Panoramas

Kari Pulli
Senior Director
NVIDIA Research

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°

Slide from Brown & Lowe

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°

Slide from Brown & Lowe

Are you getting the whole picture?

- Compact Camera FOV = 50 x 35°
- Human FOV = 200 x 135°
- Panoramic Mosaic = 360 x 180°

Slide from Brown & Lowe

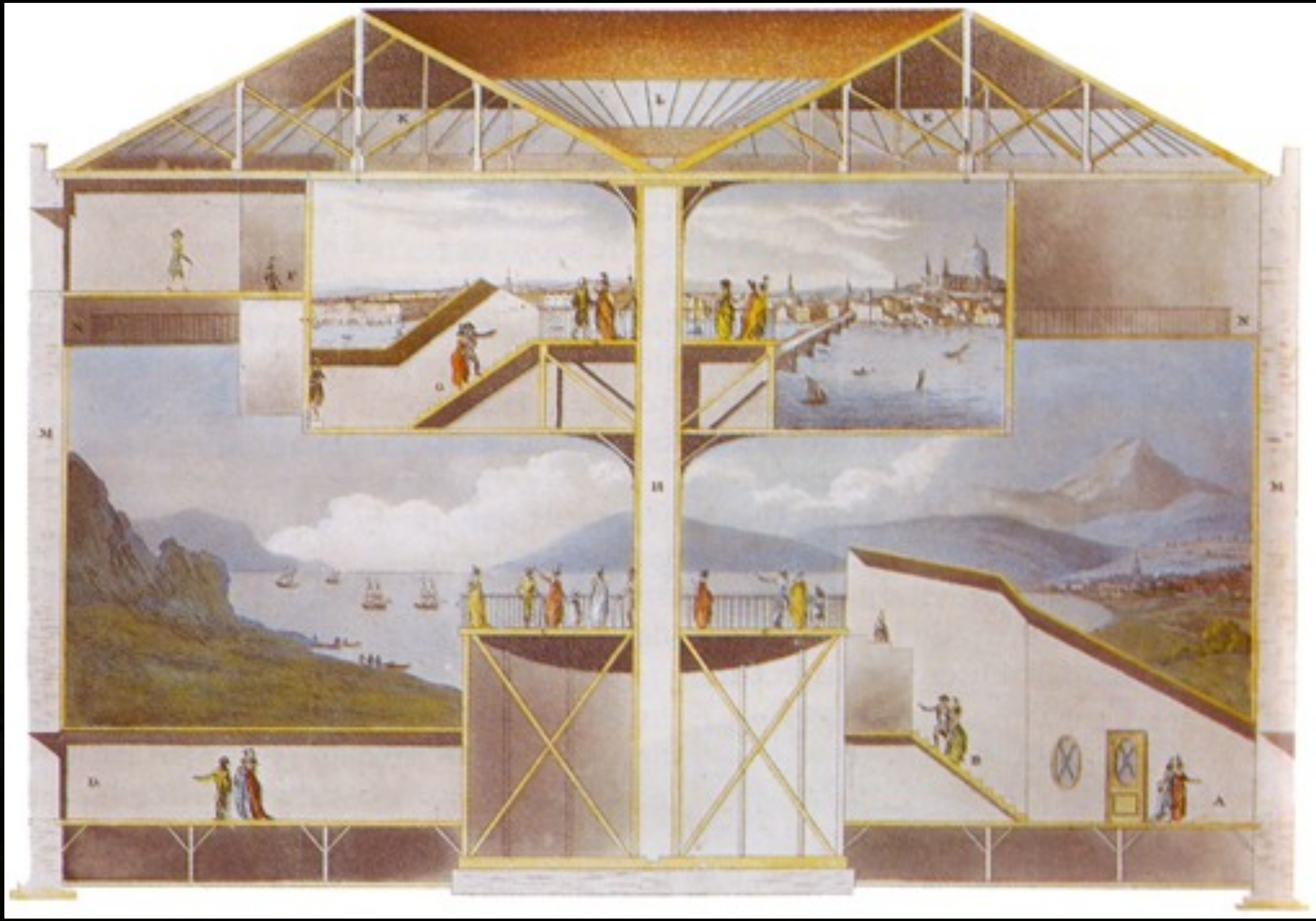
Panorama

A wide-angle representation of the scene

Panorama of Along the River During Qingming Festival
18th century remake of a 12th century original by Chinese artist Zhang Zeduan

Image from Wikipedia

Panorama: Cinema for the early 19th century



Burford's Panorama, Leicester Square, London, 1801

Painting by Robert Mitchell

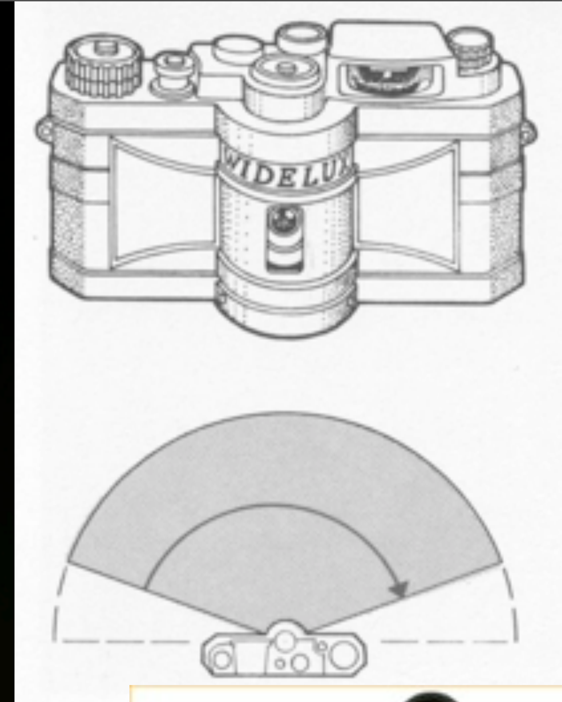
Panoramas with wide-angle optics

http://www.0-360.com

AF DX Fisheye-NIKKOR 10.5mm f/2.8G ED

Rotation cameras

- Idea
  - rotate camera or lens so that a vertical slit is exposed
- Swing lens
  - rotate the lens and a vertical slit (or the sensor)
  - typically can get 110-140 degree panoramas
  - Widelux, Seitz, …
- Full rotation
  - whole camera rotates
  - can get 360 degree panoramas
  - Panoscan, Roundshot, …



Swing-lens panoramic images

San Francisco in ruins, 1906

101 Ranch, Oklahoma, circa 1920

Flatback panoramic camera

Lee Frost, Val D'Orcia, Tuscany, Italy

Disposable panoramic camera

wide-angle lens, limited vertical FOV

Stitching images to make a mosaic

NVIDIA Research

Stitching images to make a mosaic

- Given a set of images that should stitch together
  - by rotating the camera around its center of perspective
- Step 1: Find corresponding features in a pair of image
- Step 2: Compute transformation from 2nd to 1st image
- Step 3: Warp 2nd image so it overlays 1st image
- Step 4: Blend images where they overlap one another
- repeat for 3rd image and mosaic of first two, etc.

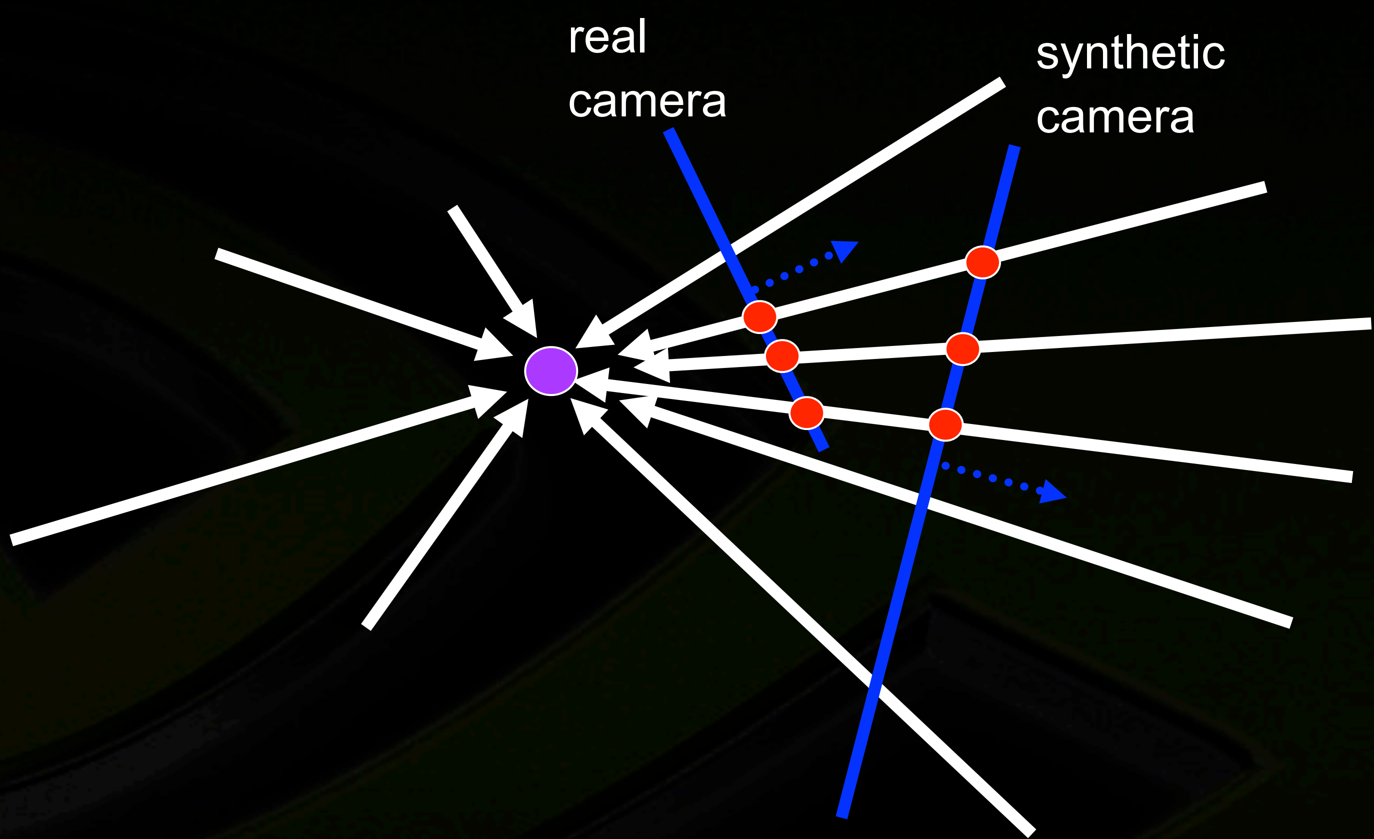
Aligning images: Translation?


left on top

right on top


Translations are not enough to align the images

A pencil of rays contains all views



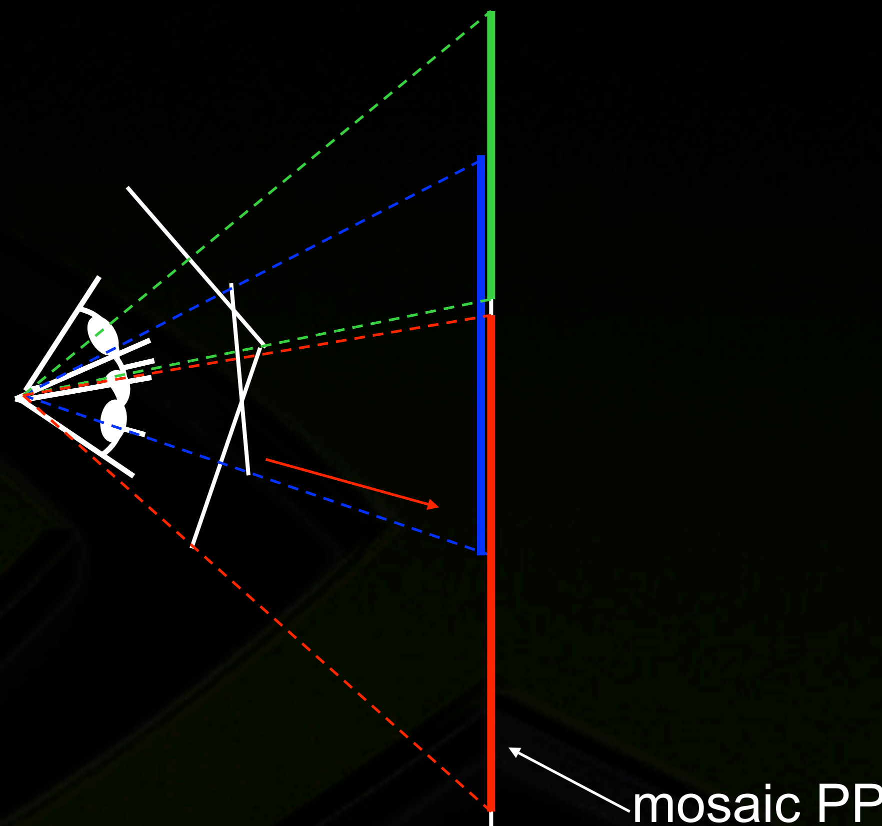
Can generate any synthetic camera view
as long as it has **the same center of projection**!
… and scene geometry does not matter …

Reprojecting an image onto a different picture plane

the sidewalk art of Julian Beever

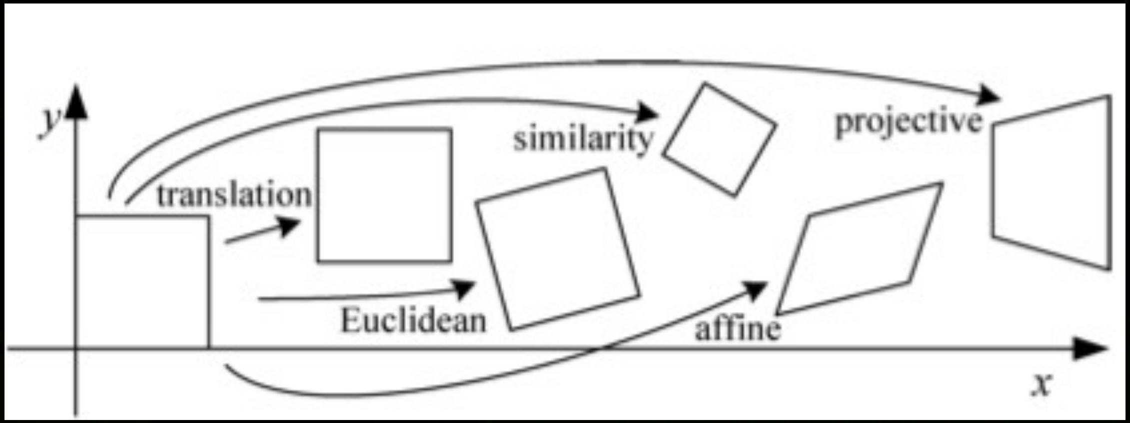
- the view on any picture plane can be projected onto any other plane in 3D without changing its appearance as seen from the center of projection

Image reprojection

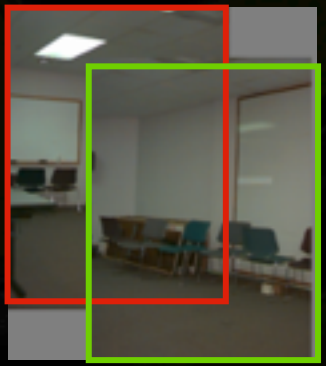


- The mosaic has a natural interpretation in 3D
  - the images are reprojected onto a common plane
  - the mosaic is formed on this plane
  - mosaic is a *synthetic wide-angle camera*

Which transform to use?

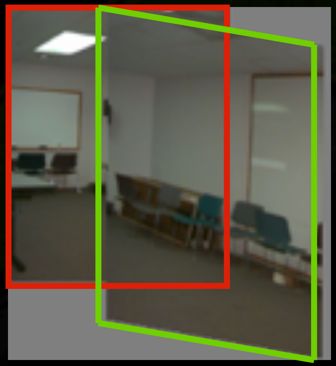


Translation



2 unknowns

Affine



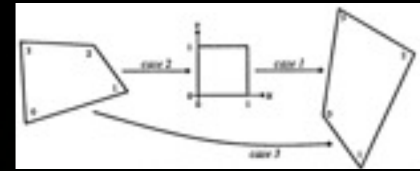
6 unknowns

Perspective

8 unknowns

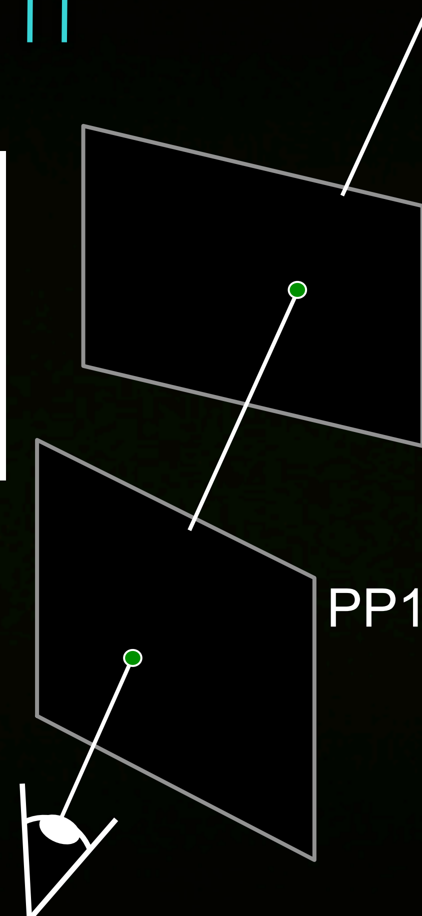
Homography

- Projective mapping between any two PPs with the same center of projection
  - rectangle should map to arbitrary quadrilateral
  - parallel lines aren't
  - but must preserve straight lines



is called a Homography

$$\underbrace{\begin{bmatrix} wx' \\ wy' \\ w \end{bmatrix}}_{\mathbf{p'}} = \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}}_{\mathbf{p}}$$



- To apply a homography H
  - compute p' = Hp *(regular matric multiply)*
  - convert p' from homogeneous to image coordinates [x', y'] *(divide by w)*

Homography from mapping quads

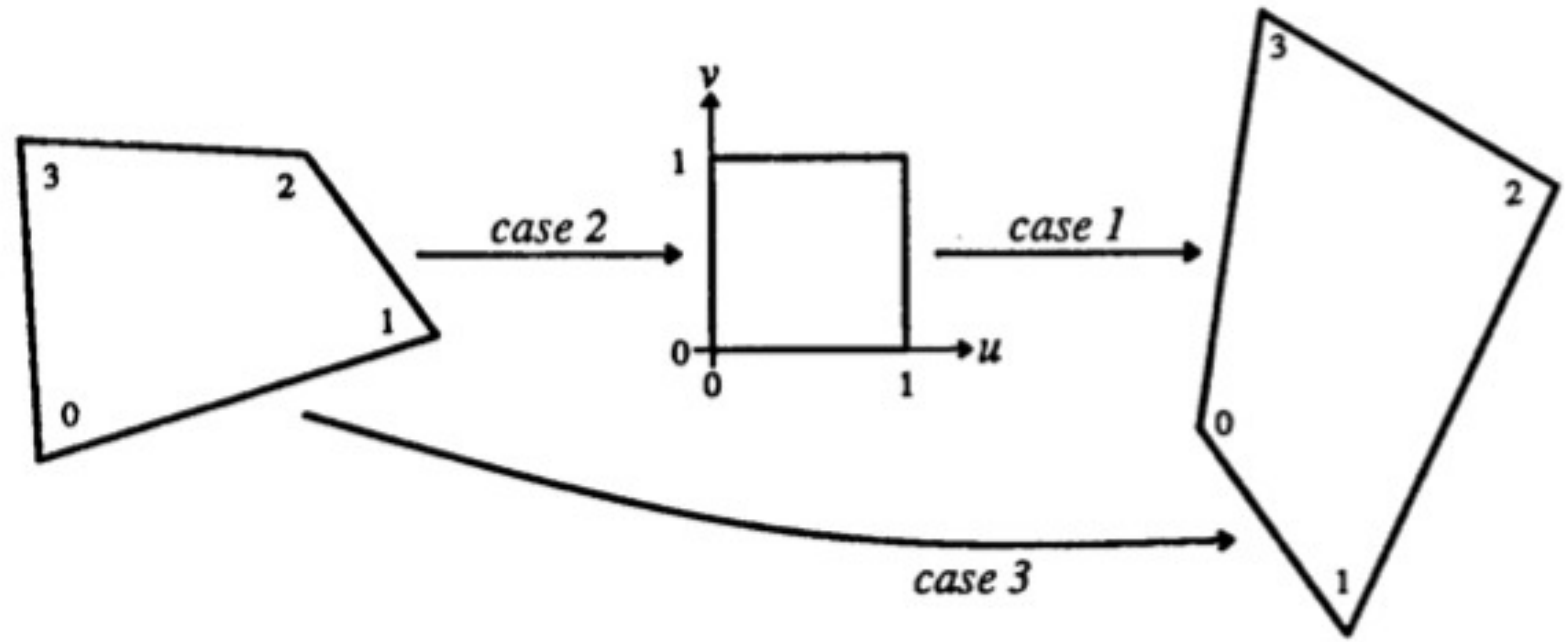


Figure 2.8: *Quadrilateral to quadrilateral mapping as a composition of simpler mappings.*

Fundamentals of Texture Mapping and Image Warping
Paul Heckbert, M.Sc. thesis, U.C. Berkeley, June 1989, 86 pp.
http://www.cs.cmu.edu/~ph/texfund/texfund.pdf

Homography from *n* point pairs (x,y ; x',y')

NVIDIA

$$\begin{bmatrix} wx' \\ wy' \\ w \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

p' **H** **p**

- Multiply out
  - $wx' = h_{11}\,x + h_{12}\,y + h_{13}$
  - $wy' = h_{21}\,x + h_{22}\,y + h_{23}$
  - $w = h_{31}\,x + h_{32}\,y + h_{33}$
- Get rid of w
  - $(h_{31}\,x + h_{32}\,y + h_{33})x' - (h_{11}\,x + h_{12}\,y + h_{13}) = 0$
  - $(h_{31}\,x + h_{32}\,y + h_{33})y' - (h_{21}\,x + h_{22}\,y + h_{23}) = 0$
- Create a new system Ah = 0
  - Each point constraint gives two rows of A

$$[-x \quad -y \quad -1 \quad 0 \quad 0 \quad 0 \quad xx' \quad yx' \quad x']$$
$$[\;0 \quad 0 \quad 0 \quad -x \quad -y \quad -1 \quad xy' \quad yy' \quad y']$$

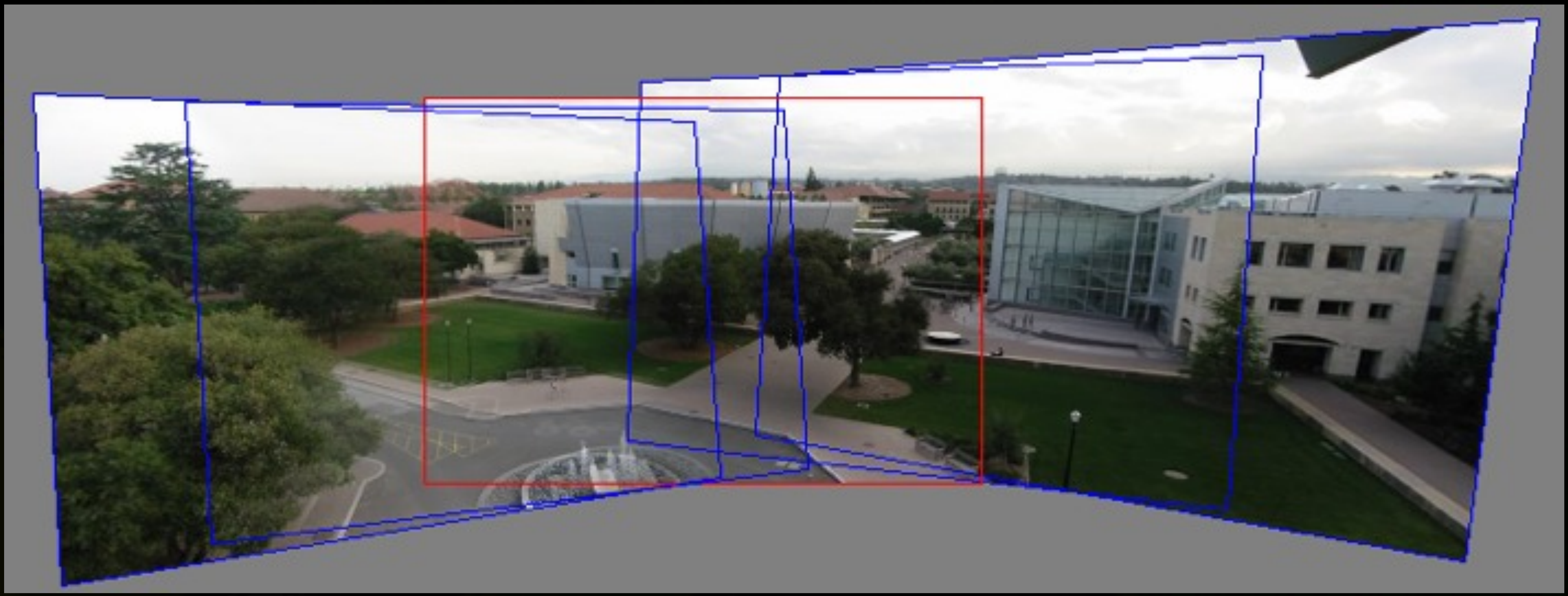
- Solve with singular value decomposition of $A = USV^T$
  - solution is in the nullspace of A
  - the last column of V (= last row of V^T)

$$h = \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix}$$

Python test code

```
from numpy import *

# create 4 random homogen. points
X = ones([3,4])             # the points are on columns
X[:2,:] = random.rand(2,4) # first row x coord, second y coord, third w = 1
x,y = X[0],X[1]
# create projective matrix
H = random.rand(3,3)
# create the target points
Y = dot(H,X)
# homogeneous division
YY = (Y / Y[2])[:2,:]
u,v = YY[0],YY[1]

A = zeros([8,9])
for i in range(4):
    A[2*i  ] = [-x[i], -y[i], -1,     0,      0,   0, x[i] * u[i], y[i] * u[i], u[i]]
    A[2*i+1] = [    0,      0,   0, -x[i], -y[i], -1, x[i] * v[i], y[i] * v[i], v[i]]

[u,s,vt] = linalg.svd(A)

# reorder the last row of vt to 3x3 matrix
HH = vt[-1,:].reshape([3,3])

# test that the matrices are the same (within a multiplicative factor)
print H - HH * (H[2,2] / HH[2,2])
```

