3DV 2016

Large-scale 3D Modeling from Crowdsourced Data

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Jared Heinly, URCV

Johannes Schönberger, ETHZ

URCV ETH zürich

Image Registration and Connected-Component Discovery

Jared Heinly

URCV

urcventures.com

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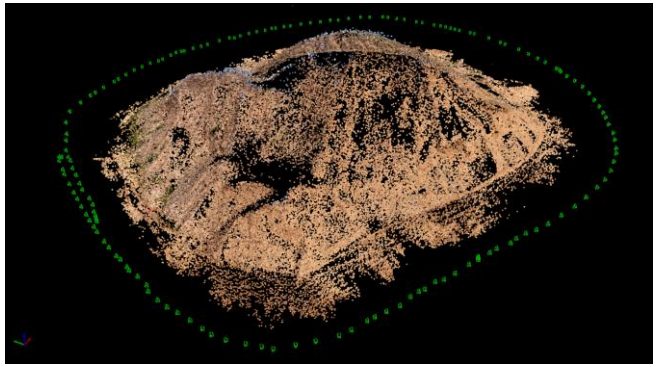
URCV

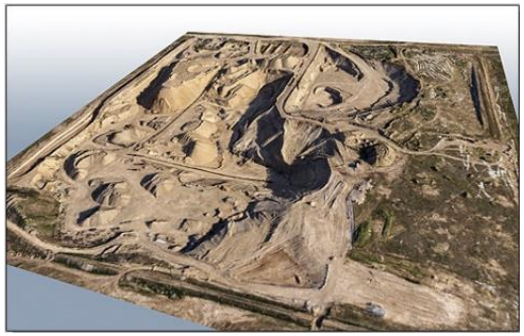
urcventures.com

Ground-Based



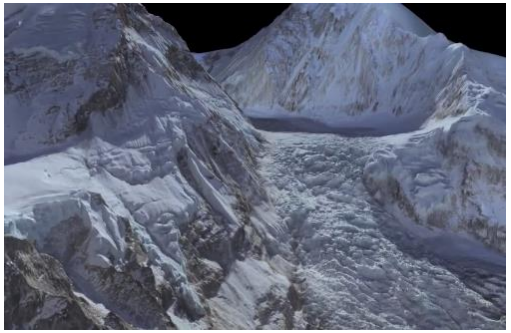
Aerial-Based

Stockpiles

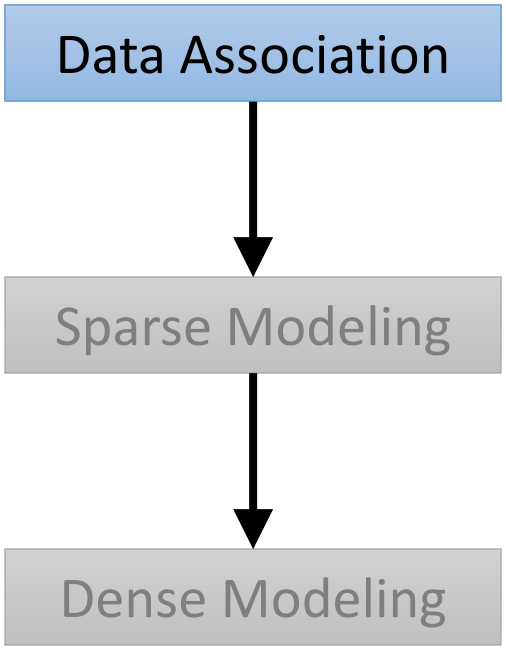


Housing

Education



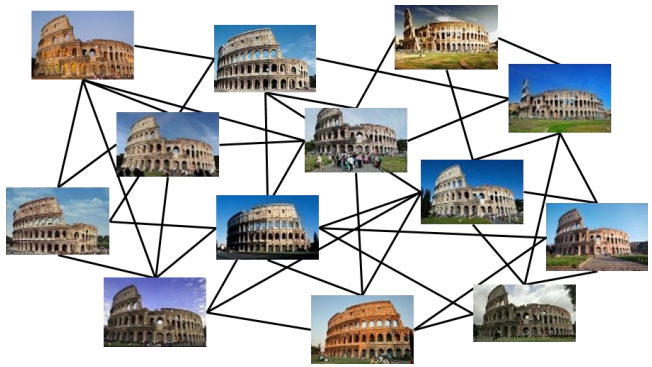
3D Modeling Pipeline



Outline – Data Association

- 2D features → Image registration
  - Features
  - Matching
  - Verification

- Image registration → Connected components
  - Exhaustive
  - Image retrieval
  - Clustering
  - Streaming



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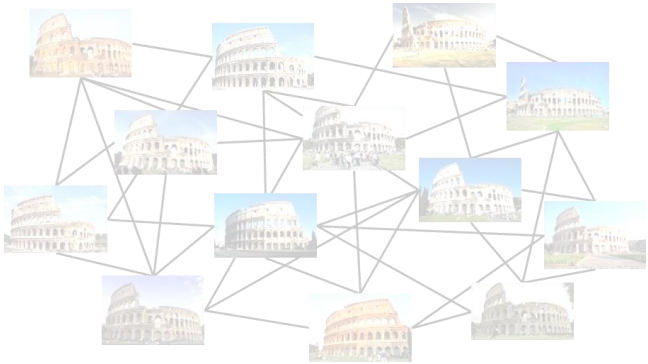

