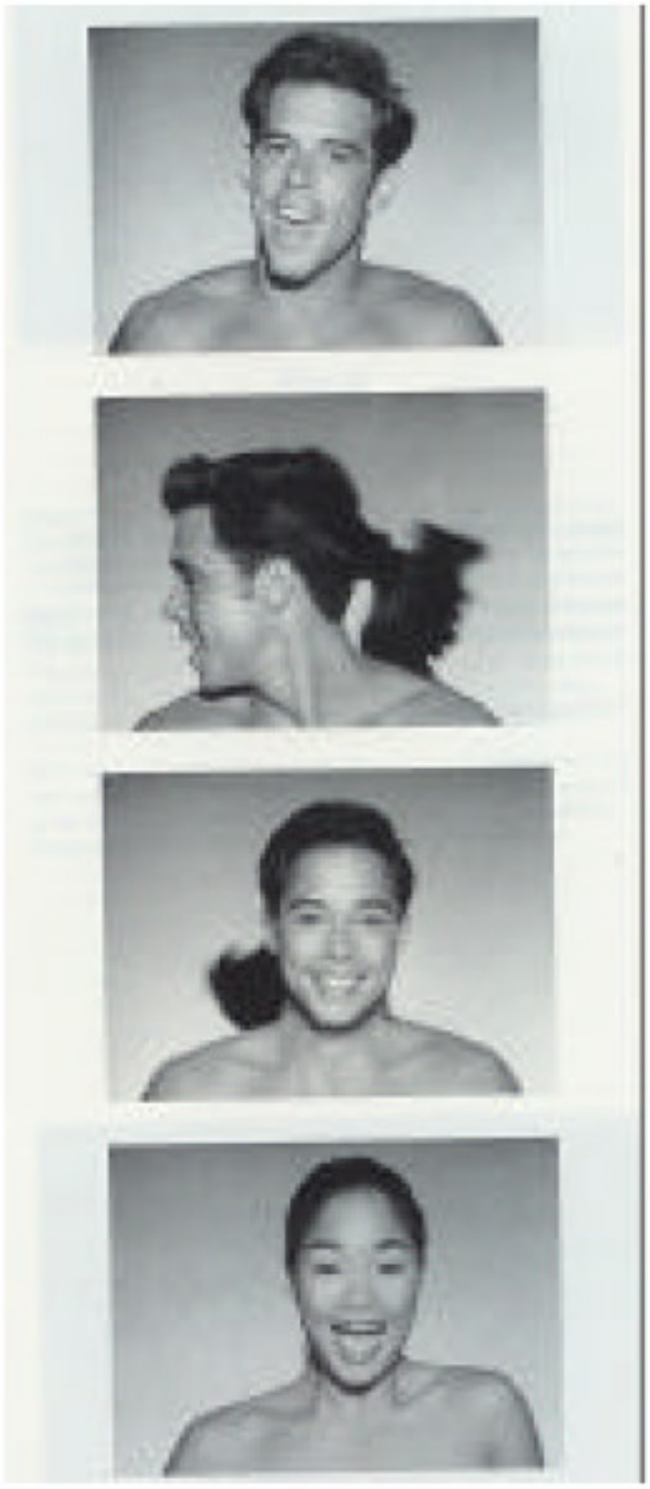


Figure 5. Nonuniform metamorphosis

http://www-cs.ccny.cuny.edu/~wolberg/pub/cgi96.pdf

Video

- **Lots of manual work**



Recap & Significance

Recap

- **Idea that linear interpolation introduces blur**
- **Separation of shape and color**
- **Idea of non-rigid alignment of different images**
  - Applications to medical data
- **Applications, related to**
  - Special effects
  - Face recognition
  - Video frame interpolation
  - MPEG

More morphing madness

- **Gondry's Rolling Stones Video**

- **Gondry's Beck "Cell Phones are Dead"**

Apps!