Summary of perspective stitching



- Pick one image, typically the central view (red outline)
- Warp the others to its plane
- Blend

Example

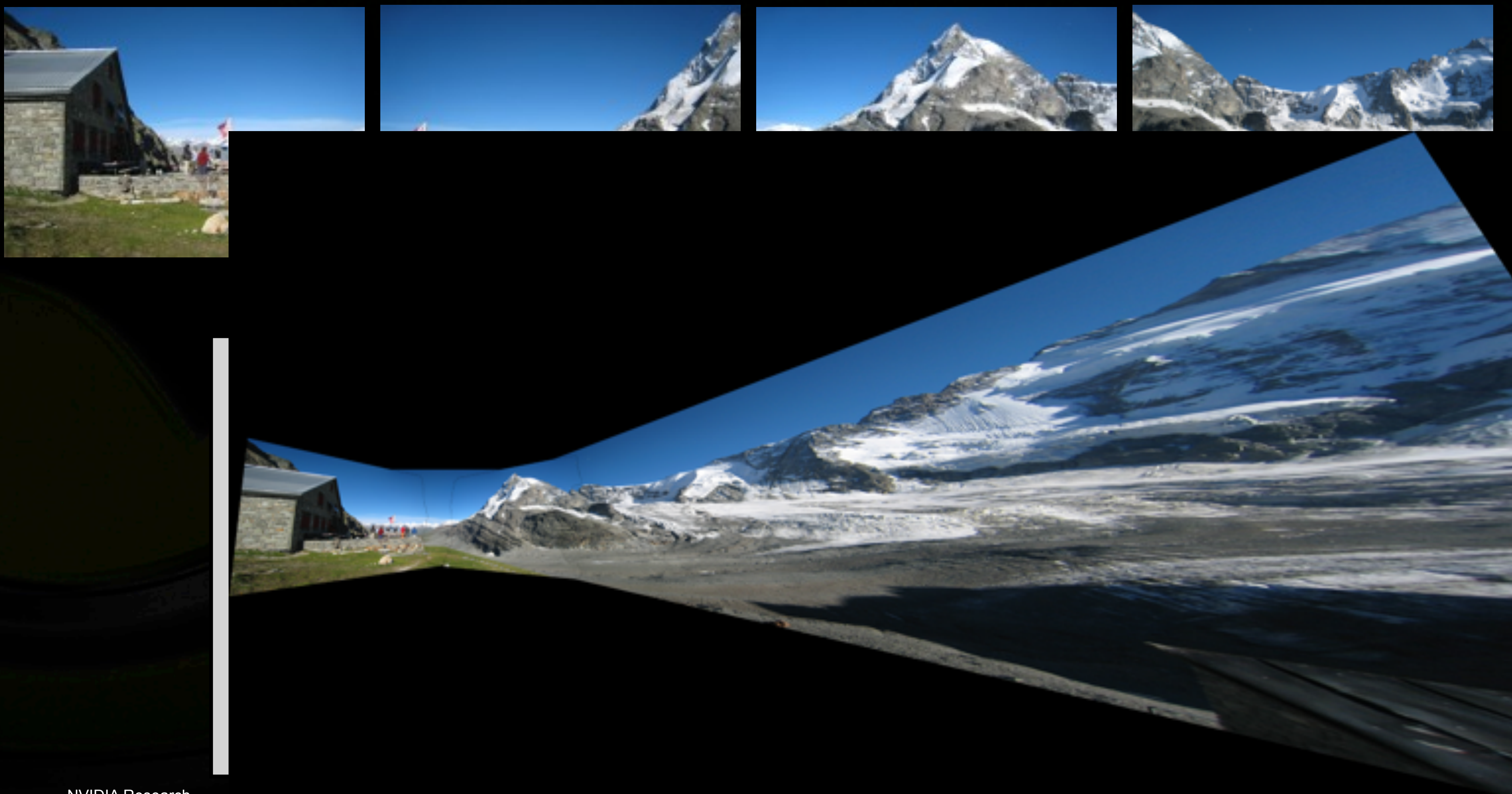


common picture plane of mosaic image

perspective reprojection

Pics: Marc Levoy

Using 4 shots instead of 3



Back to 3 shots

surface of

cylindrical reprojection

Back to 3 shots

surface
of

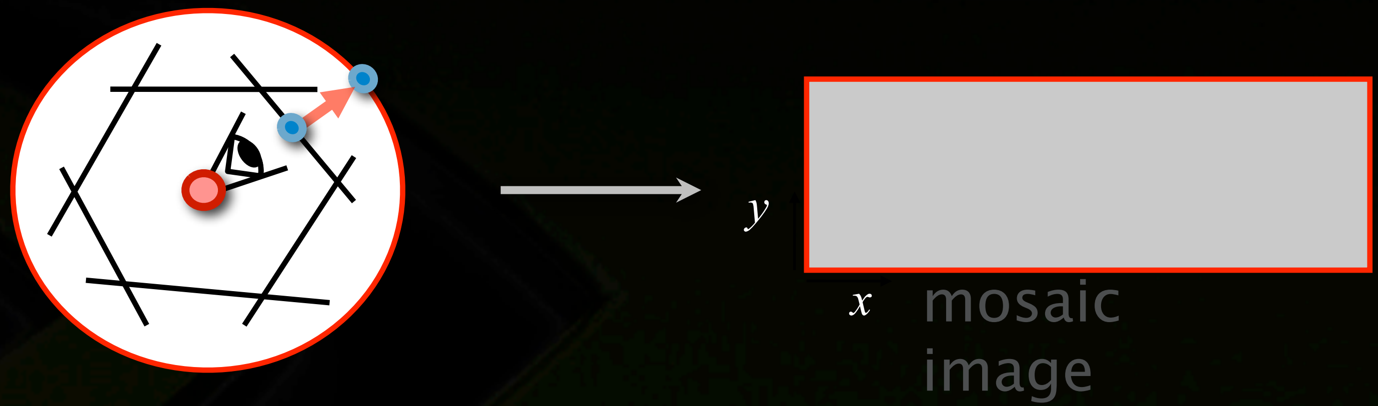
cylindrical reprojection

Back to 3 shots

perspective reprojection

Cylindrical panoramas

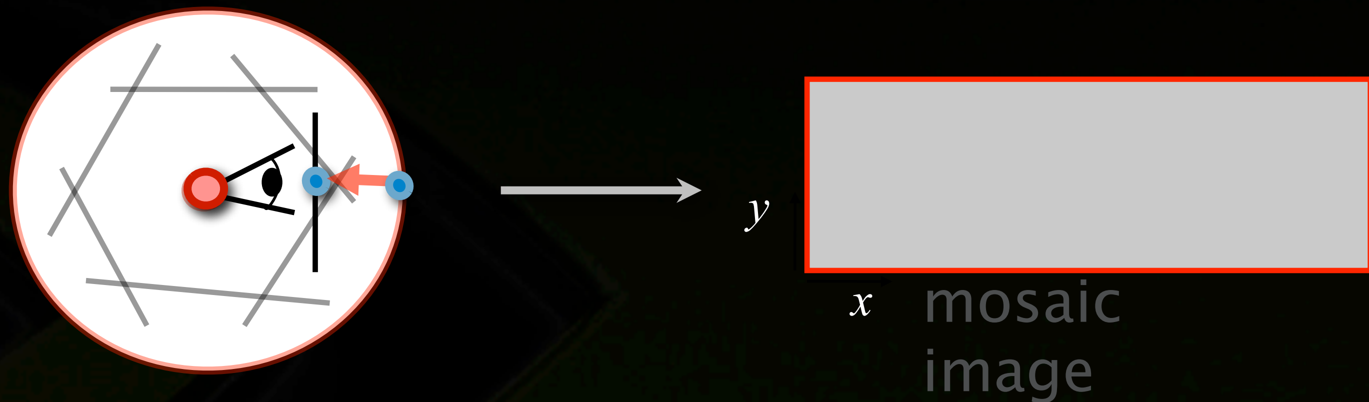
- What if you want a 360° panorama?



- Project each image onto a cylinder
- A cylindrical image is a rectangular array

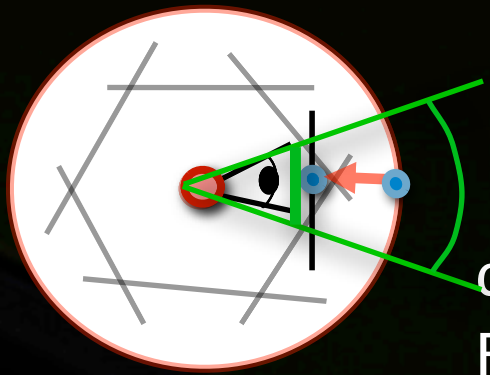
Cylindrical panoramas

- What if you want a 360° panorama?



- Project each image onto a cylinder
- A cylindrical image is a rectangular array
- To view without distortion
  - reproject a portion of the cylinder onto a picture plane representing the display screen

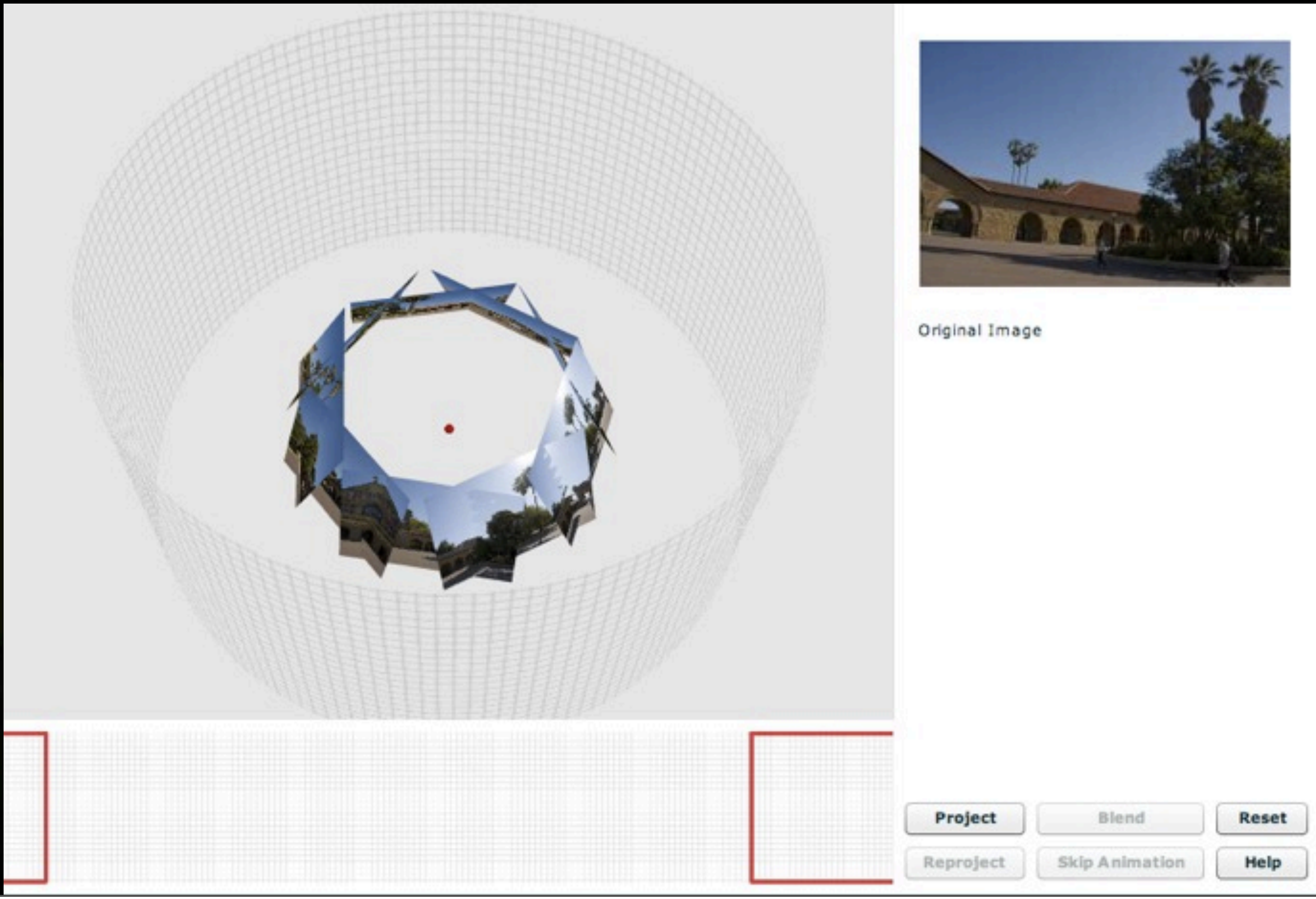
2nd reprojection to a plane for display



Imagine photographing the inside of a cylinder that is wallpapered with this panorama

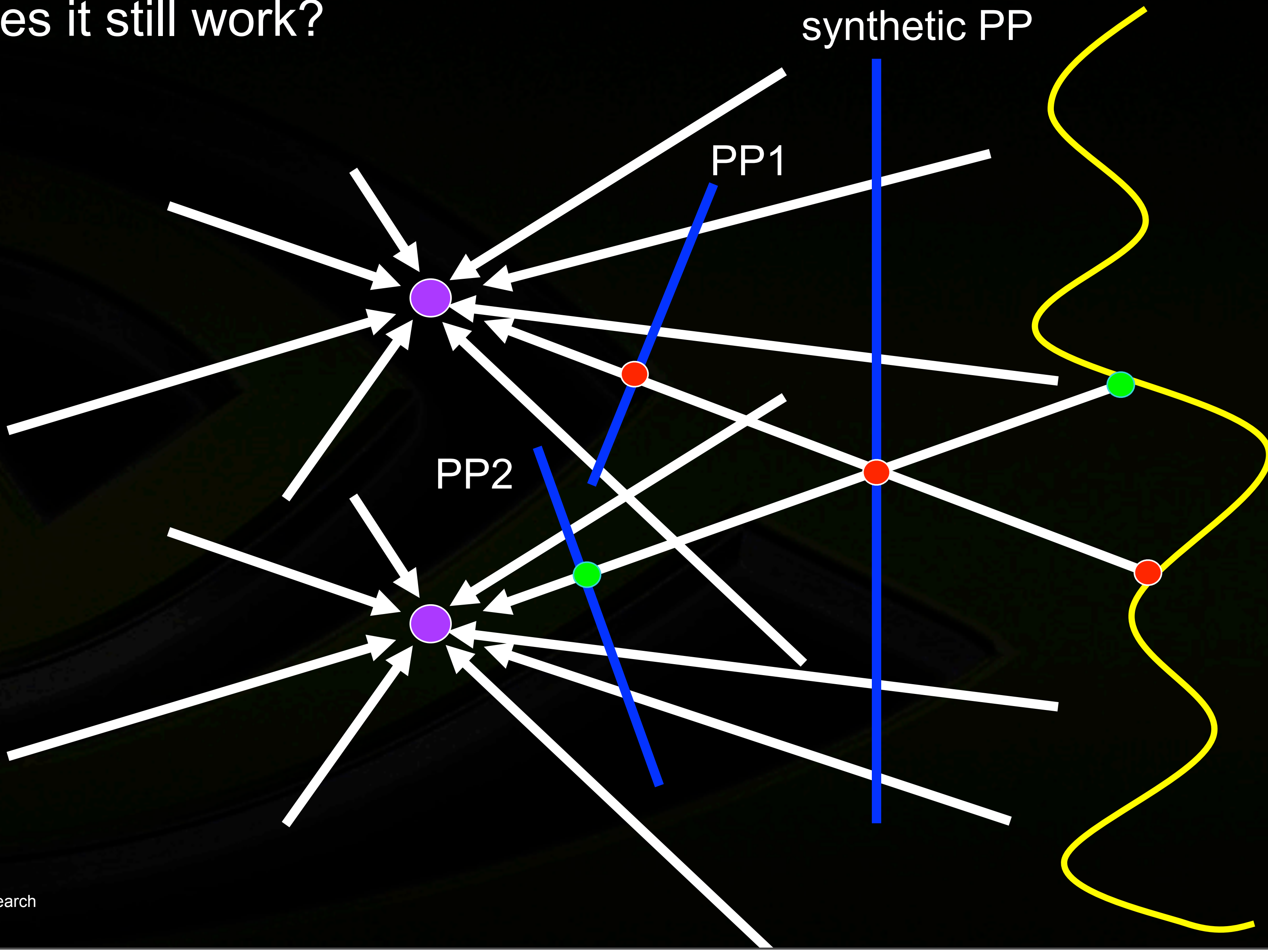
- if your FOV is narrow, your photo won't be too distorted

Demo http://graphics.stanford.edu/courses/cs178/applets/projection.html



Changing camera center

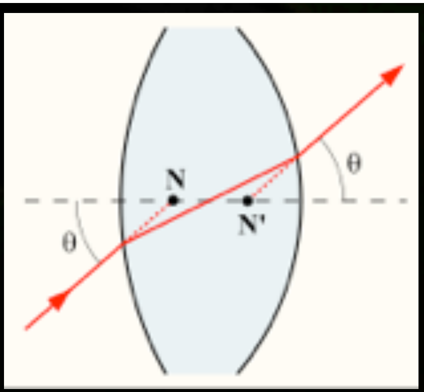
- Does it still work?



Where to rotate? Nodal point?

- http://www.reallyrightstuff.com/pano/index.html

If you aim a ray at one of the nodal points, it will be refracted by the lens so it appears to have come from the other,
and with the same angle with respect to the optical axis



Rotate around center of lens perspective

- Many instructions say rotate around the nodal point
  - wrong! http://toothwalker.org/optics/misconceptions.html#m6
- Correct: the entrance pupil
  - the optical image of the physical aperture stop as 'seen' through the front of the lens
  - due to the magnifying effect of the front lens, the entrance pupil's location is nearer than that of the physical aperture

Test for parallax

Figure 3. Configuration to reveal the presence or absence of parallax. The subject is first placed at the left side of the frame, and subsequently at the right side after rotation of the camera about a vertical axis with the help of a panoramic tripod head.

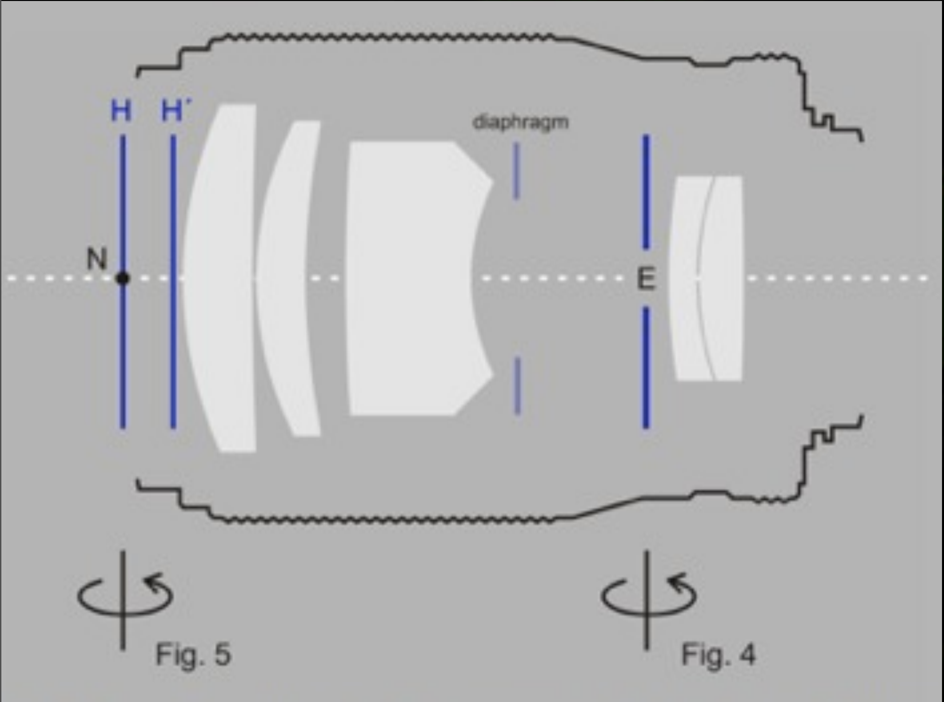


Figure 2. Diagram of a 135/2.8 lens with rotation axes through the front nodal point N and entrance pupil E.

http://toothwalker.org/optics/cop.html#stitchin

Correct center of rotation → no parallax

Figure 4. Rotation about an axis through the entrance pupil.

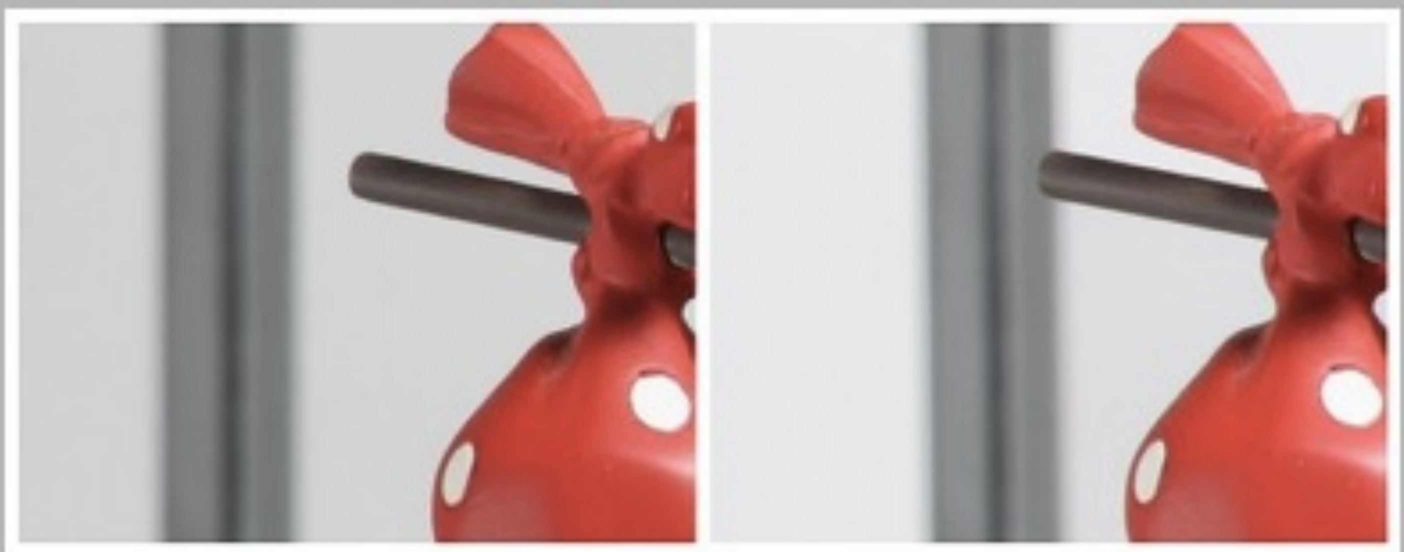
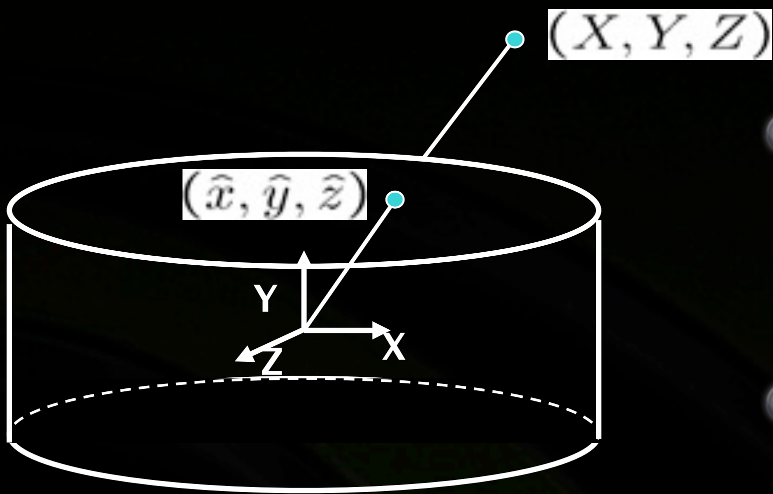
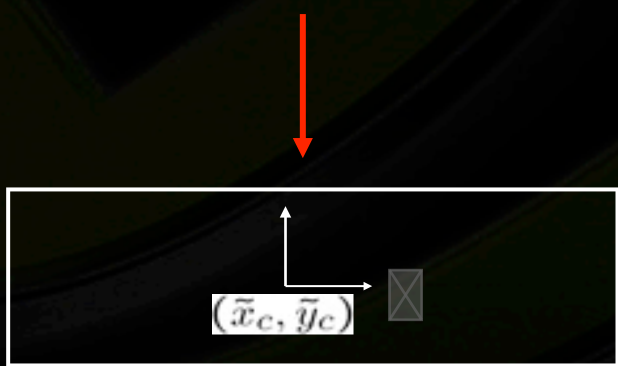


Figure 5. Rotation about an axis through the front nodal point.

Cylindrical projection



unit cylinder



unwrapped cylinder

- Map 3D point (X,Y,Z) onto cylinder

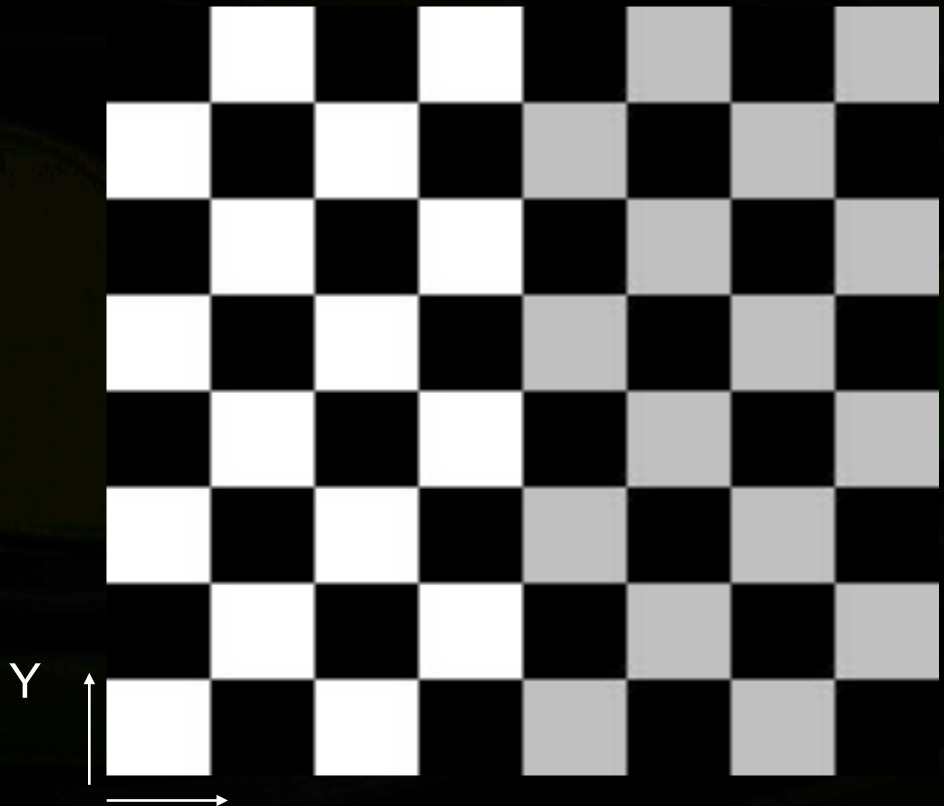
$$(\hat{x},\hat{y},\hat{z}) = \frac{1}{\sqrt{X^2+Z^2}}(X,Y,Z)$$

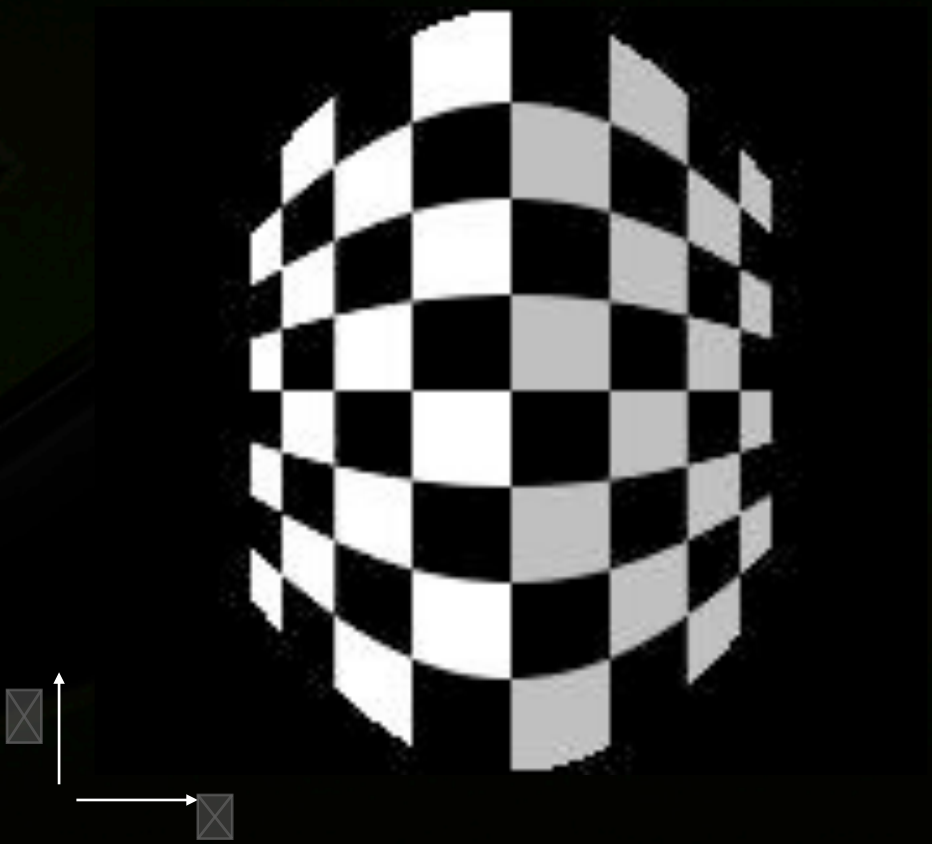
- Convert to coordinates on unit cylinder

- Conv $(sin\theta, h, cos\theta) = (\hat{x},\hat{y},\hat{z})$ es on unwrapped cylinder

$$(\tilde{x},\tilde{y}) = (f\theta, fh) + (\tilde{x}_c, \tilde{y}_c)$$

Cylindrical projection

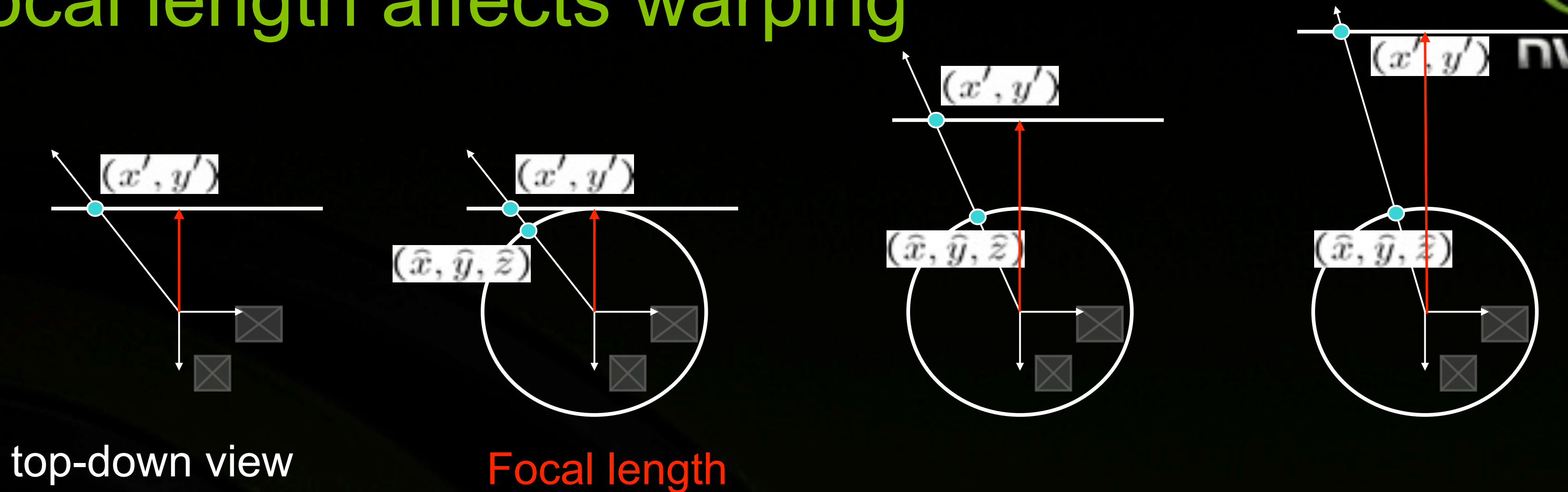




NVIDIA Research

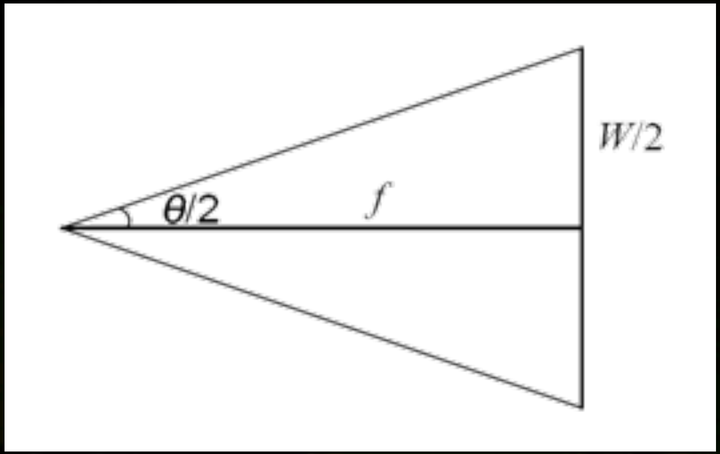
Wednesday, February 15, 12

Focal length affects warping



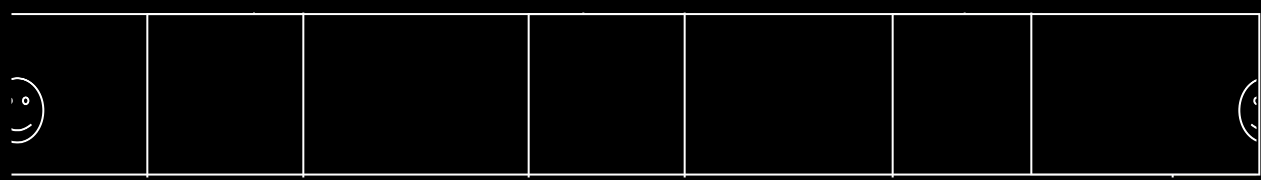
Focal length is (very!) camera dependent

- Can get a rough estimate by measuring the FOV:
  - if the sensor size is known…



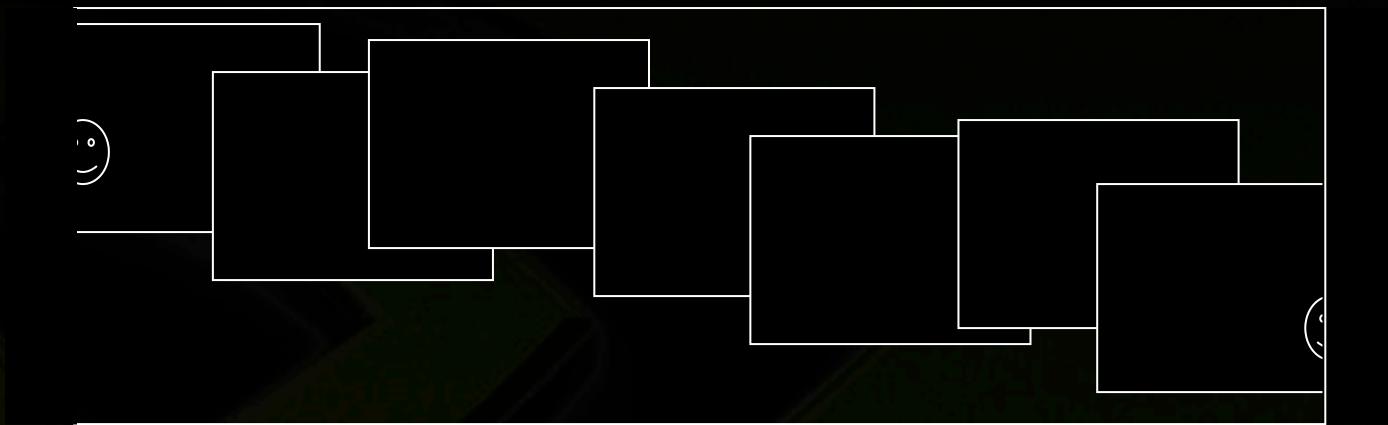
- Can use the EXIF tag
  - might not give the correct value
- Can use several images together
  - find *f* that makes them match
- Etc.

Assembling the panorama



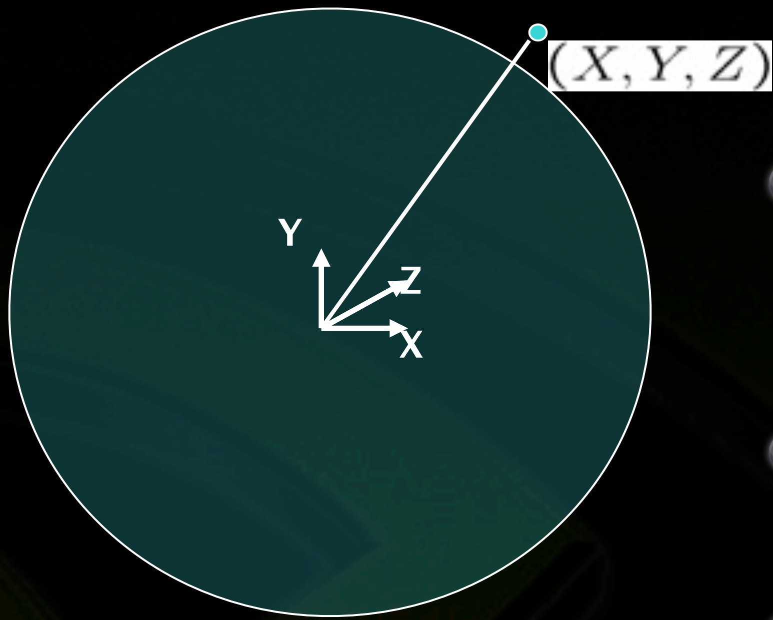
- Stitch pairs together, blend, then crop

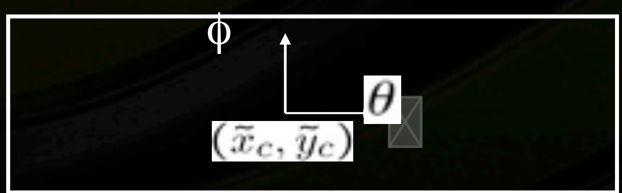
Problem: Drift



- Vertical Error accumulation
  - small (vertical) errors accumulate over time
  - apply correction so that sum = 0 (for 360° panorama)
- Horizontal Error accumulation
  - can reuse first/last image to find the right panorama radius

Spherical projection





unwrapped sphere

- Map 3D point (X,Y,Z) onto sphere

$$(\hat{x}, \hat{y}, \hat{z}) = \frac{1}{\sqrt{X^2 + Y^2 + Z^2}}(X, Y, Z)$$

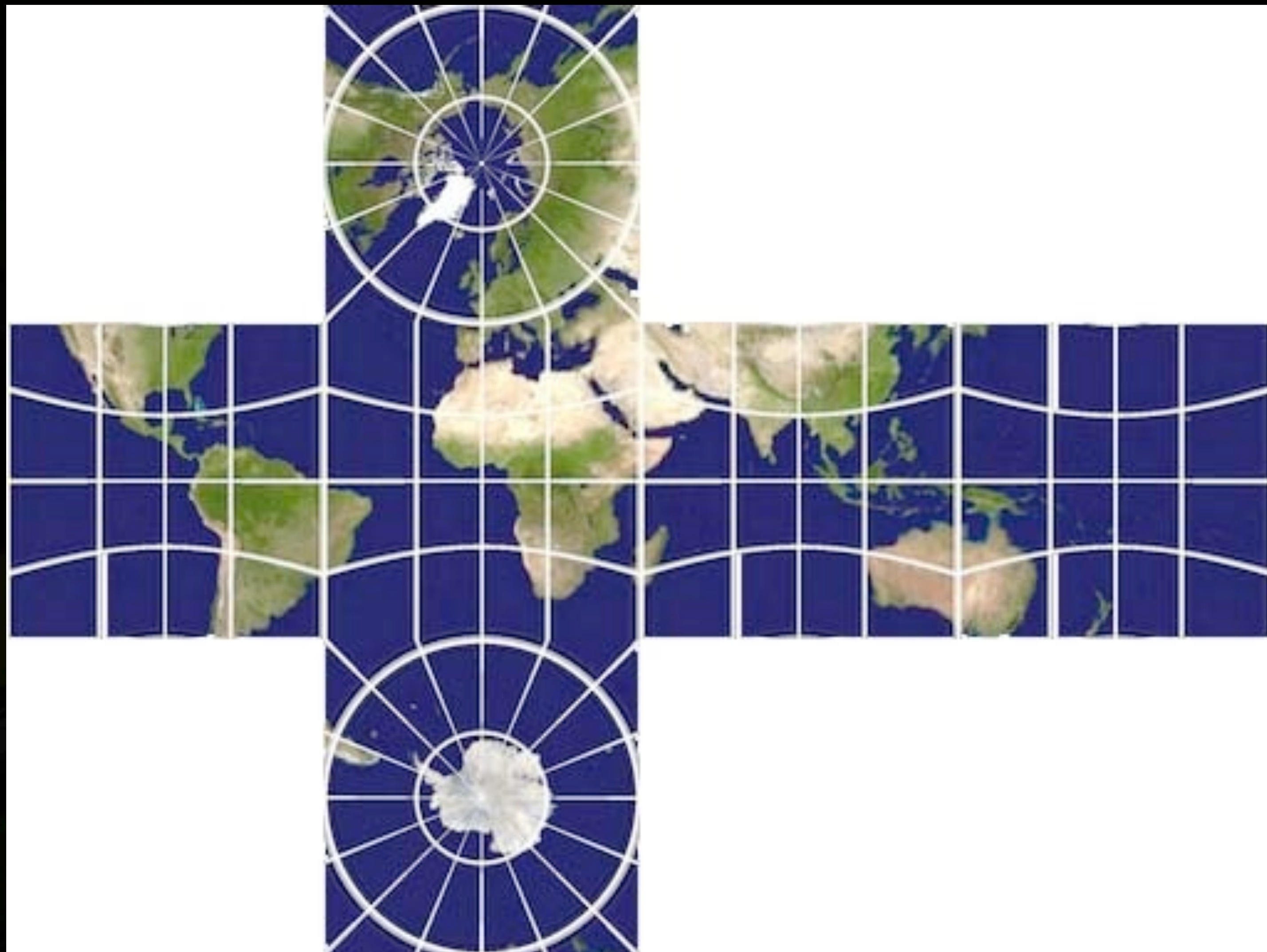
- Convert to spherical coordinates

$$(\sin\theta \cos\phi, \sin\phi, \cos\theta \cos\phi) = (\hat{x}, \hat{y}, \hat{z})$$

- Convert to spherical image coordinates

$$(\tilde{x}, \tilde{y}) = (f\theta, f\phi) + (\tilde{x}_c, \tilde{y}_c)$$

Spherical Projection



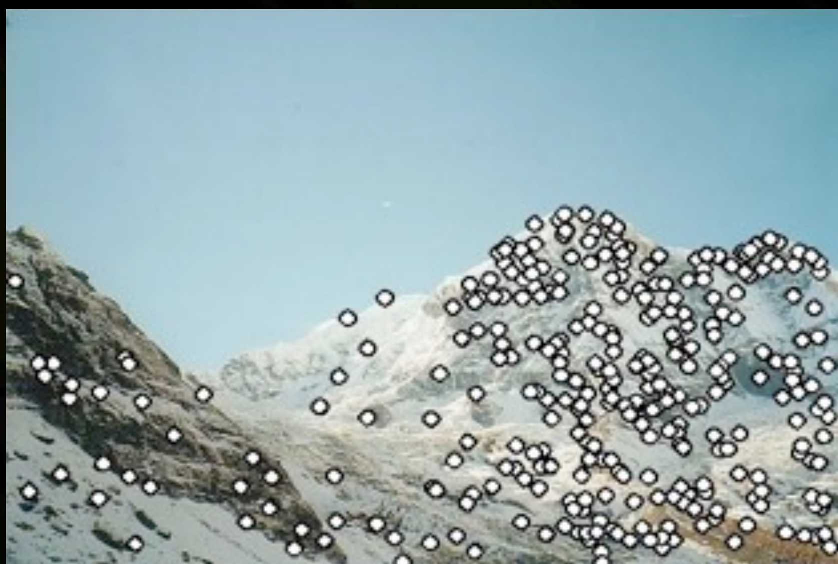
NVIDIA Research

Building a Panorama

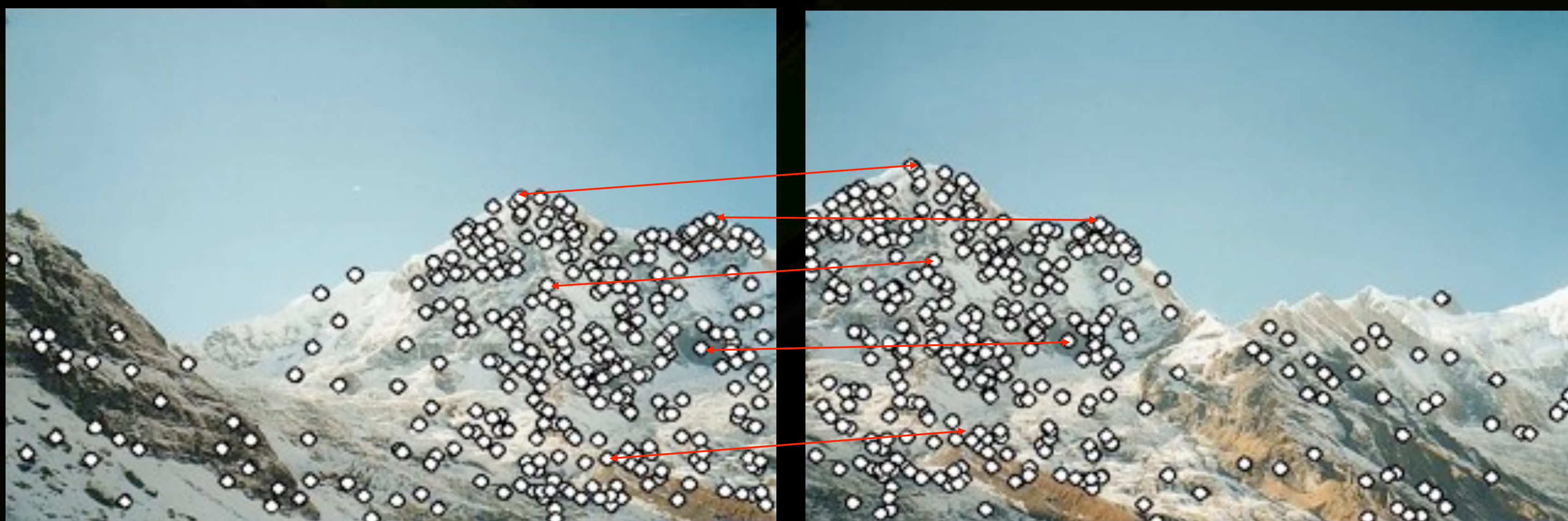
M. Brown and D. G. Lowe. Recognising Panoramas. ICCV 2003

We need to match (align) images


Detect feature points in both images



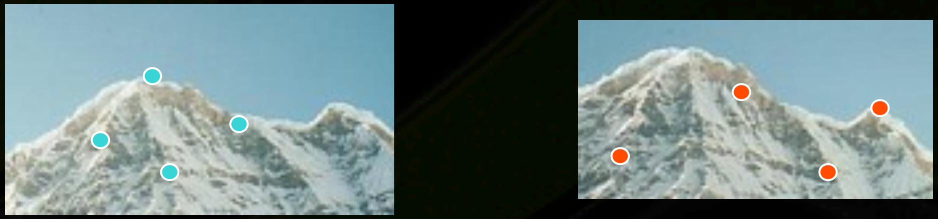
Find corresponding pairs



Use these pairs to align images

Matching with Features

- Problem 1:
  - Detect the *same* point *independently* in both images



no chance to match!