- **Most polished app add ever: http://www.demoncam.com/**

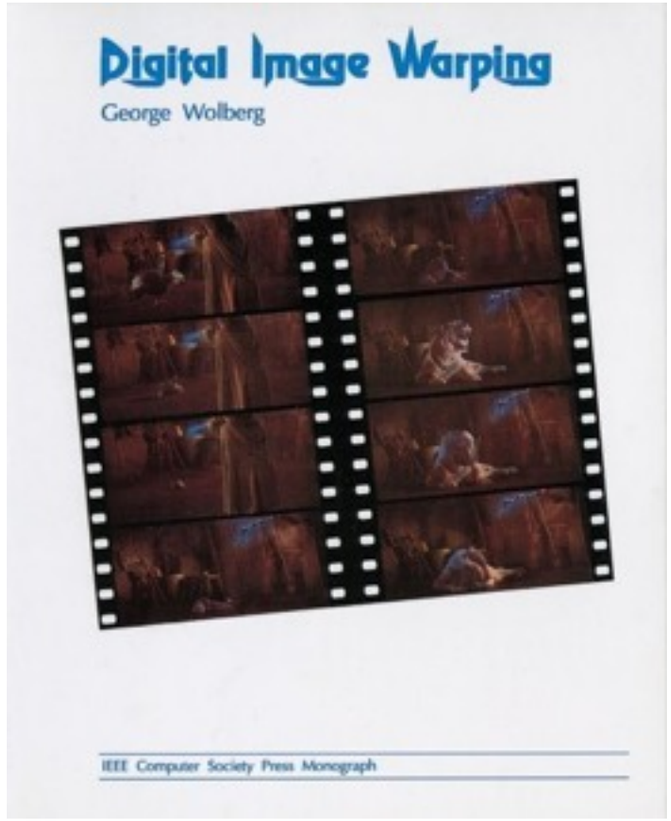
Making of Demoncam ad

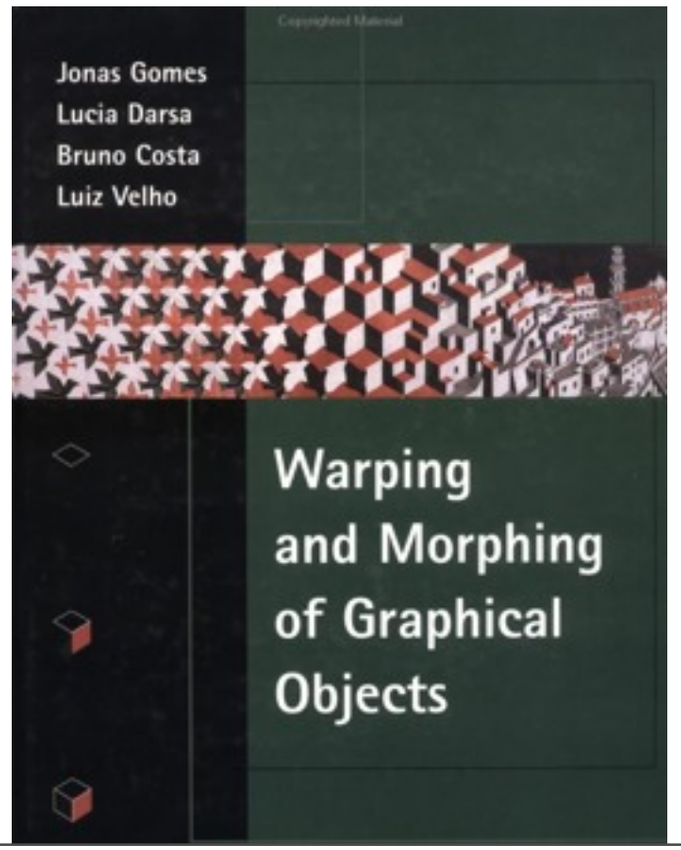
- **http://www.youtube.com/watch?v=YSBqXtOco5g&feature=related**

References

Refs

- http://portal.acm.org/citation.cfm?id=134003&coll=GUIDE&dl=GUIDE&CFID=72901489&CFTOKEN=24335444
- http://www.visgraf.impa.br/cgi-bin/morphQuery.cgi?output=html
- http://www.cg.tuwien.ac.at/research/ca/mrm/
- http://w3.impa.br/~morph/sites.html
- http://w3.impa.br/~morph/sig-course/slides.html
- http://www.owlnet.rice.edu/~elec539/Projects97/morphjrks/morph.html
- http://www.fmrib.ox.ac.uk/~yongyue/thinplate.html
- http://www.uoguelph.ca/~mwirth/PHD_Chapter4.pdf





Software

- http://www.morpheussoftware.net/
- http://www.debugmode.com/winmorph/
- http://www.stoik.com/products/morphman/mm1_main.htm
- http://www.creativecow.net/articles/zwar_chris/morph/index.html
- http://meesoft.logicnet.dk/SmartMorph/
- http://www.asahi-net.or.jp/~FX6M-FJMY/mop00e.html
- http://morphing-software-review.toptenreviews.com/
- http://www.freedownloadscenter.com/Search/morphing.html

- http://www.collegehumor.com/video/6705603/north-korean-photoshop-tutorial