We need a repeatable detector

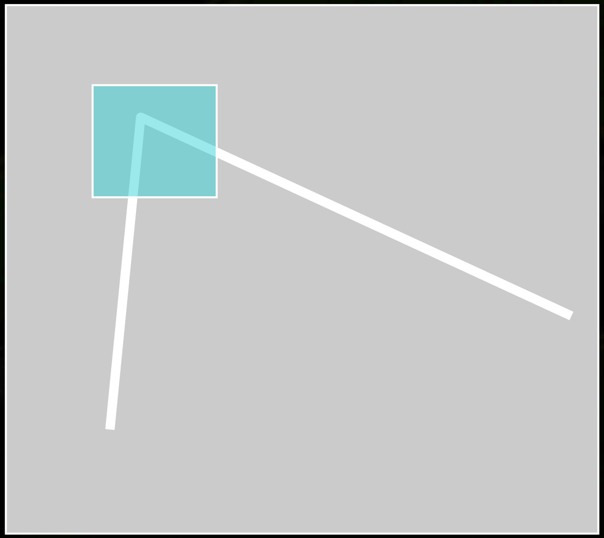
Matching with Features

- Problem 2:
  - For each point correctly recognize the corresponding one

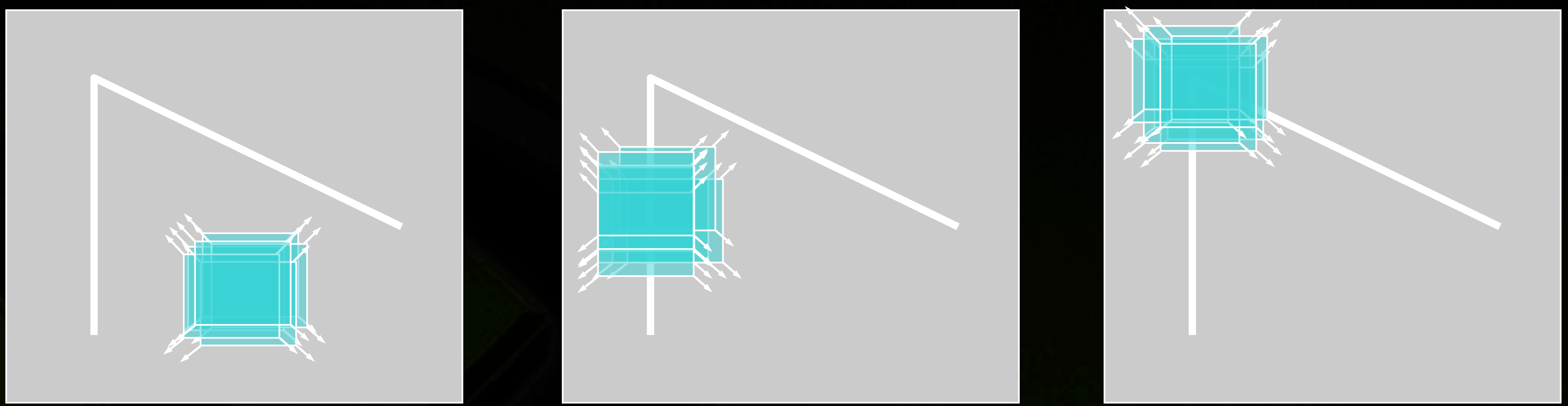
We need a reliable and distinctive descriptor

Harris Corners: The Basic Idea

- We should easily recognize the point by looking through a small window
- Shifting a window in any direction should give a large change in intensity



Harris Detector: Basic Idea



"flat" region:
no change in all directions

"edge":
no change along the edge direction

"corner":
significant change in all directions

Harris Detector: Mathematics

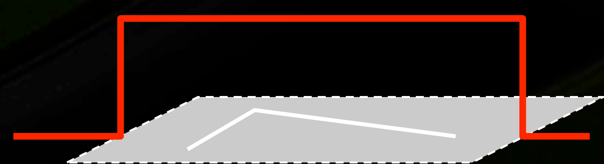
NVIDIA

Window-averaged change of intensity for the shift [u,v]:

$$E(u,v) = \sum_{x,y} w(x,y)\left[I(x+u,y+v) - I(x,y)\right]^2$$

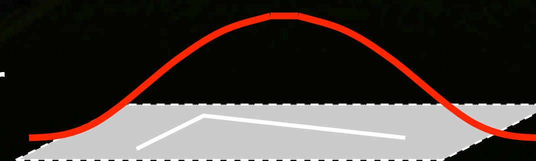
Window function — Shifted intensity — Intensity

Window function $w(x,y)$ =



1 in window, 0 outside

or



Gaussian

Harris Detector: Mathematics

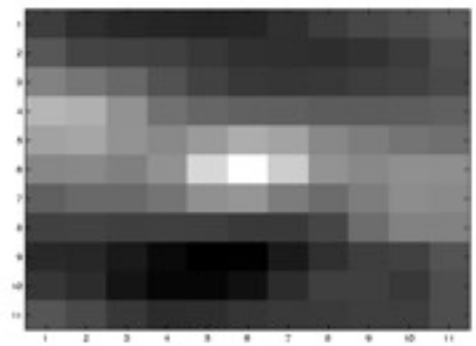
Expanding E(u,v) in a 2nd order Taylor series expansion, we have, for small shifts [u,v], a bilinear approximation:

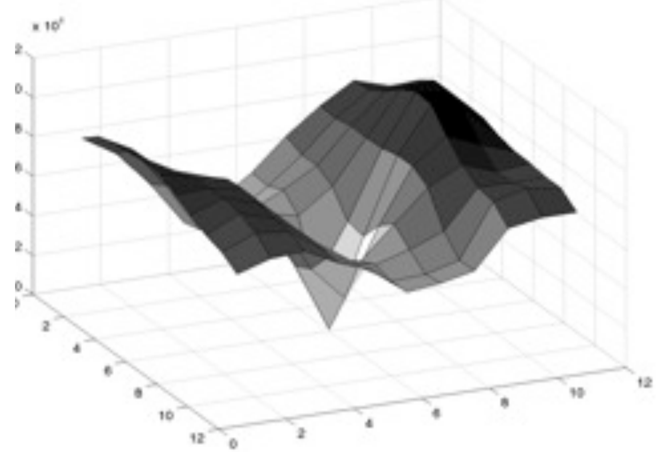
$$E(u,v) \cong [u,v] \; M \begin{bmatrix} u \\ v \end{bmatrix}$$

where M is a 2×2 matrix computed from image derivatives:

$$M = \sum_{x,y} w(x,y) \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$

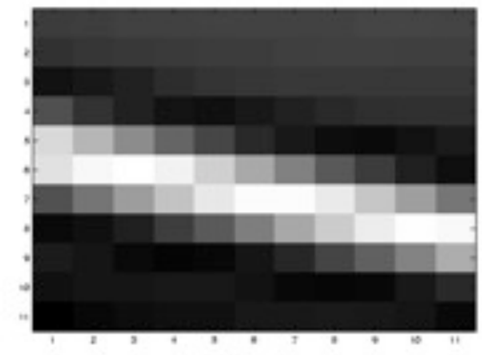
Eigenvalues λ_1, λ_2 of M at different locations

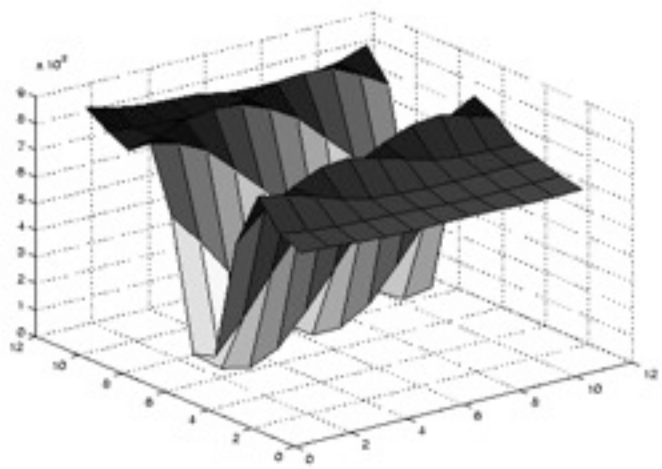




λ_1 and λ_2 are large

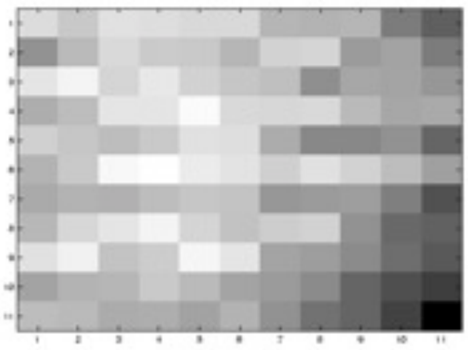
Eigenvalues λ_1, λ_2 of M at different locations

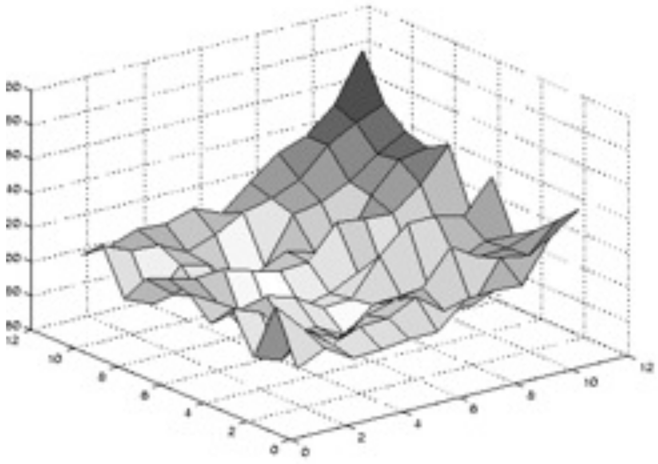




large λ_1, small λ_2

Eigenvalues λ_1, λ_2 of M at different locations

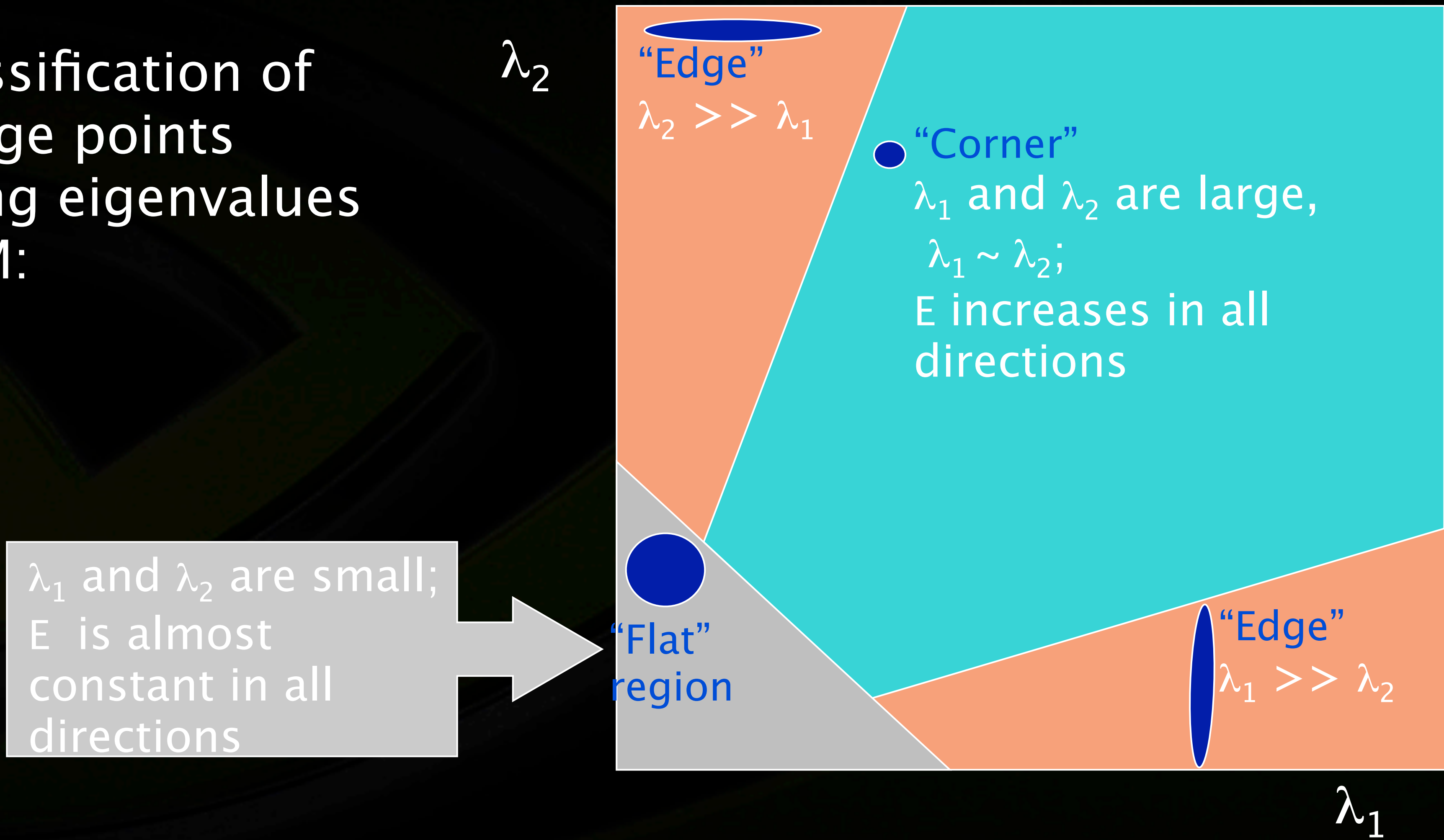




small λ_1, small λ_2

Harris Detector: Mathematics

Classification of image points using eigenvalues of M:



Harris Detector: Mathematics

$$M = \sum_{x,y} w(x,y) \begin{bmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{bmatrix}$$

Measure of corner response:

$$R = \det M - k\left(\operatorname{trace} M\right)^2$$

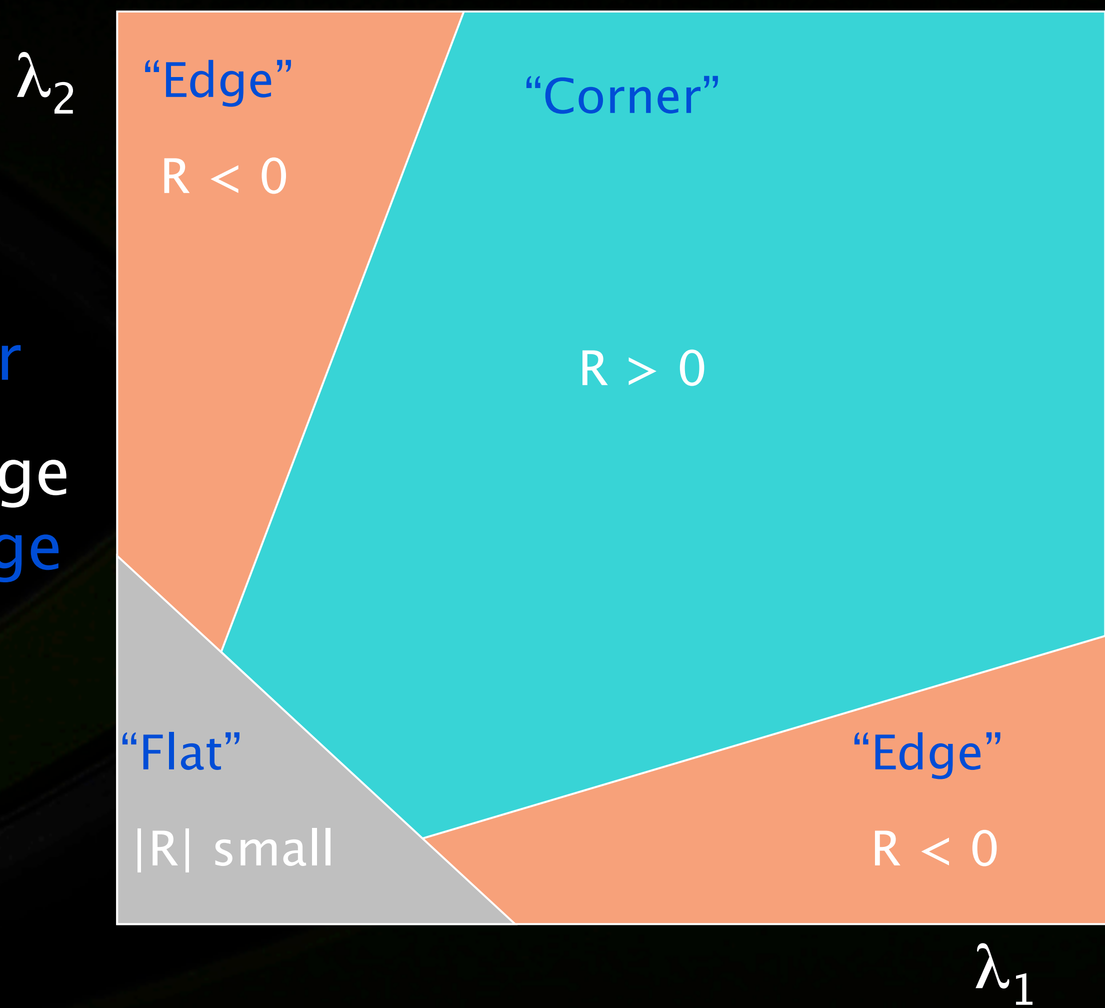
$$\det M = \lambda_1 \lambda_2$$

$$\operatorname{trace} M = \lambda_1 + \lambda_2$$

(k – empirical constant, k = 0.04 - 0.06)

Harris Detector: Mathematics

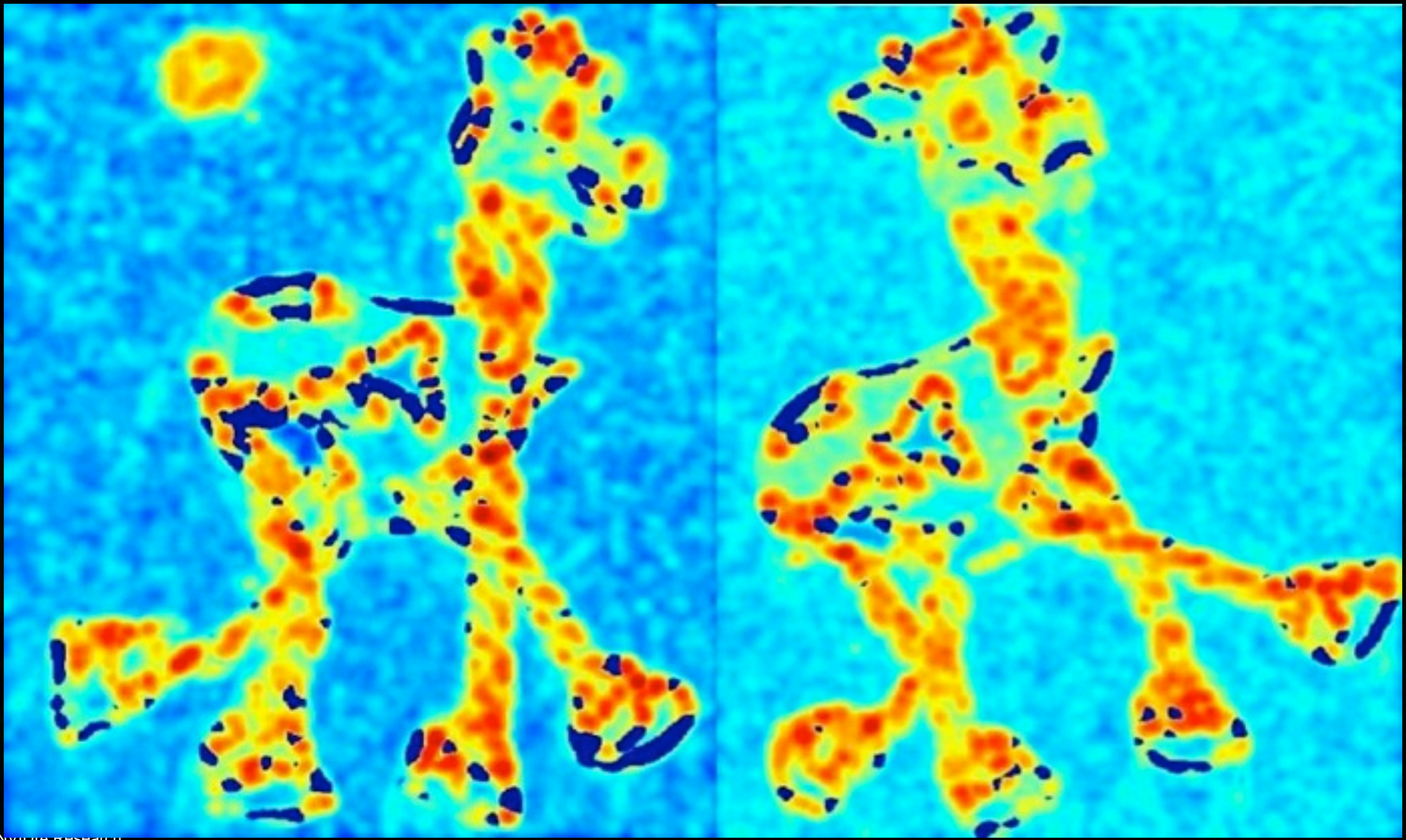
- R depends only on eigenvalues of M
- R is large for a corner
- R is negative with large magnitude for an edge
- |R| is small for a flat region



Harris Detector: Workflow

Harris Detector: Workflow

Compute corner response R



Harris Detector: Workflow

Find points with large corner response: $R >$ threshold

Harris Detector: Workflow

Take only the points of local maxima of R

Harris Detector: Workflow

Harris Detector: Summary

- Average intensity change in direction $[u,v]$ can be expressed as a bilinear form:

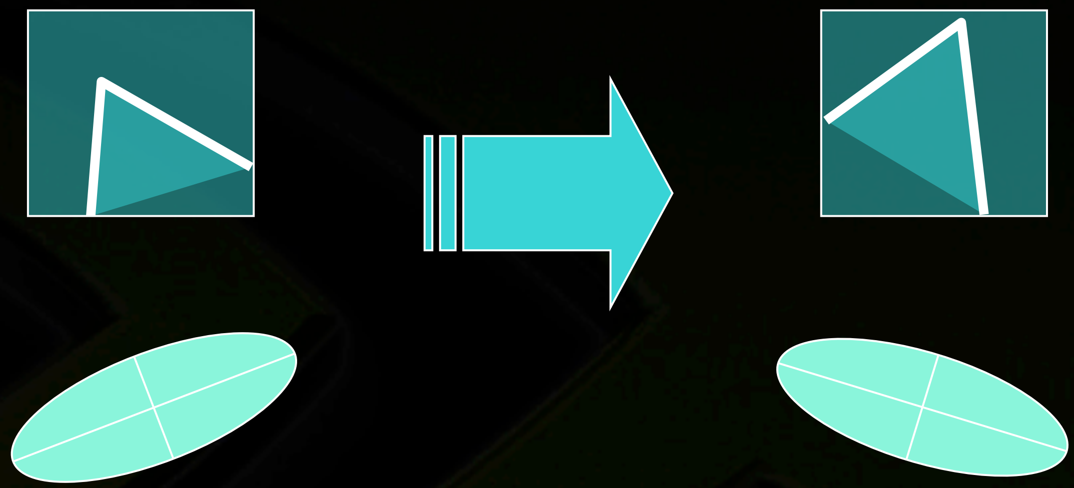
$$E(u,v) \cong [u,v] \; M \begin{bmatrix} u \\ v \end{bmatrix}$$

- Describe a point in terms of eigenvalues of M: *measure of corner response*

$$R = \lambda_1 \lambda_2 - k\left(\lambda_1 + \lambda_2\right)^2$$

- A good (corner) point should have a *large intensity change* in *all directions*, i.e., R should be large positive

Harris Detector: Invariant to rotation

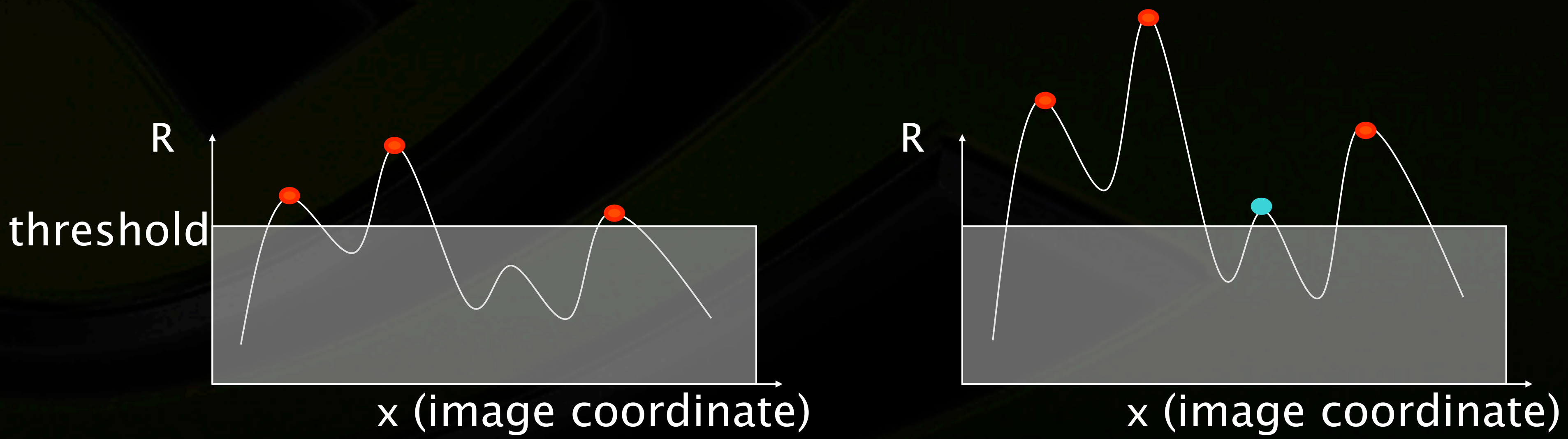


Ellipse rotates
but its shape (i.e., eigenvalues) remains the same

Corner response R is invariant to image rotation

Almost invariant to intensity change

- Partial invariance
  - ✓ Only derivatives are used
    =>
    invariance to intensity shift $I \rightarrow I + b$
  - ✓ Intensity scale: $I \rightarrow a\,I$



Not invariant to image scale!

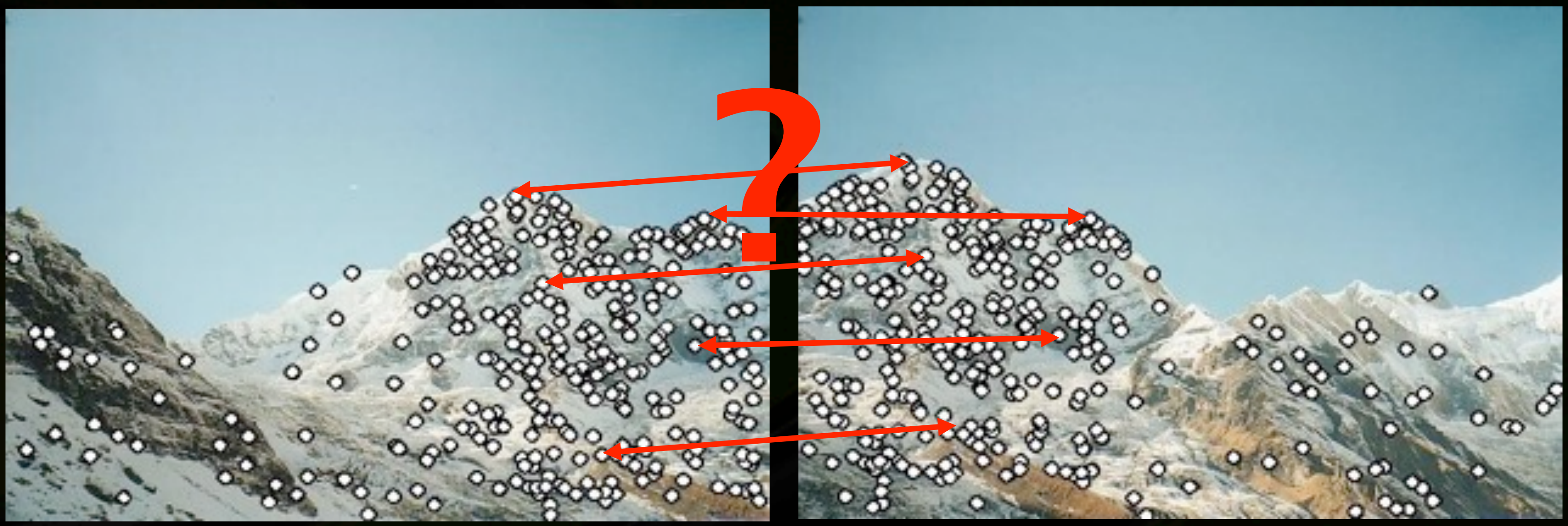
All points will be classified as edges

Corner !

Point Descriptors

- We know how to detect points
- Next question:

How to match them?



Point descriptor should be:

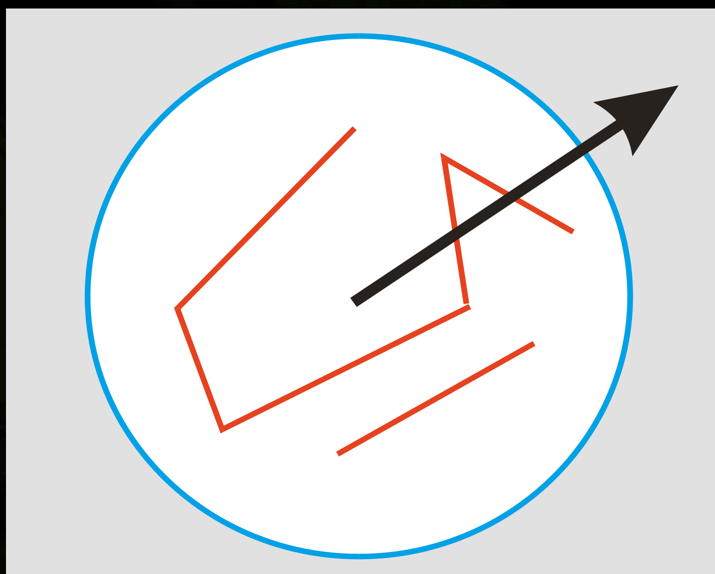
1. Invariant
2. Distinctive

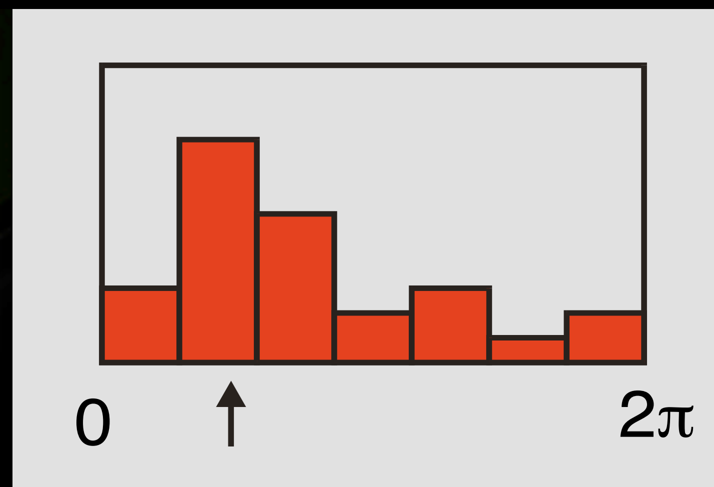
SIFT – Scale Invariant Feature Transform

Figure 12: The training images for two objects are shown on the left. These can be recognized in a cluttered image with extensive occlusion, shown in the middle. The results of recognition are shown on the right. A parallelogram is drawn around each recognized object showing the boundaries of the original training image under the affi ne transformation solved for during recognition. Smaller squares indicate the keypoints that were used for recognition.

SIFT – Scale Invariant Feature Transform

- Descriptor overview:
  - Determine scale (by maximizing DoG in scale and in space), local orientation as the dominant gradient direction
  - Use this scale and orientation to make all further computations invariant to scale and rotation

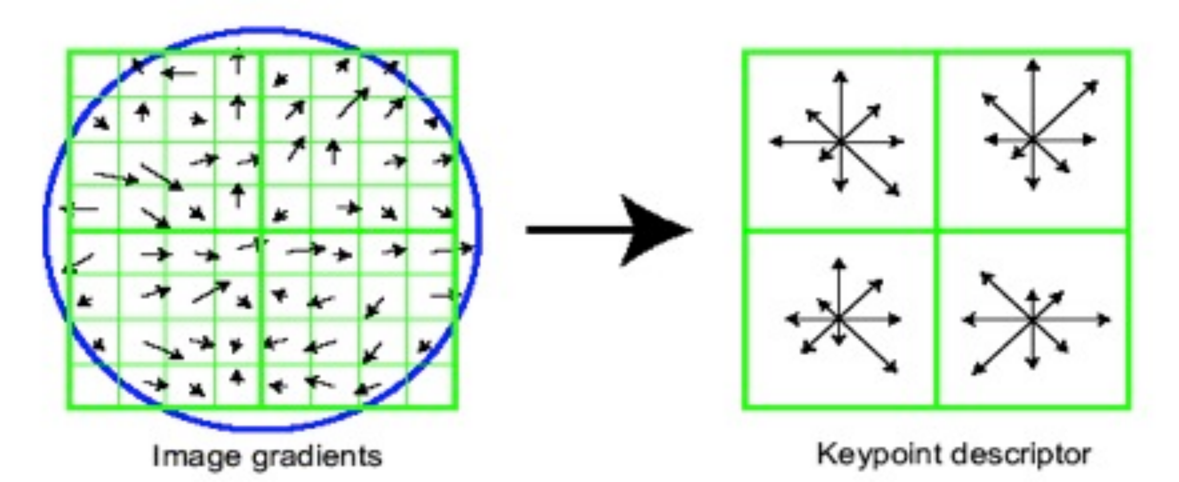




D. Lowe. “Distinctive Image Features from Scale-Invariant Keypoints” IJCV 2004

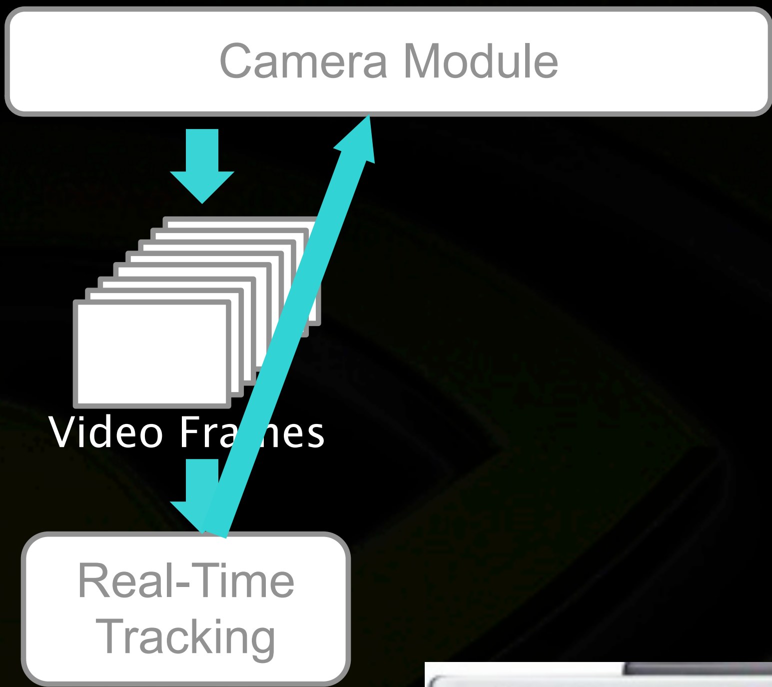
SIFT – Scale Invariant Feature Transform

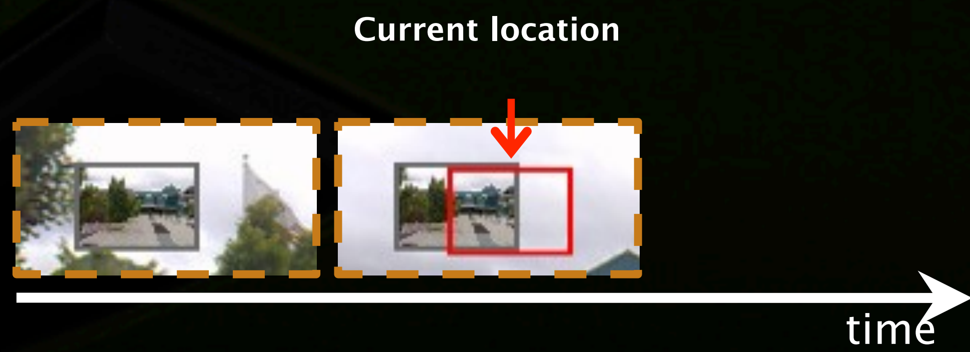
- Descriptor overview:
  - Determine scale (by maximizing DoG in scale and in space), local orientation as the dominant gradient direction
  - Use this scale and orientation to make all further computations invariant to scale and rotation
  - Compute gradient orientation histograms of several small windows (128 values for each point)
  - Normalize the descriptor to make it invariant to intensity change



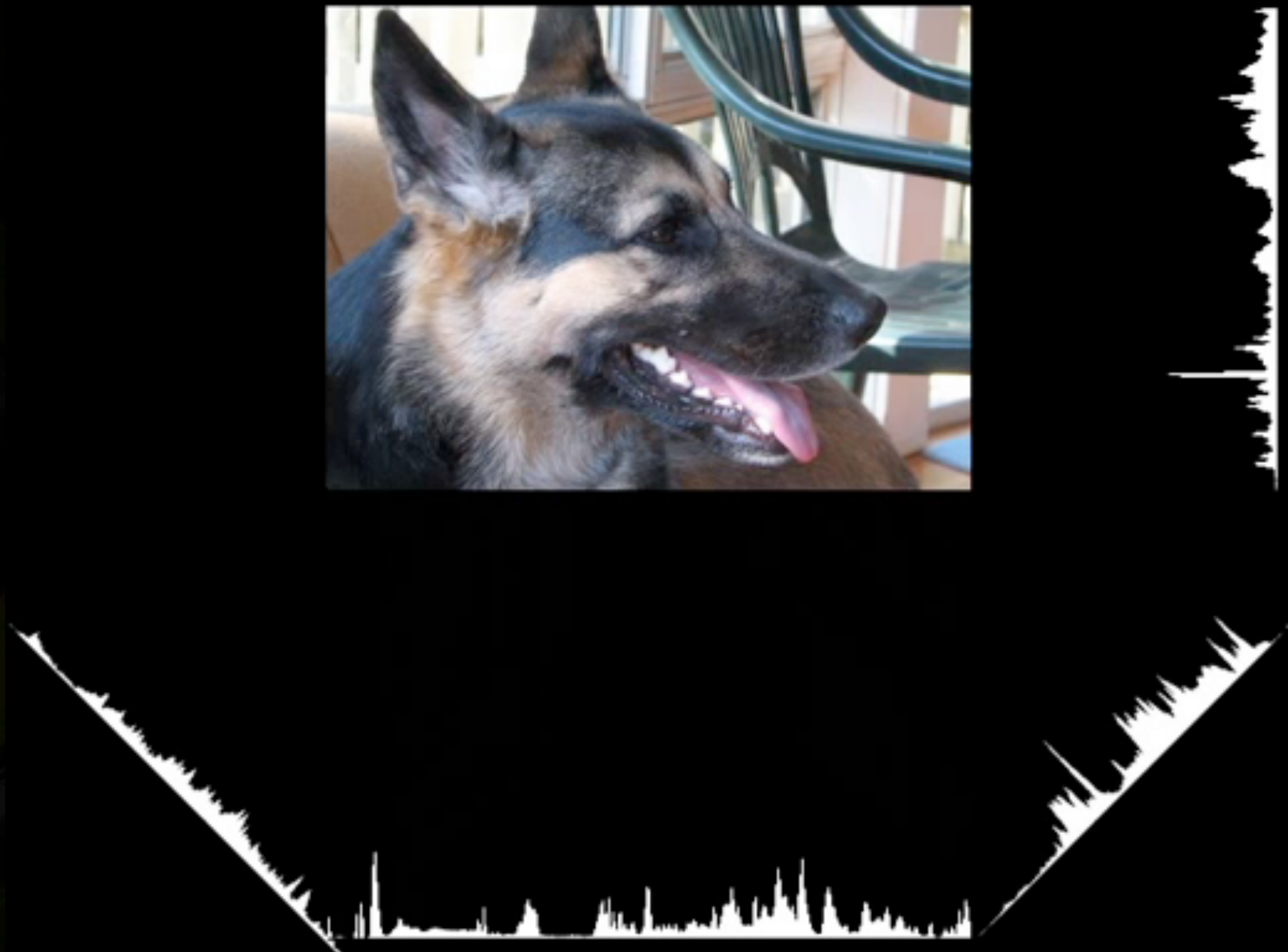
D. Lowe. "Distinctive Image Features from Scale-Invariant Keypoints" IJCV 2004

Registration in practice: tracking





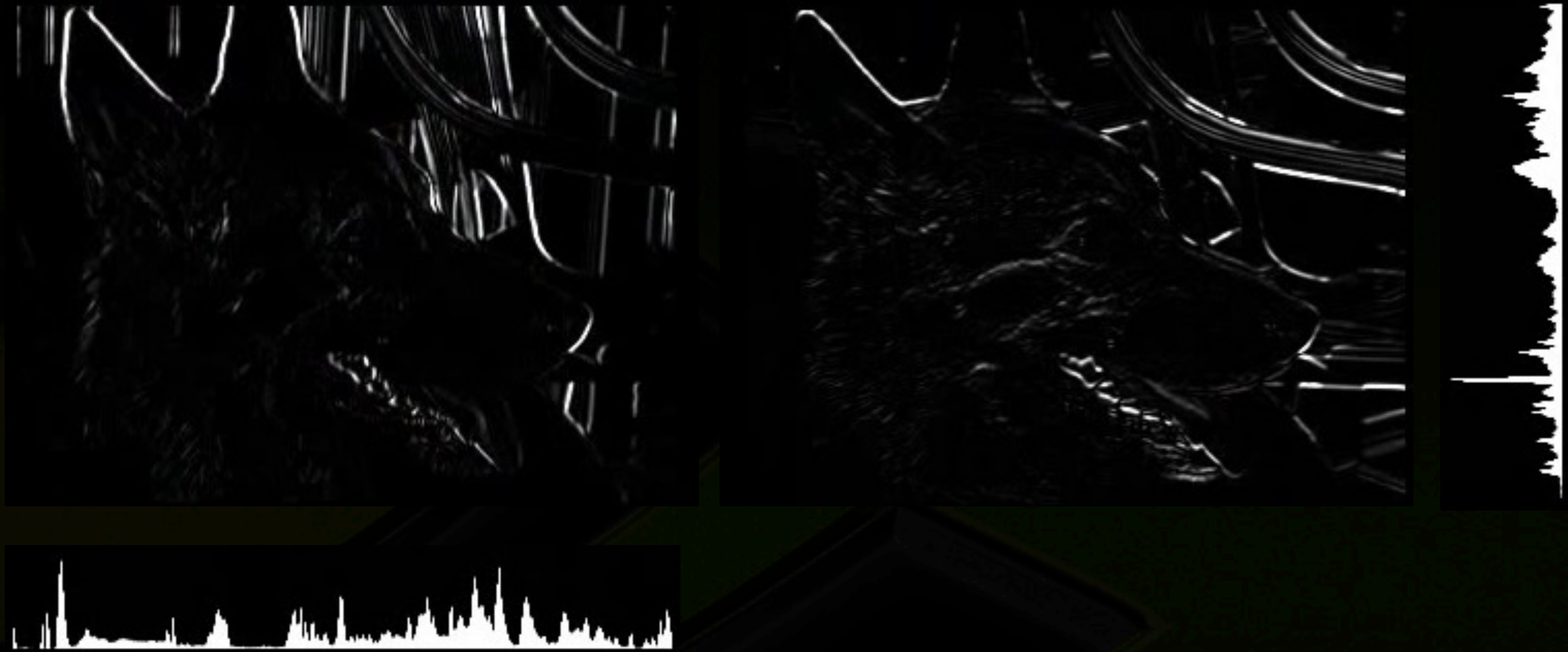
Viewfinder alignment for tracking



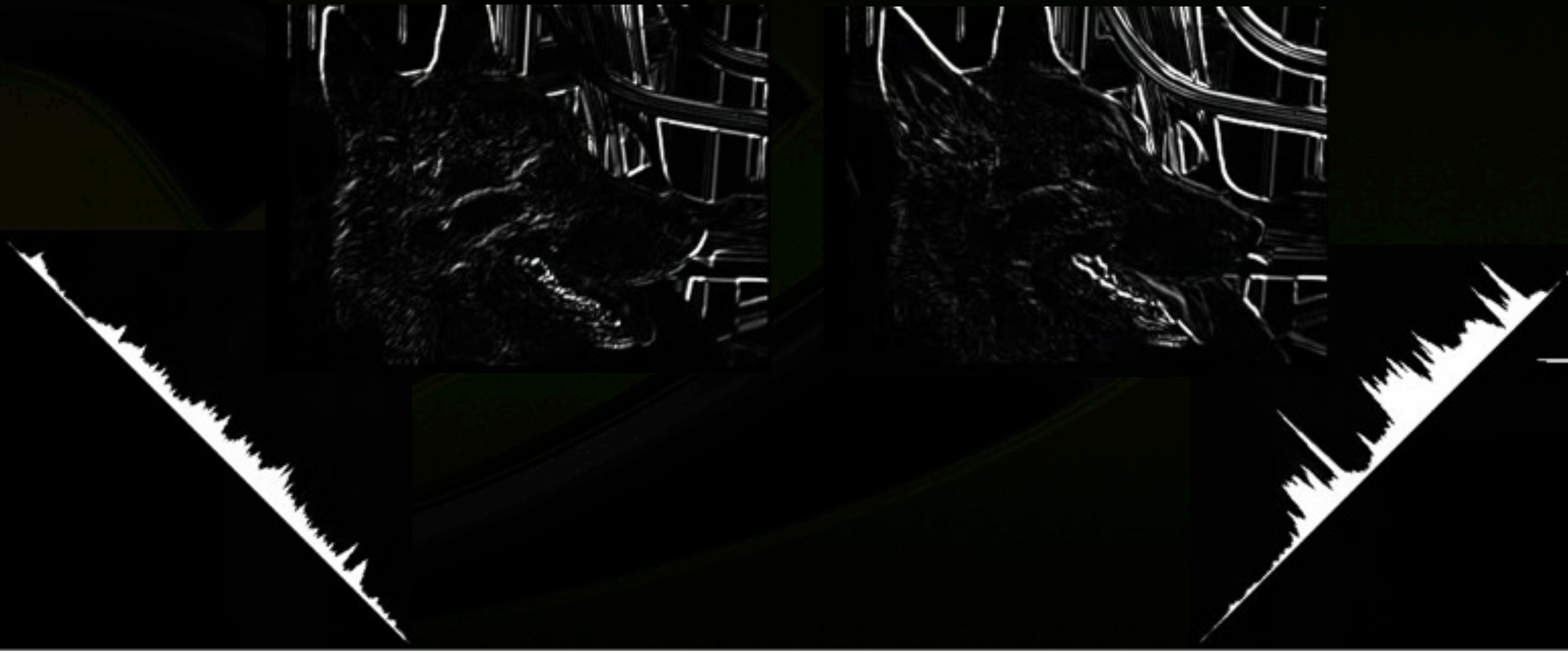
Andrew Adams, Natasha Gelfand, Kari Pulli
Viewfinder Alignment
Eurographics 2008

http://graphics.stanford.edu/papers/viewfinderalignment/

Project gradients along columns and rows



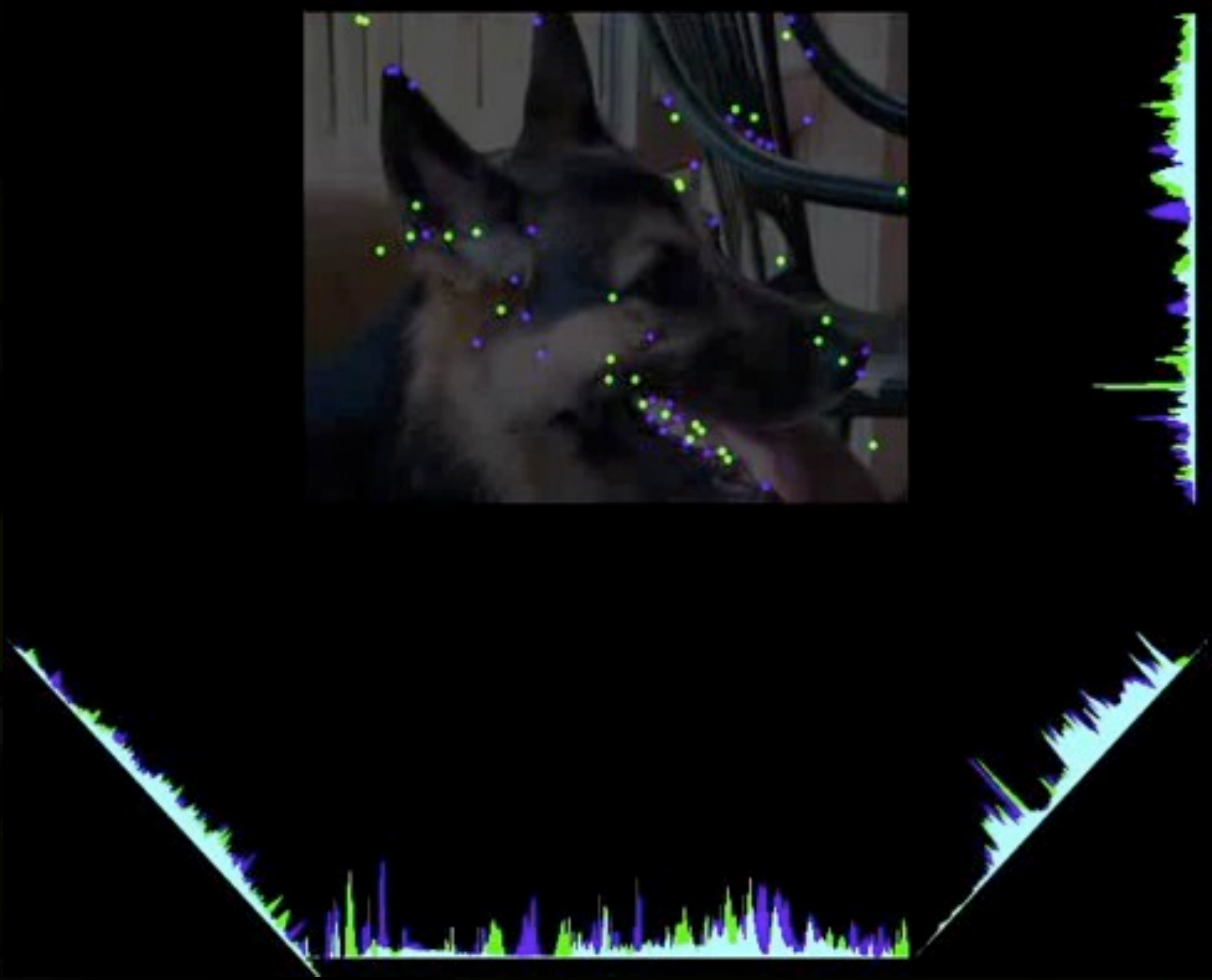
… diagonal gradients along diagonals …



… and find corners

NVIDIA Research

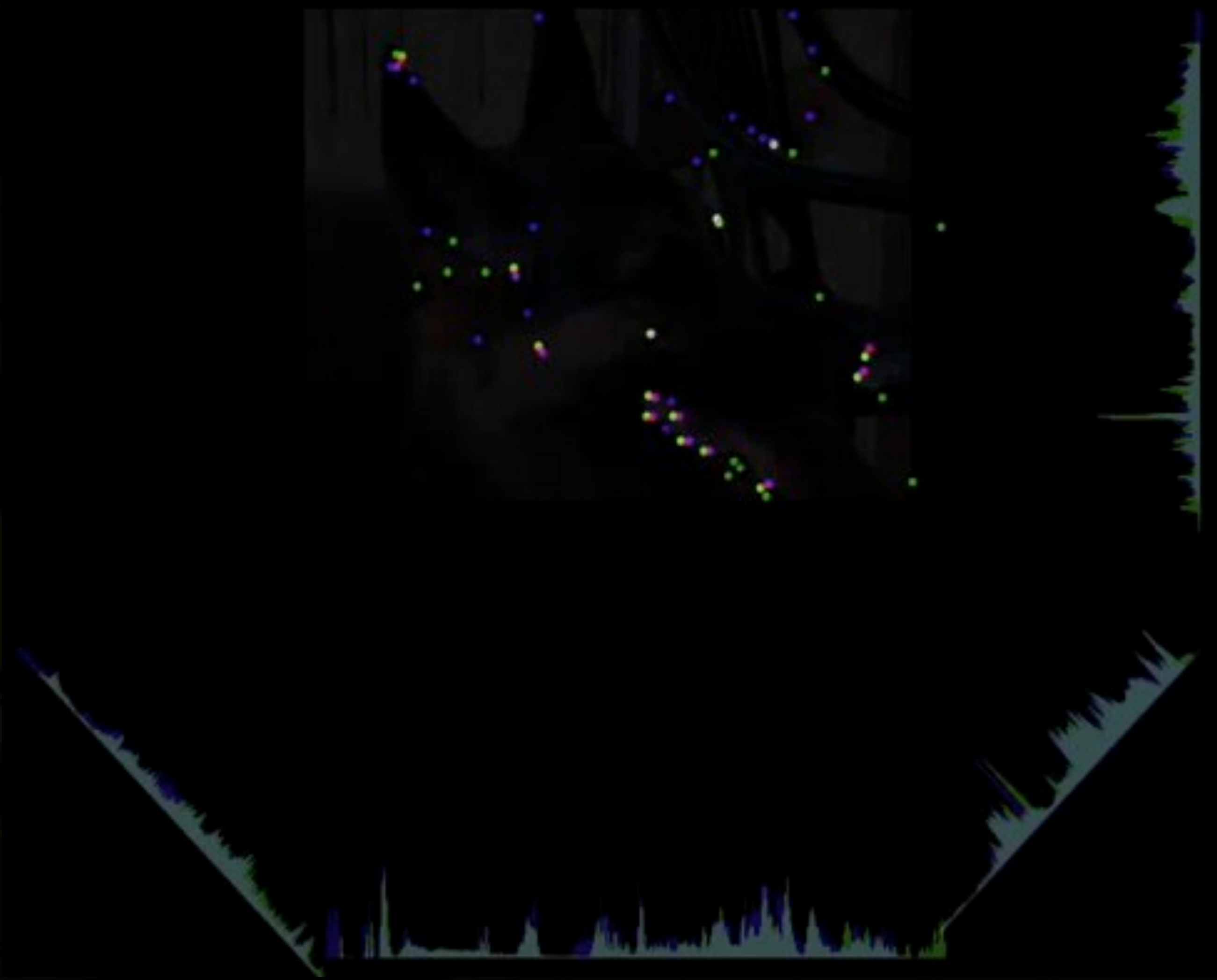
Overlap and match the gradient projections



NVIDIA Research

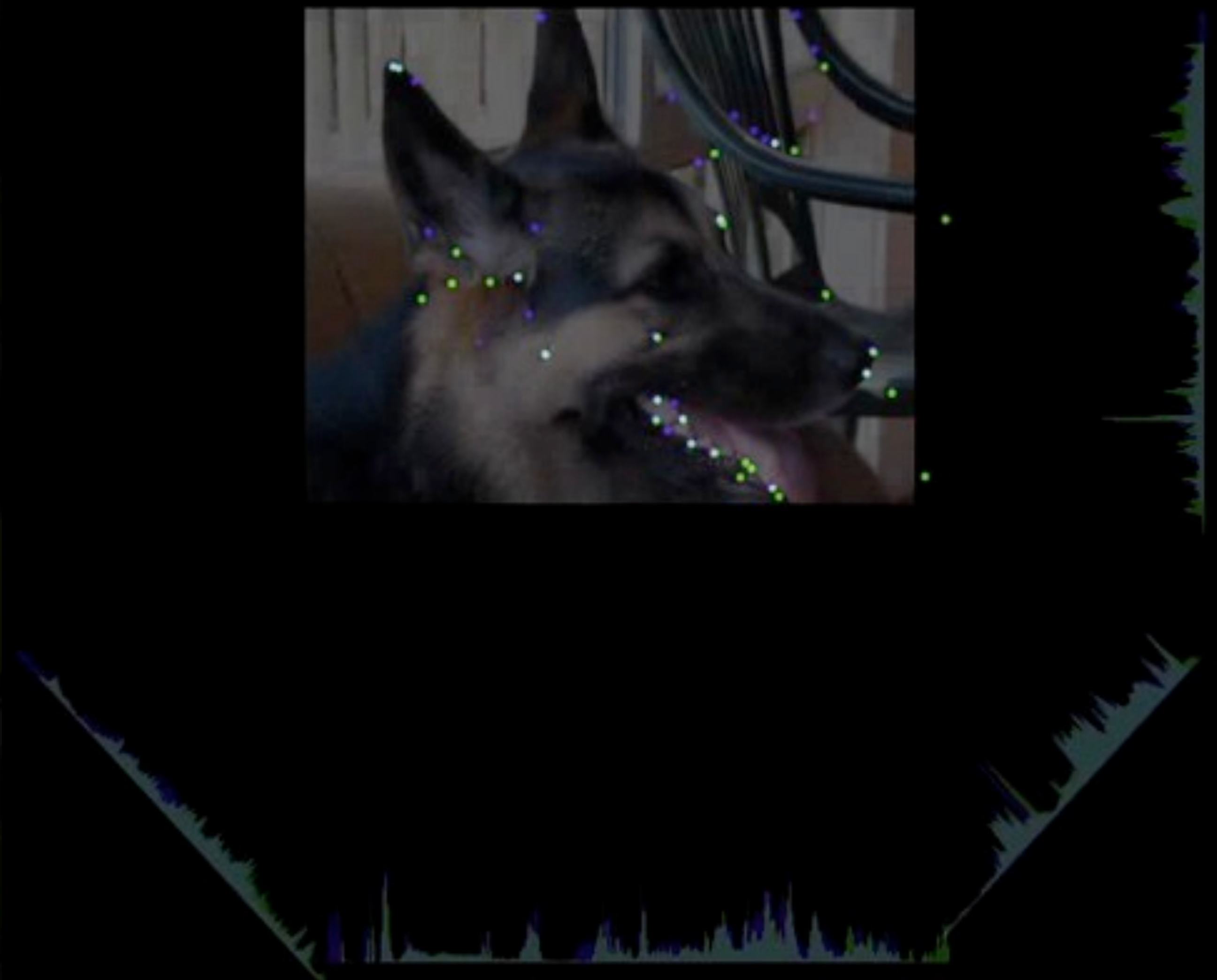
Wednesday, February 15, 12

Apply the best translation to corners

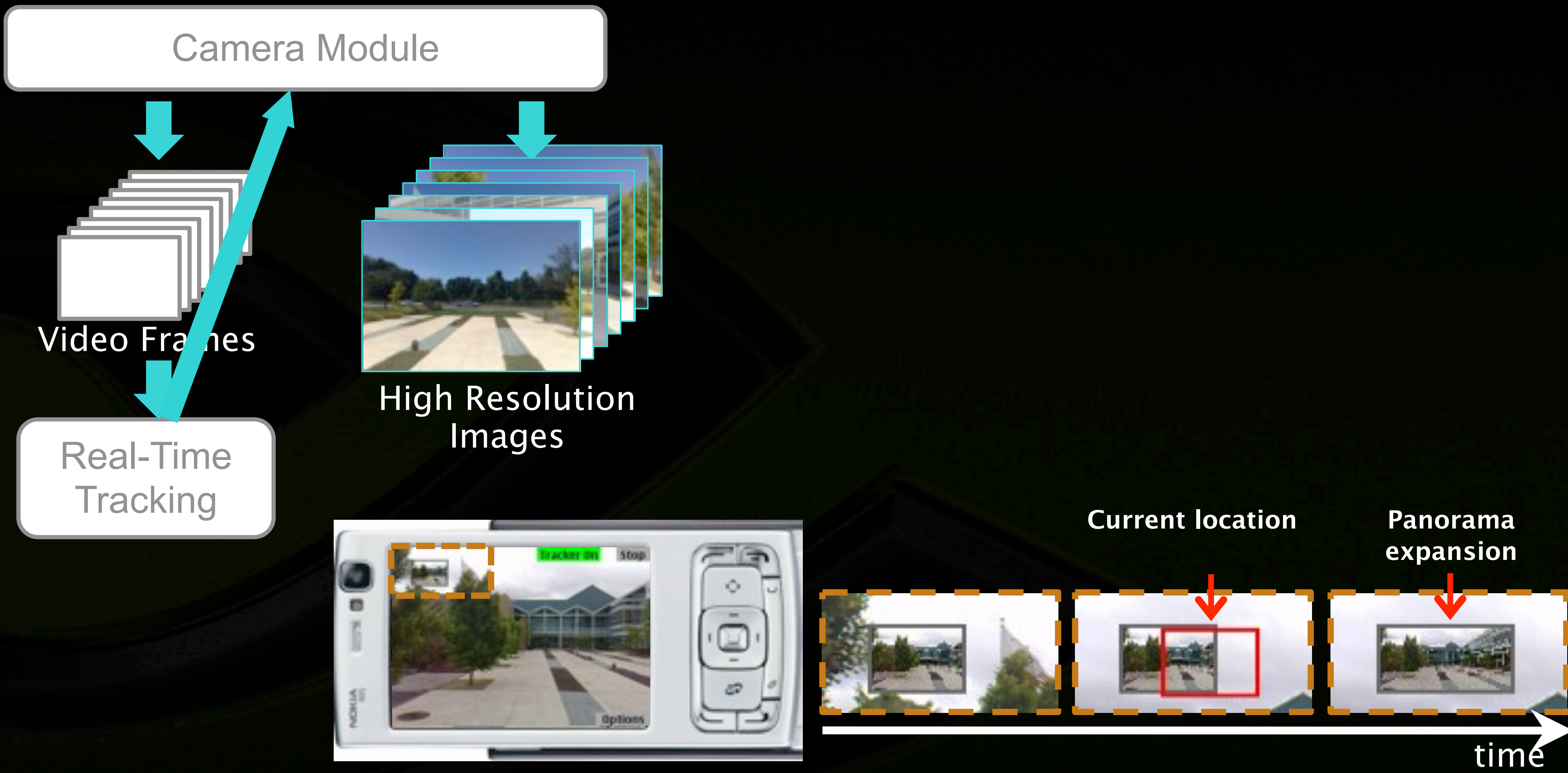


NVIDIA Research

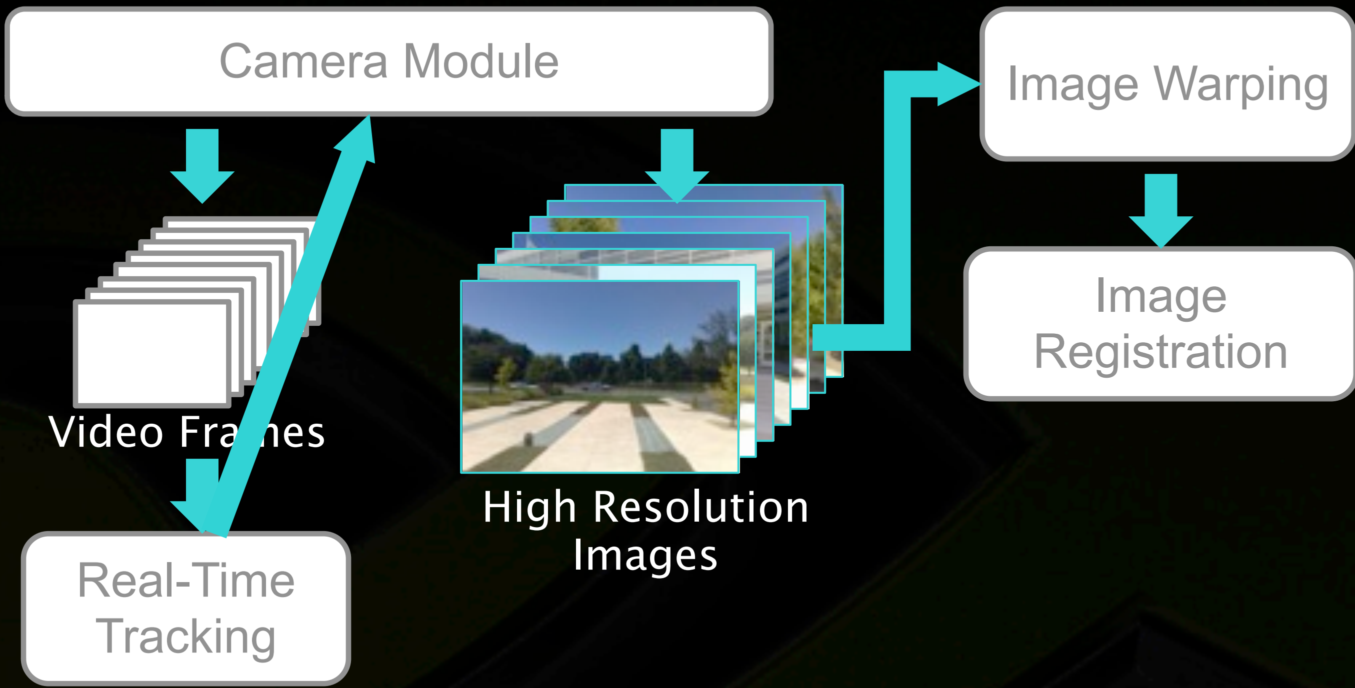
Match corners, refine translation & rotation



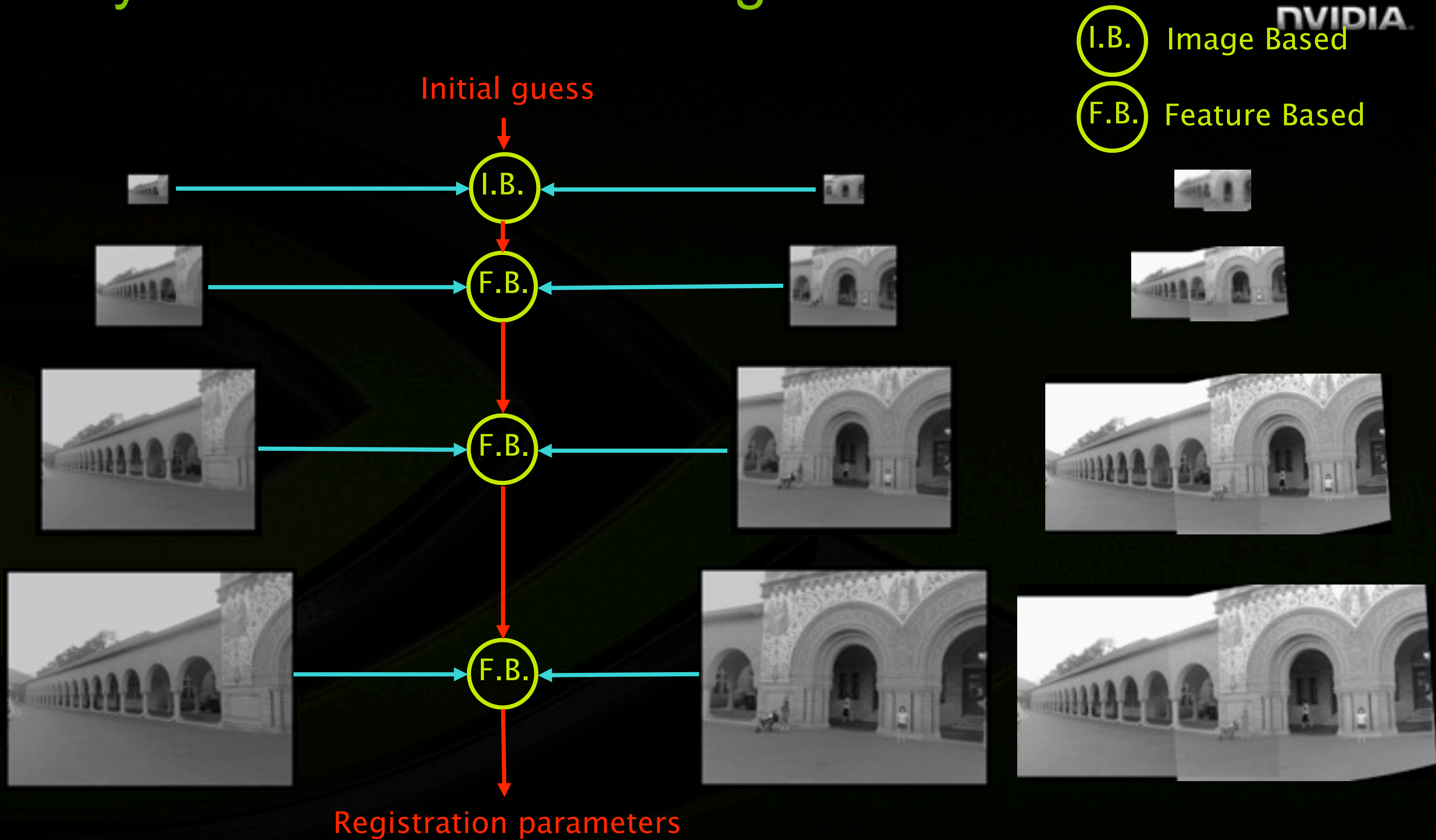
System Overview



System Overview



Hybrid multi-resolution registration



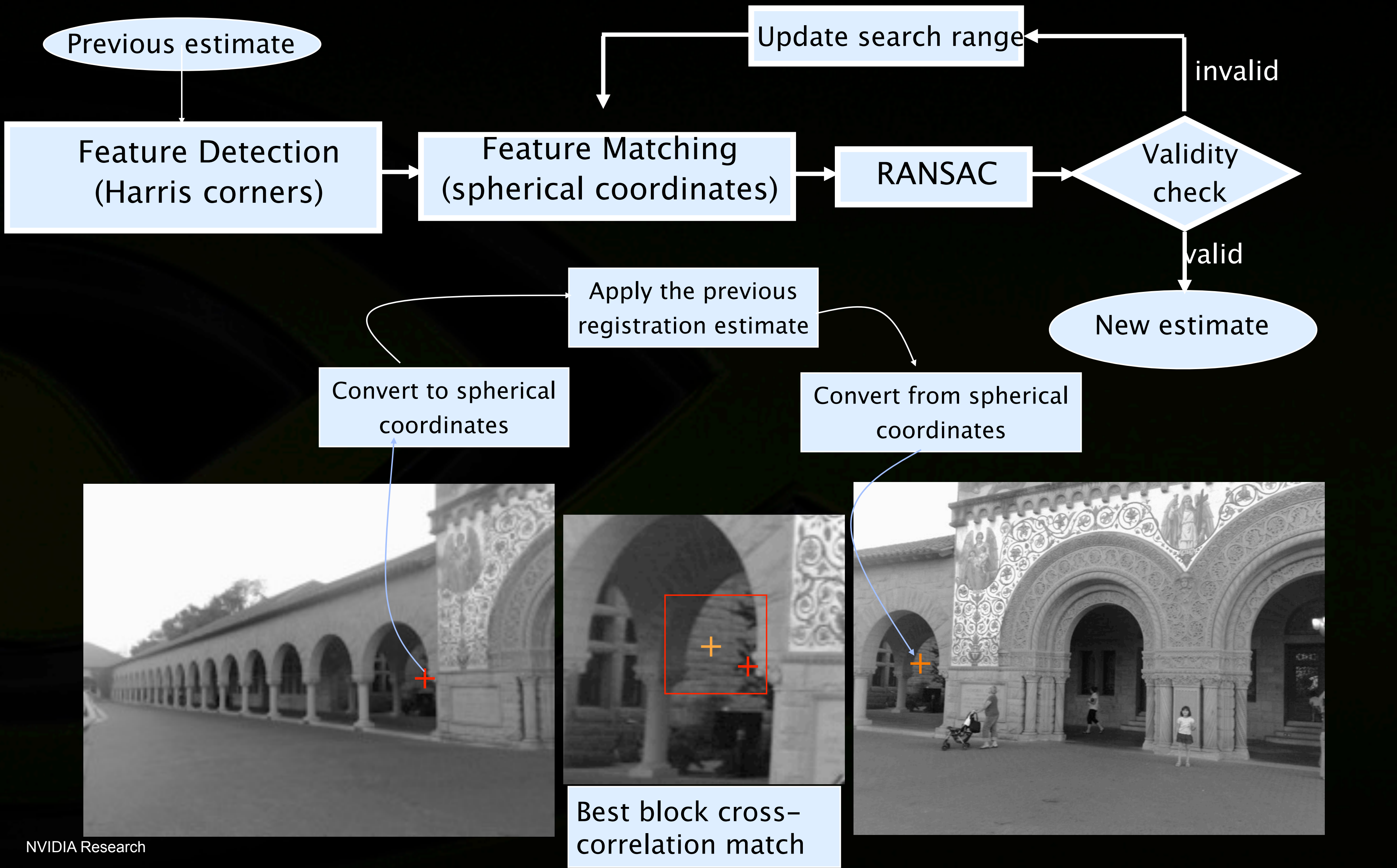
K. Pulli, M. Tico, Y. Xiong, X. Wang, C-K. Liang, “Panoramic Imaging System for Camera Phones”, ICCE 2010

Progression of multi-resolution registration

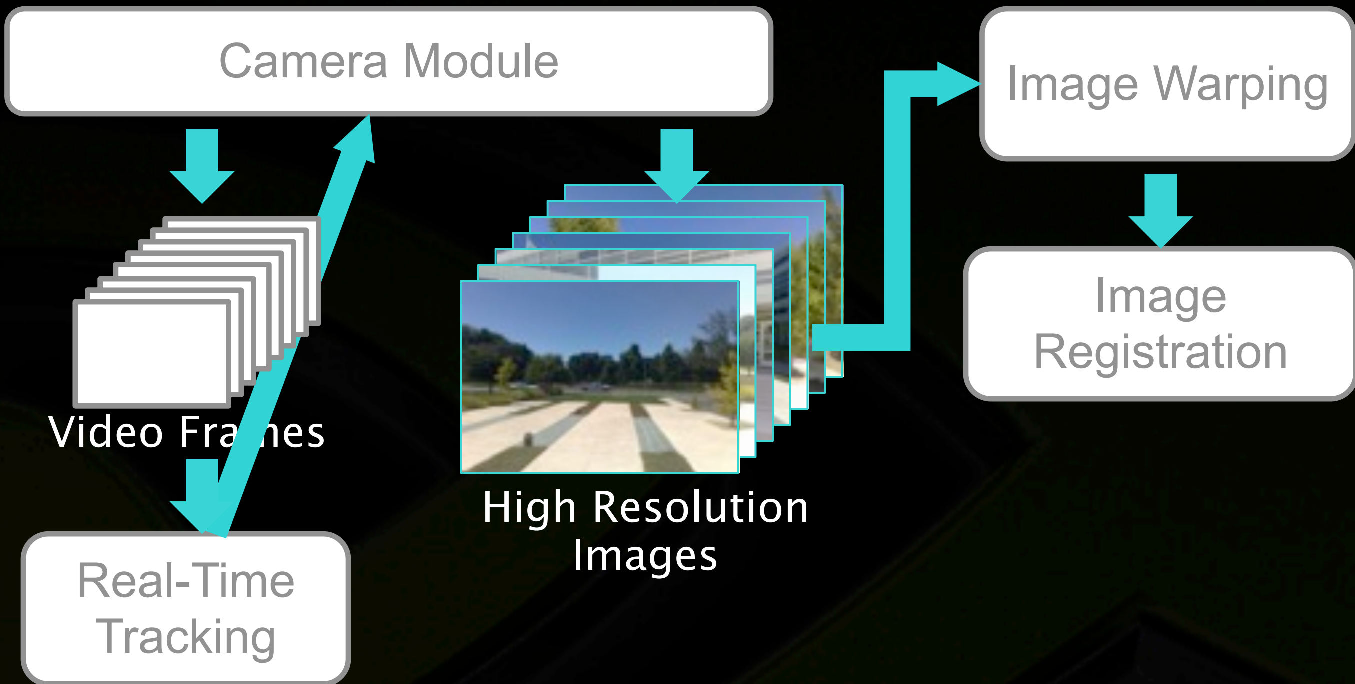
Actual size

Applied to hi-res

Feature-based registration



System overview



System overview

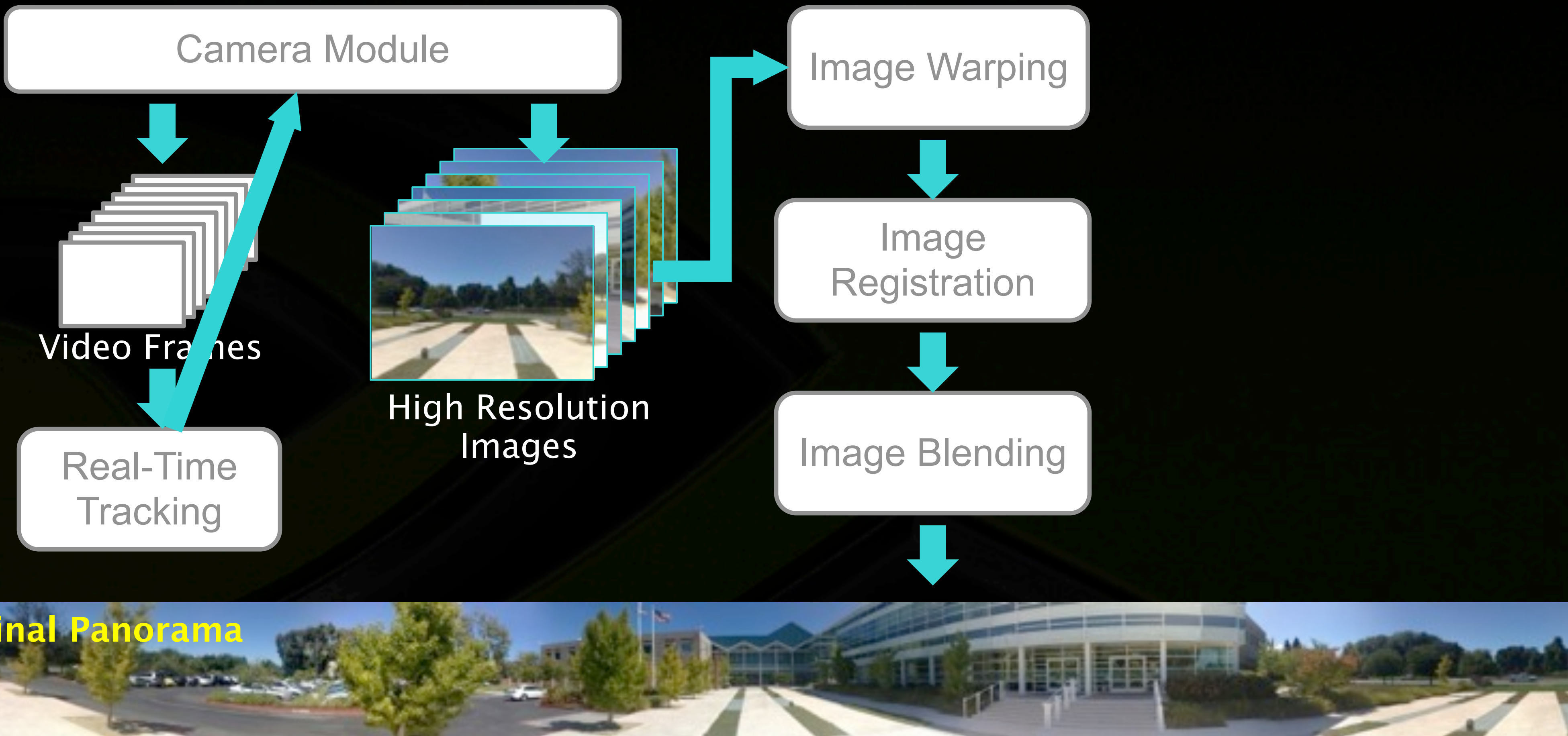


Photo by Marius Tico

Image blending

- Directly averaging the overlapped pixels results in ghosting artifacts
  - Moving objects, errors in registration, parallax, etc.

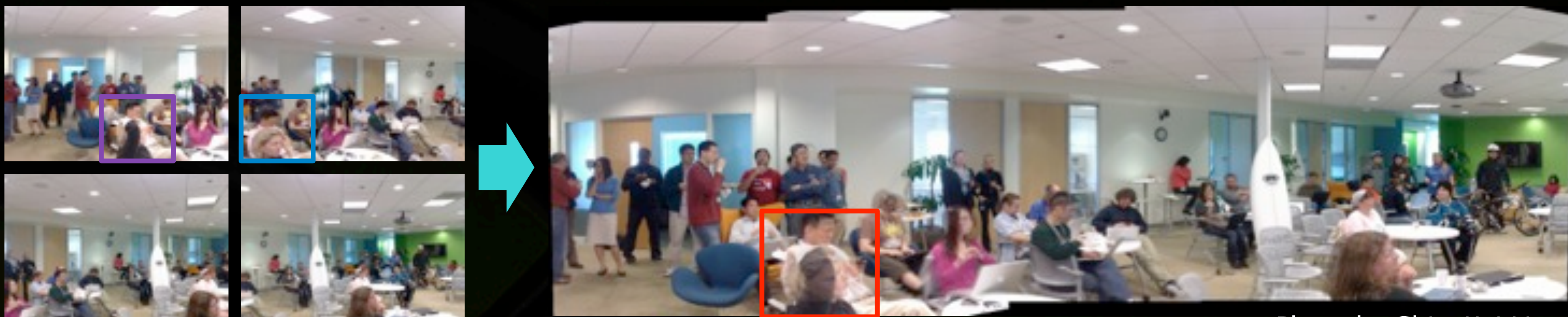


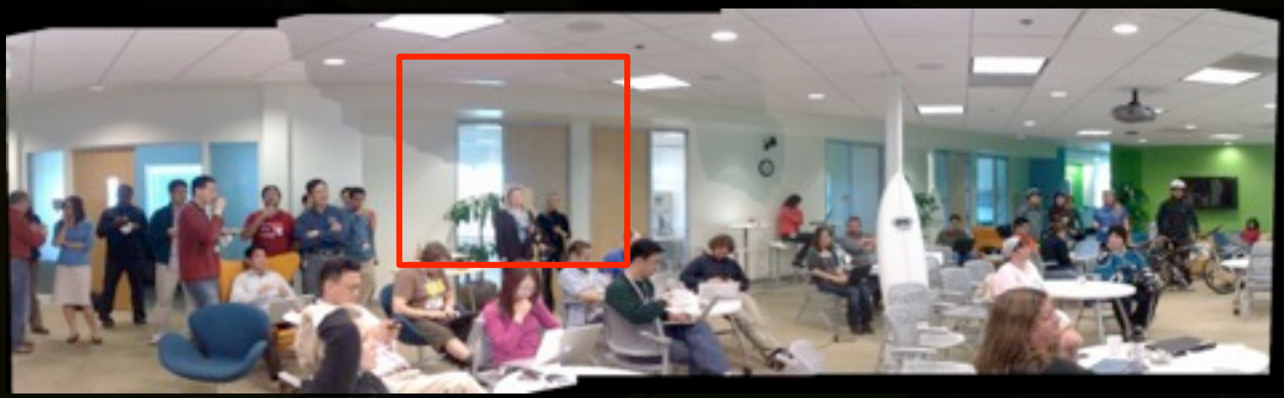
Photo by Chia-Kai Liang

Solution: Image labeling

- Assign one input image each output pixel
  - Optimal assignment can be found by graph cut [Agarwala et al. 2004]

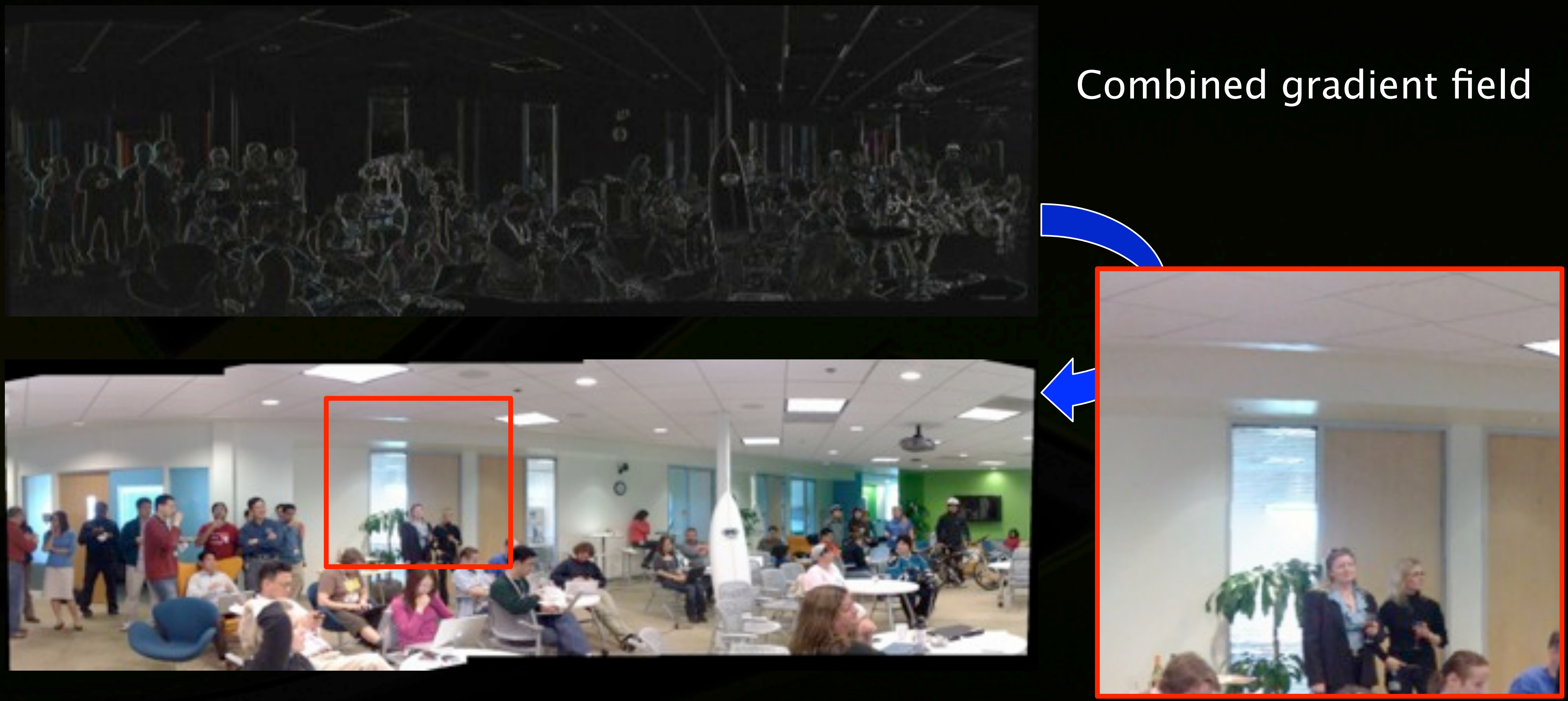
New artifacts

- Inconsistency between pixels from different input images
  - Different exposure/white balance settings
  - Photometric distortions (e.g., vignetting)

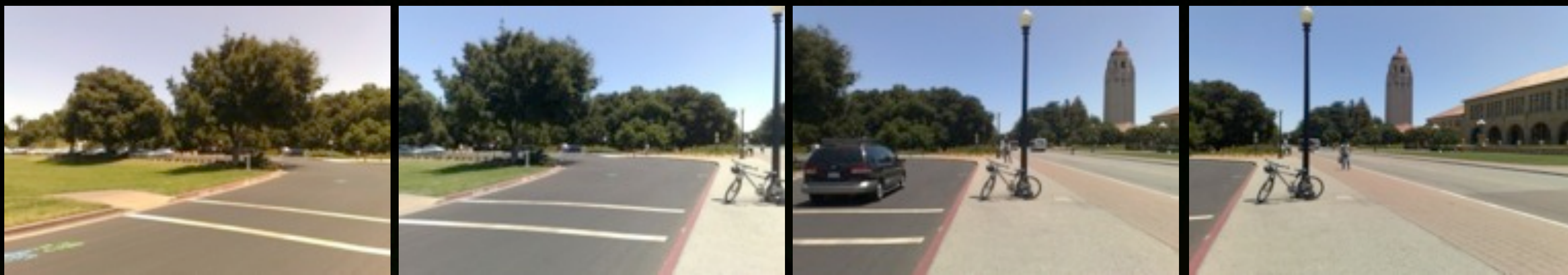


Solution: Poisson blending

- Copy the gradient field from the input image
- Reconstruct the final image by solving a Poisson equation



Seam finding is difficult when colors differ

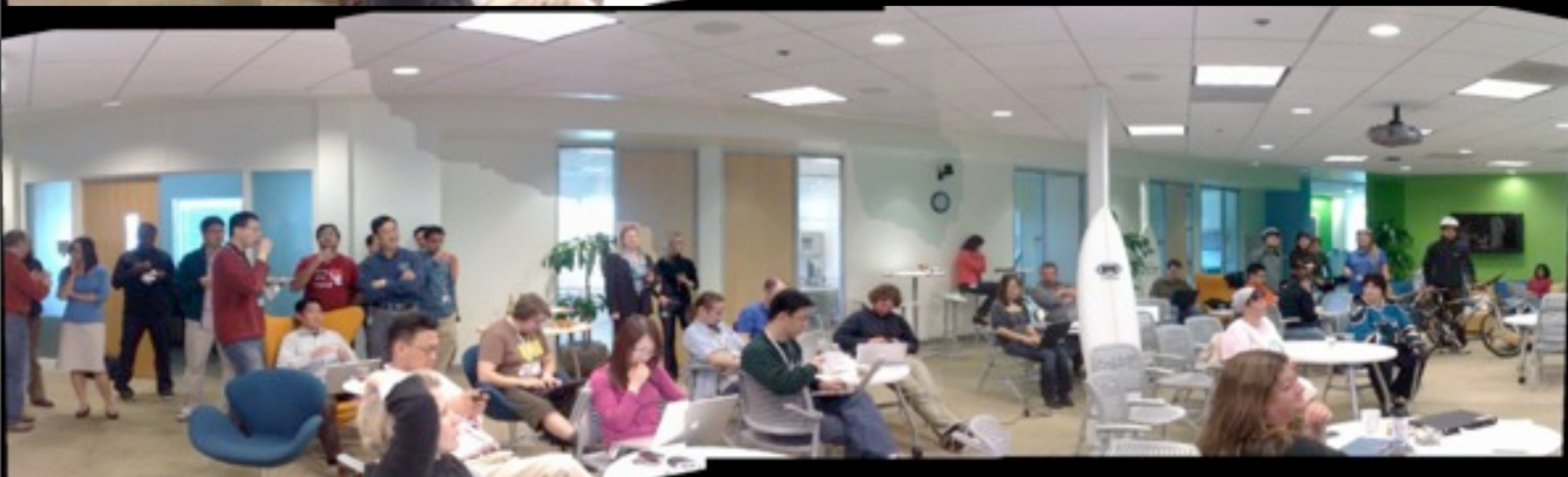


No color correction

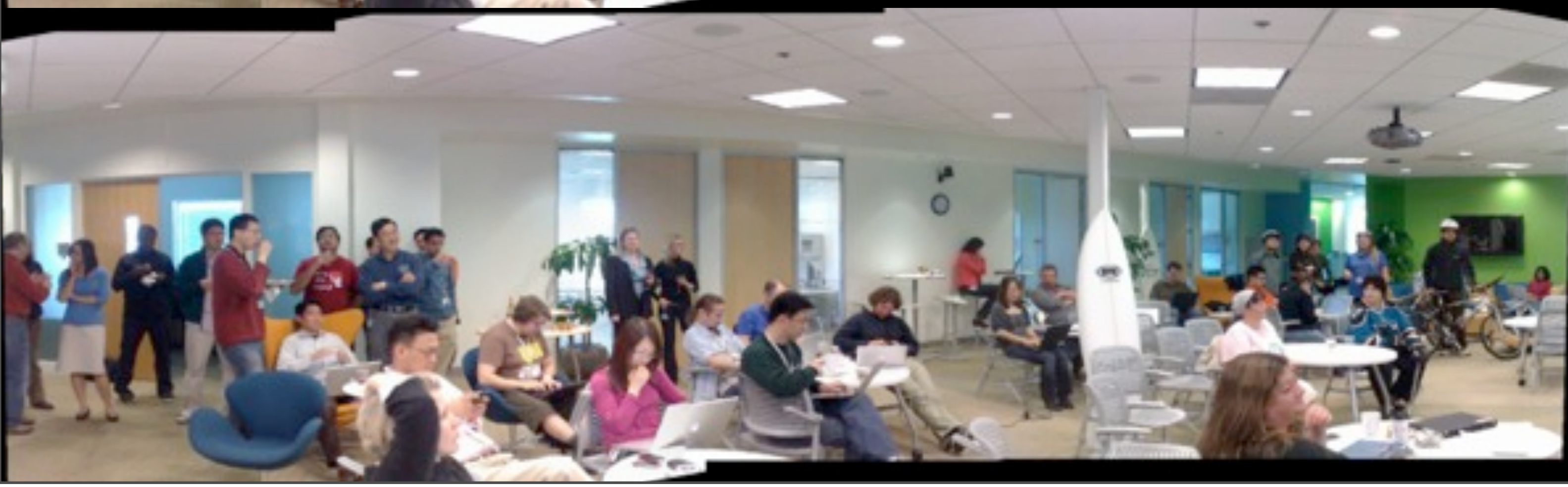
With color correction

Y. Xiong, K. Pulli, “Fast Panorama Stitching on Mobile Devices”, ICCE 2010

Alpha blending



After labeling



Poisson blending

System Overview

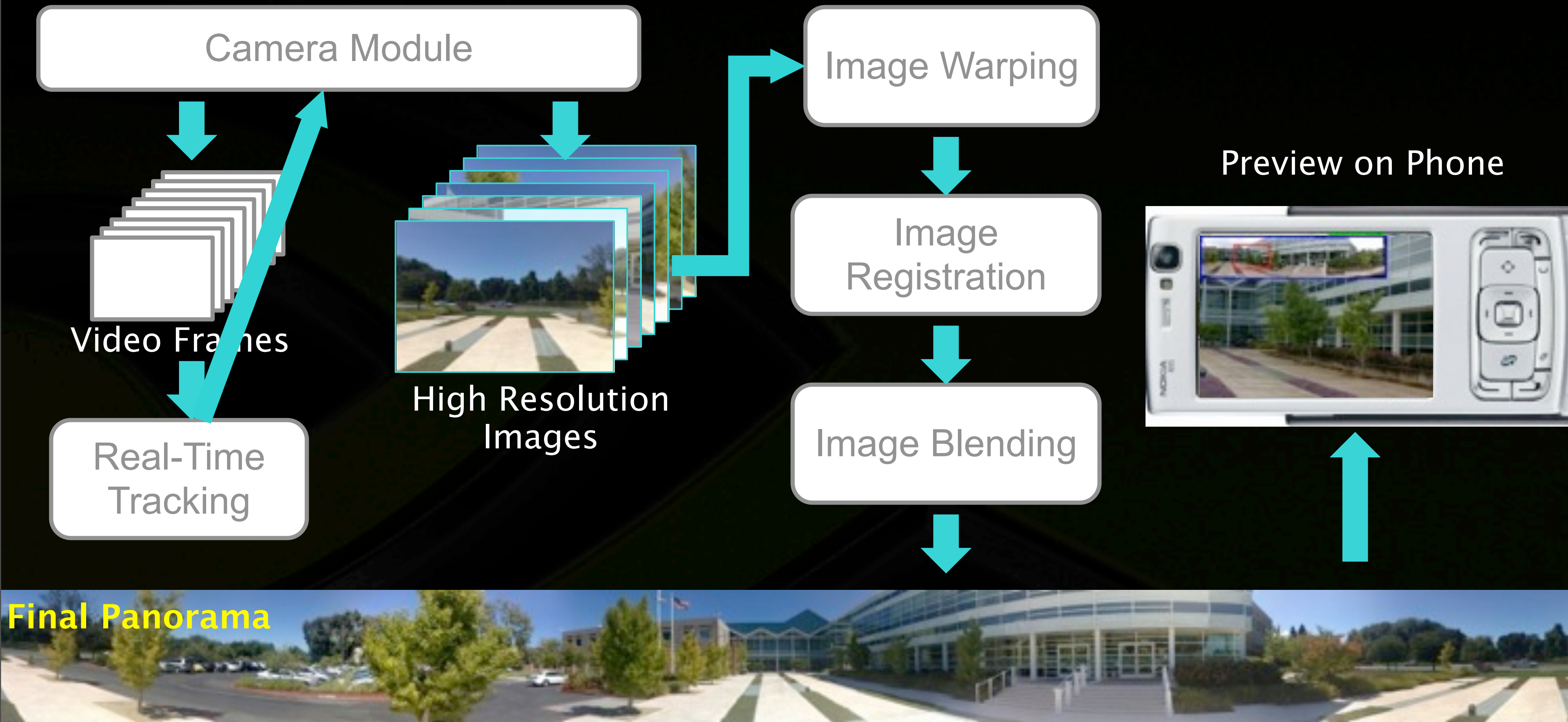


Photo by Marius Tico

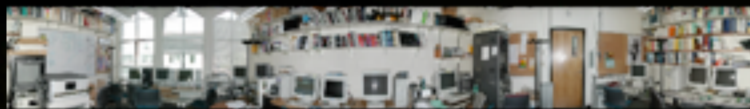
Panorama Visualization

- Trivial method:
  - Show the whole panorama on the screen
  - Zooming and panning

No Projection Method is Optimal

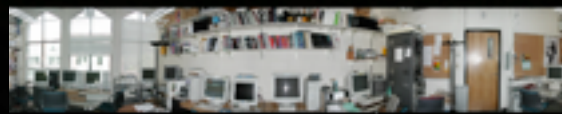
Zoom

Spherical Projection



Perspective Projection

Interpolate the Projection Coordinates



Zoom

- Weights are determined by a sigmoid function of zoom factor

Capturing and Viewing Gigapixel Images

Johannes Kopf [1,2]
Matt Uyttendaele [1]
Oliver Deussen [2]
Michael Cohen [1]

1 Microsoft Research
2 Universität Konstanz

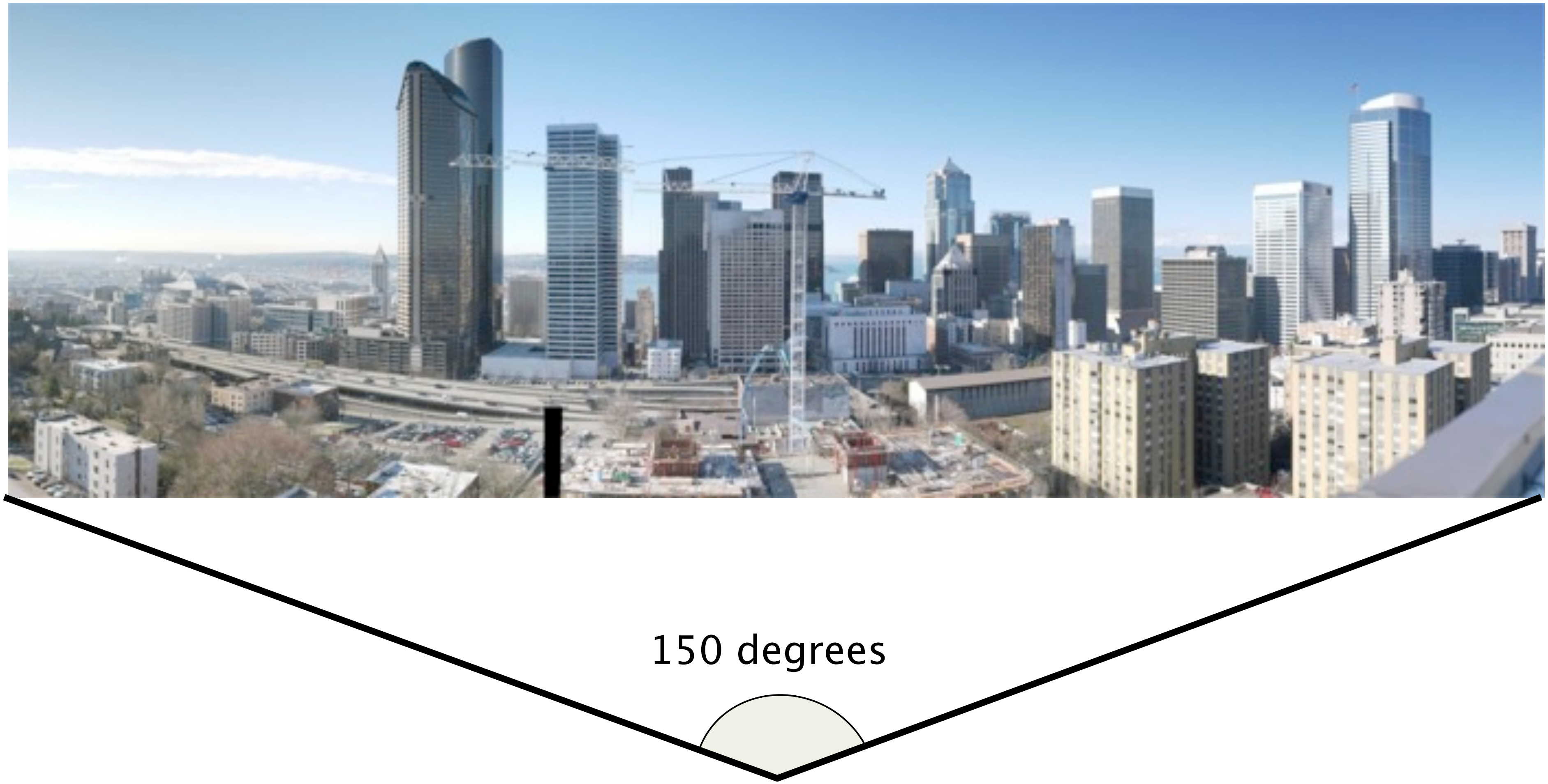
BIG

3,600,000,000 Pixels

Created from about 800 8 MegaPixel Images

BIG

Wide



150 degrees

“Normal” perspective projections cause distortions.

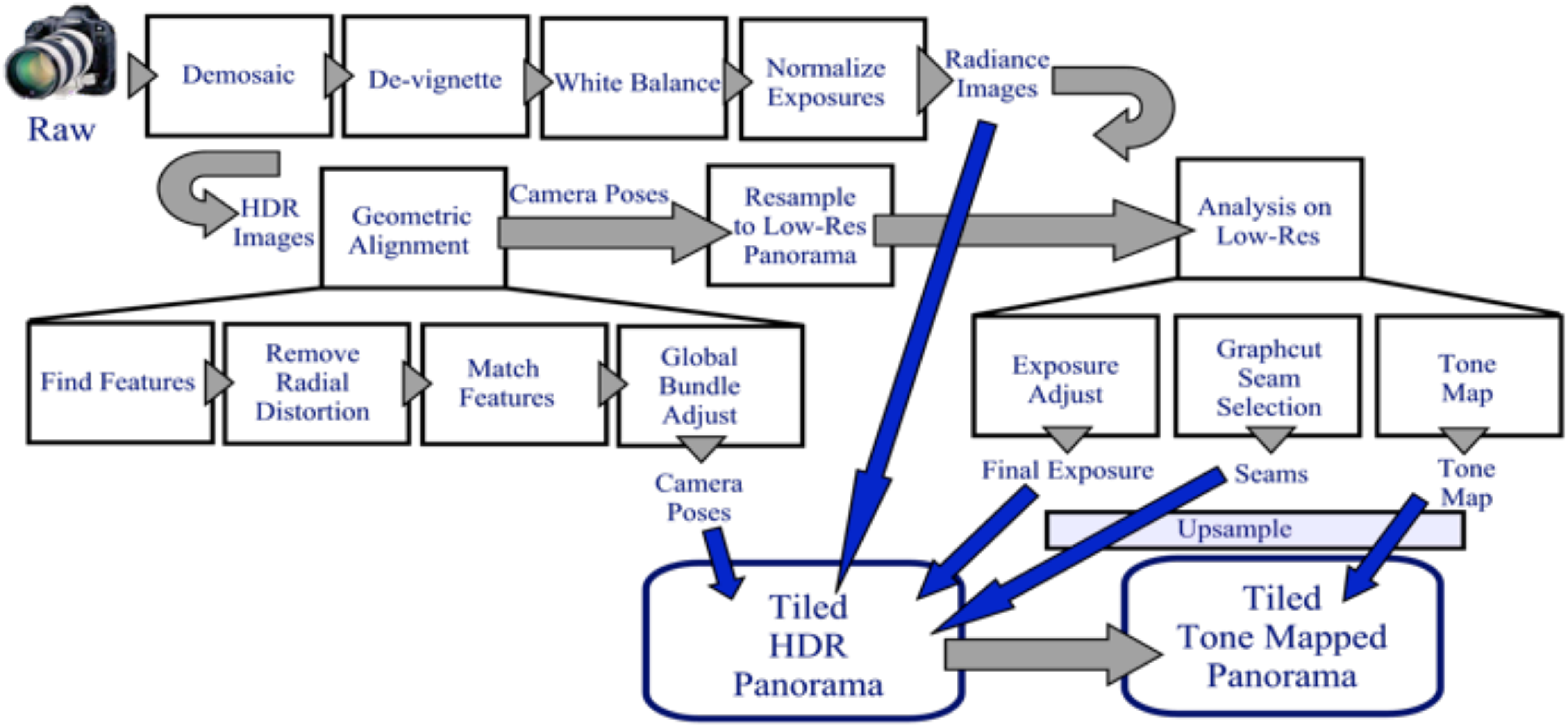
Deep

100X variation in Radiance

High Dynamic Range

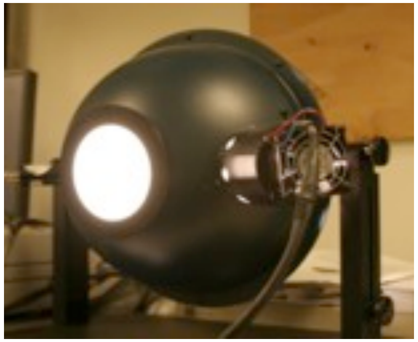
Capture

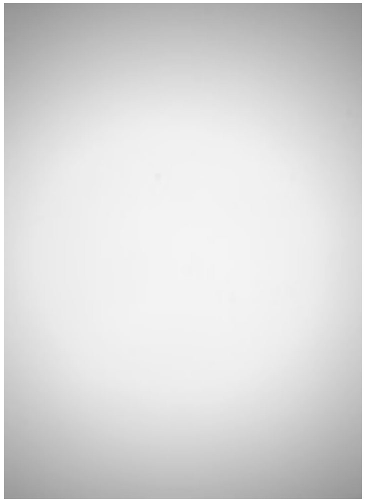
Capturing Gigapixel Images



RAW

DeVignette



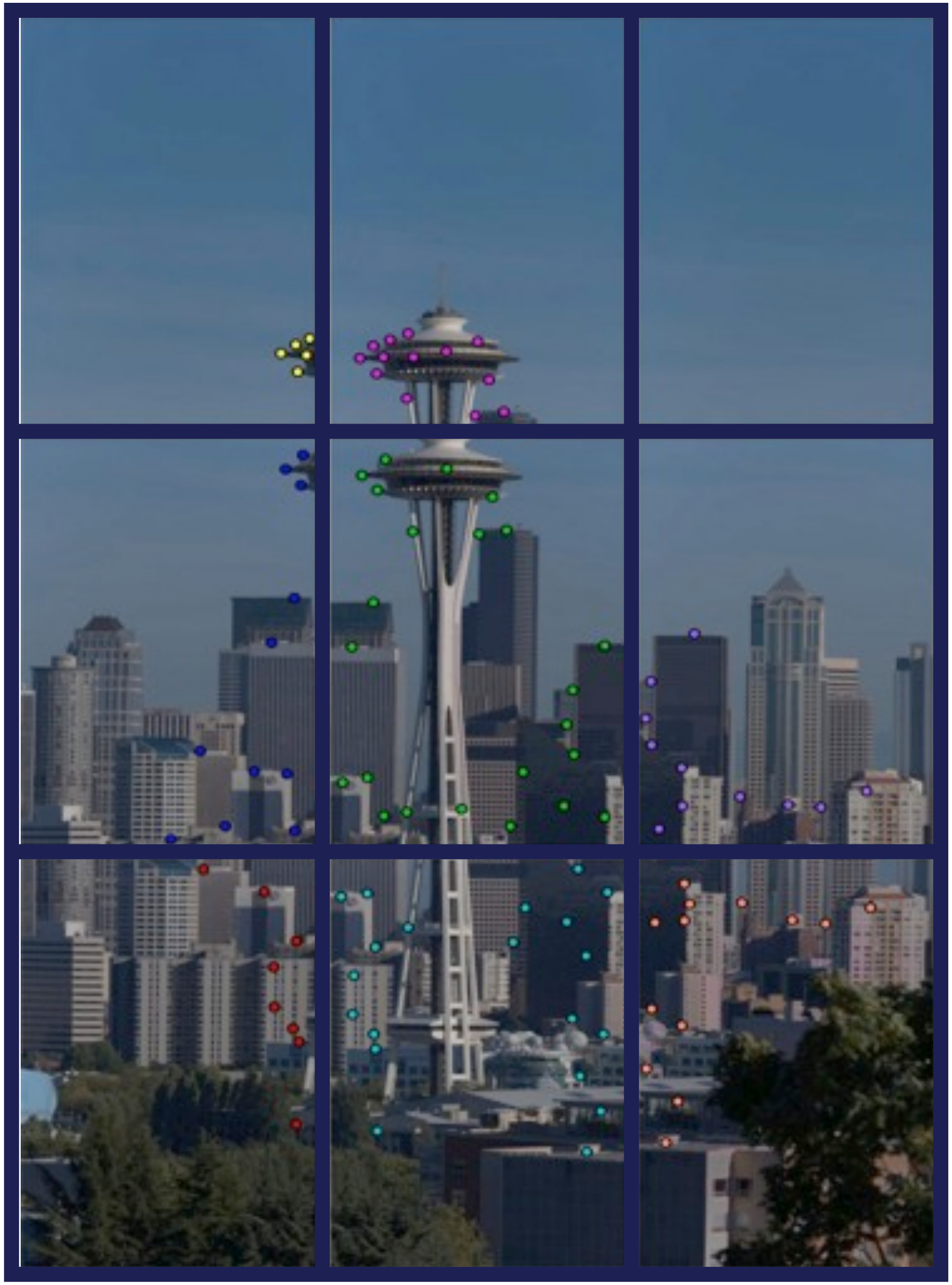


White Balance

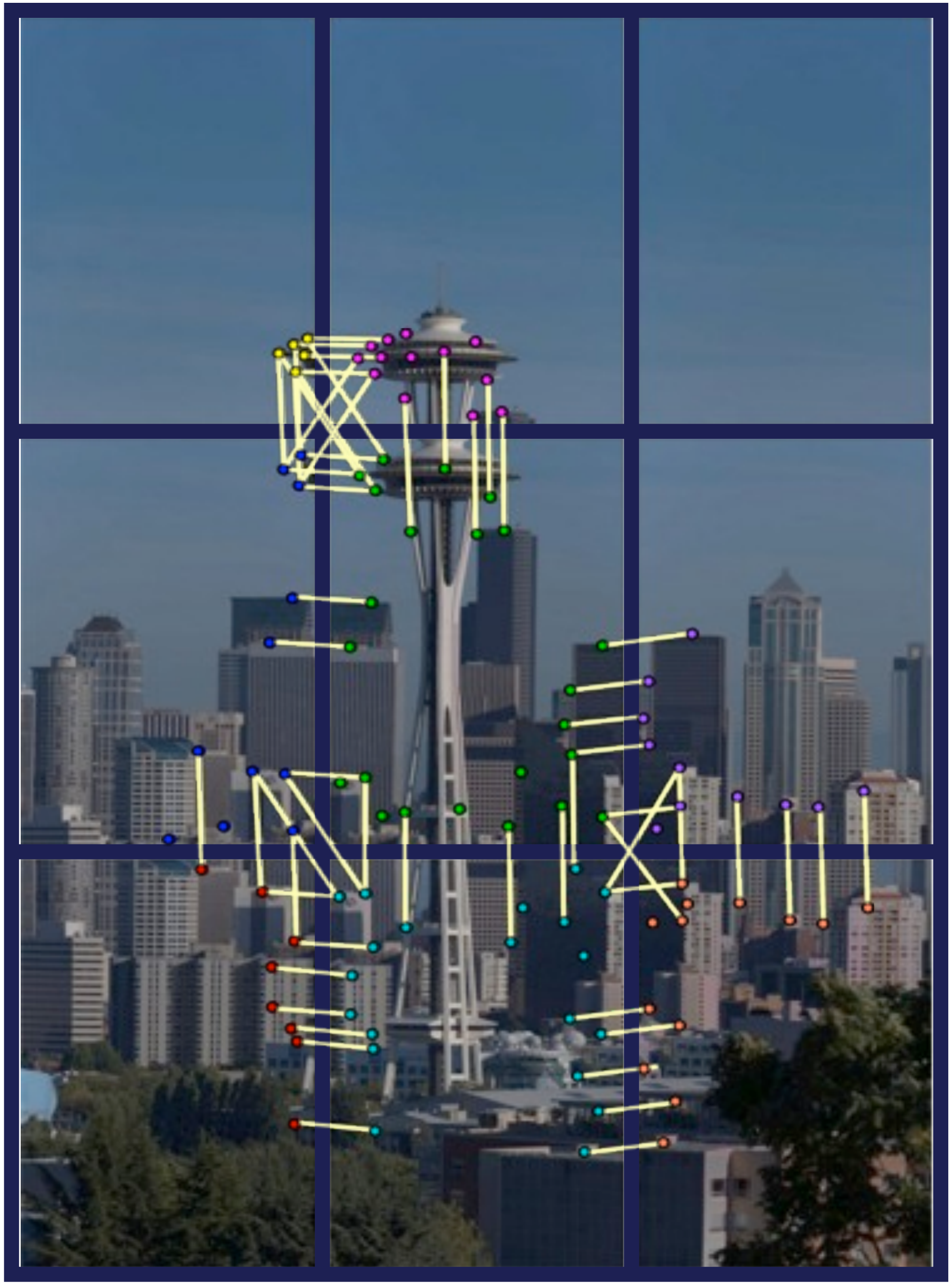
Exposure Balance

Radiance Map

Feature Points



Feature Matches




Aligned
Tone Mapped

Radiometric Alignment

1 / 1000th
of a second

1 / 10th
of a second

High Dynamic Range

Radiometric Alignment

Laplacian Blend

Radiometric Alignment

Poisson Blend

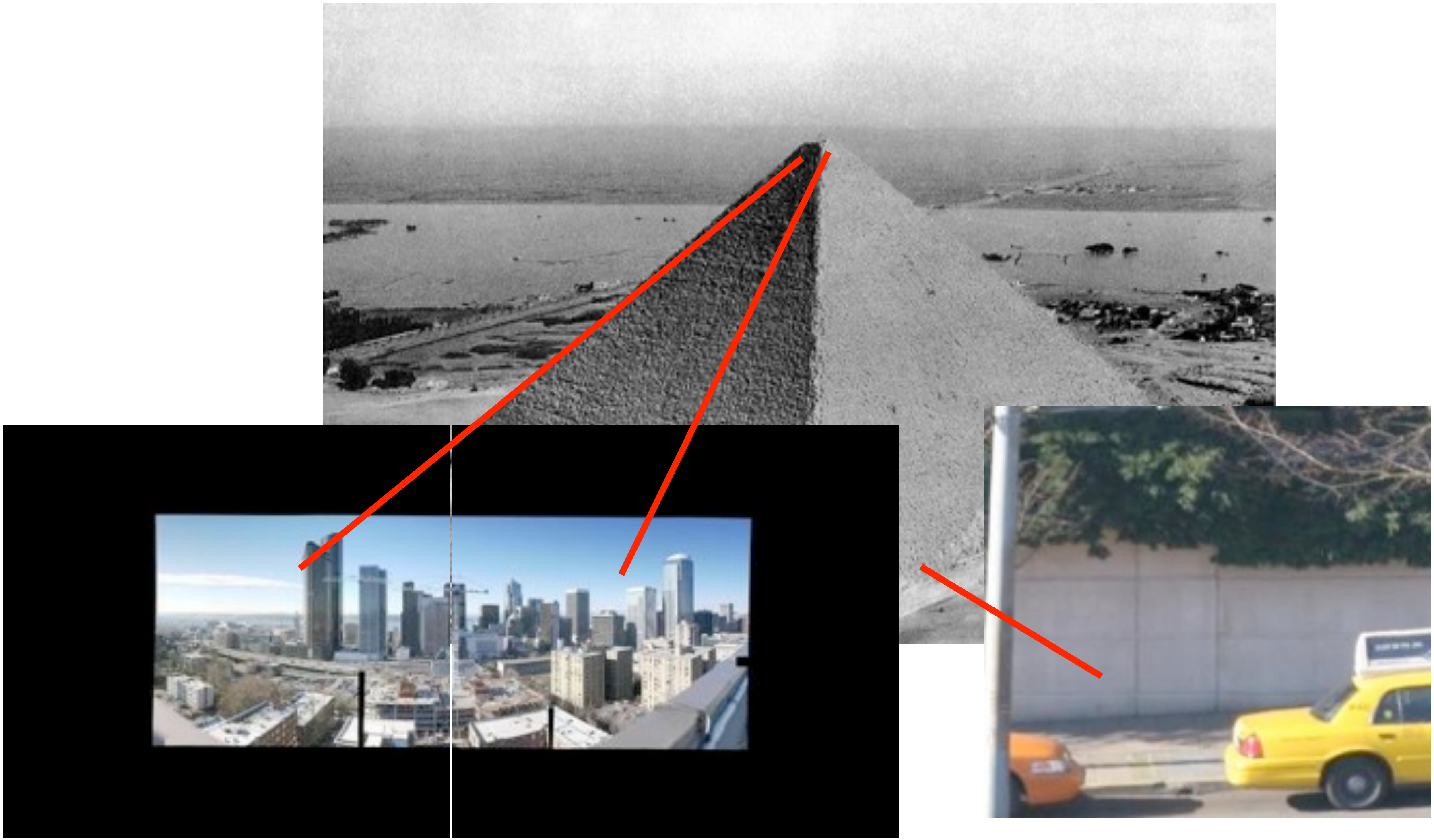
Radiometric Alignment

Pure Radiometric

Radiometric Alignment

High Dynamic Range

Tile Pyramid



272 Gigapixel Image Made Using 12,000 Photos from a Canon 7D

by ERIC REAGAN on JANUARY 14, 2011
in PHOTOGRAPHERS

http://gigapan.org/gigapans/66

Photographer Alfred Zhao captured this 272 gigapixel image of the Shanghai skyline using the GigaPan EPIC Pro and a Canon 7D with a 400mm f/5.6 lens and 2x teleconverter attached. He was setup and started shooting at around 8:30am and after 12,000 images were in the bag, it was just before dusk. It took months to complete image and get the final 1.09TB file uploaded.

Just how big is a 272 gigapixel image? 1 gigapixel = 1000 megapixels = 1 billion pixels. That's 272 BILLION pixels. Printed at standard resolution, this image would cover over 7000 billboards.

But now it's done and Zhao holds a world record for the largest digital photo. There's no time to rest though, as Zhao says, "This is not the end of my panorama journey, it is a new start, challenging the limit is an infinite process. New records will appear in the future, it is only a matter of time."

Optimizing Content-Preserving Projections for Wide-Angle Images

Robert Carroll
University of California, Berkeley

Maneesh Agrawala
University of California, Berkeley

Aseem Agarwala
Adobe Systems, Inc.

Figure 1: *Wide-angle photographs can appear badly distorted under existing projections, such as the perspective, Mercator and stereographic projections. Perspective projection preserves linear structures in the scene, but distorts shapes of objects. Mercator and stereographic projections preserve shapes locally, but bend linear structures. Our projection is designed to both preserve local shape and maintain straight scene lines that are marked by the user with our interactive tool.*

Push broom / slit scan panoramas

Photographing long scenes with multi-viewpoint panoramas

Aseem Agarwala[1] Maneesh Agrawala[4] Michael Cohen[3] David Salesin[1,2] Rick Szeliski[3]

[1]University of Washington [2]Adobe Systems [3]Microsoft Research [4]UC Berkeley

Abstract

We present a system for producing multi-viewpoint panoramas of long, roughly planar scenes, such as the facades of buildings along a city street, from a relatively sparse set of photographs captured with a handheld still camera that is moved along the scene. Our work is a significant departure from previous methods for creating multi-viewpoint panoramas, which composite thin vertical strips from a video sequence captured by a translating video camera, in that the resulting panoramas are composed of relatively large regions of ordinary perspective. In our system, the only user input required beyond capturing the photographs themselves is to identify the dominant plane of the photographed scene; our system then computes a panorama automatically using Markov Random Field optimization. Users may exert additional control over the appearance of the result by drawing rough strokes that indicate various high-level goals. We demonstrate the results of our system on several scenes, including urban streets, a river bank, and a grocery store aisle.