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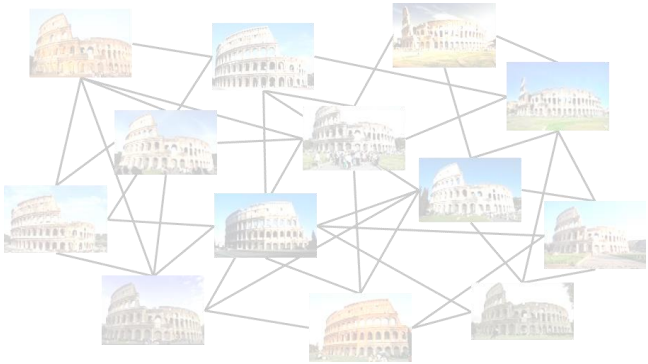
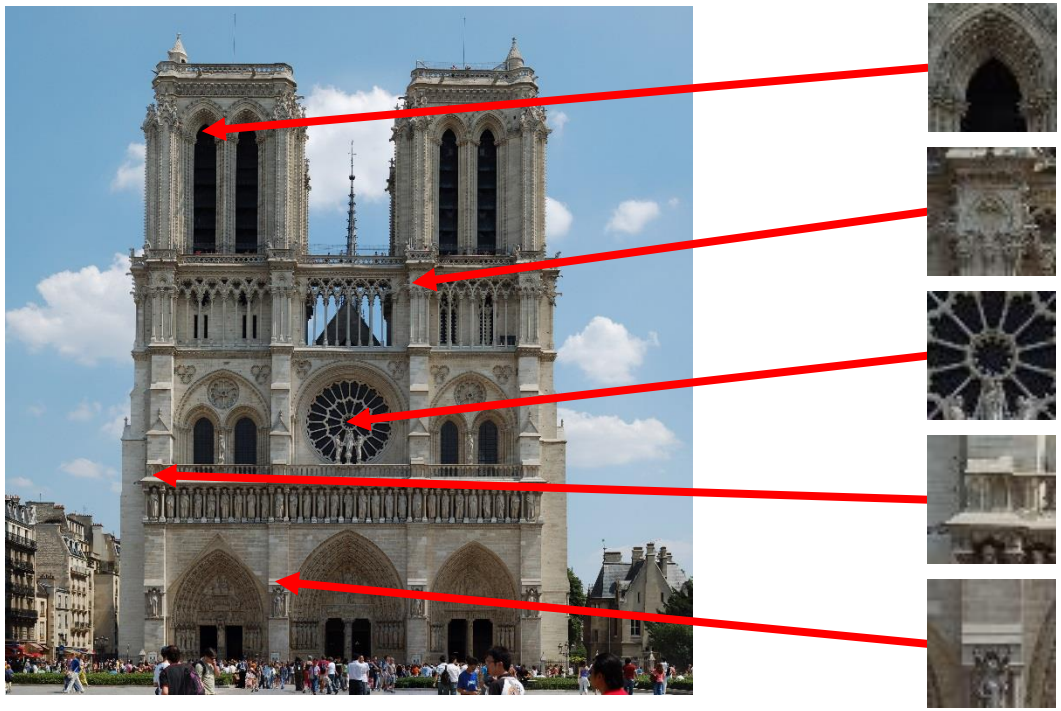


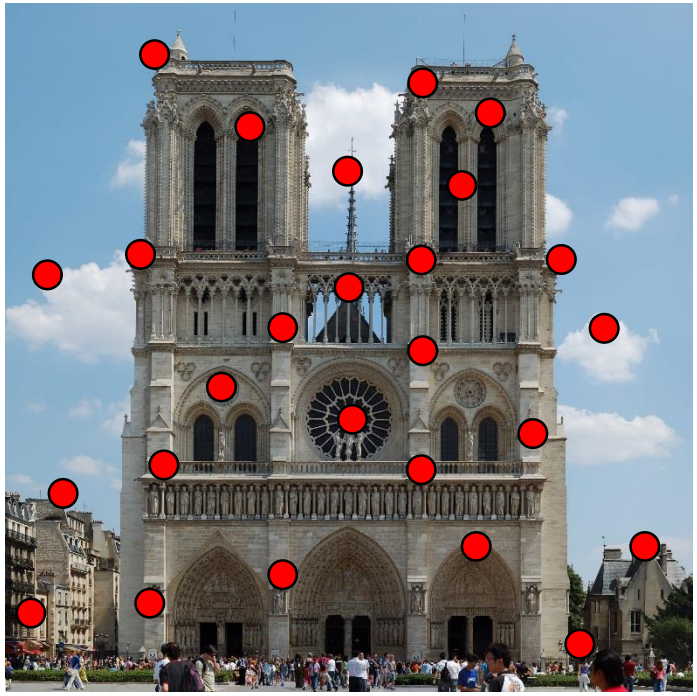
2D Features

- Represent an image by individual 2D components



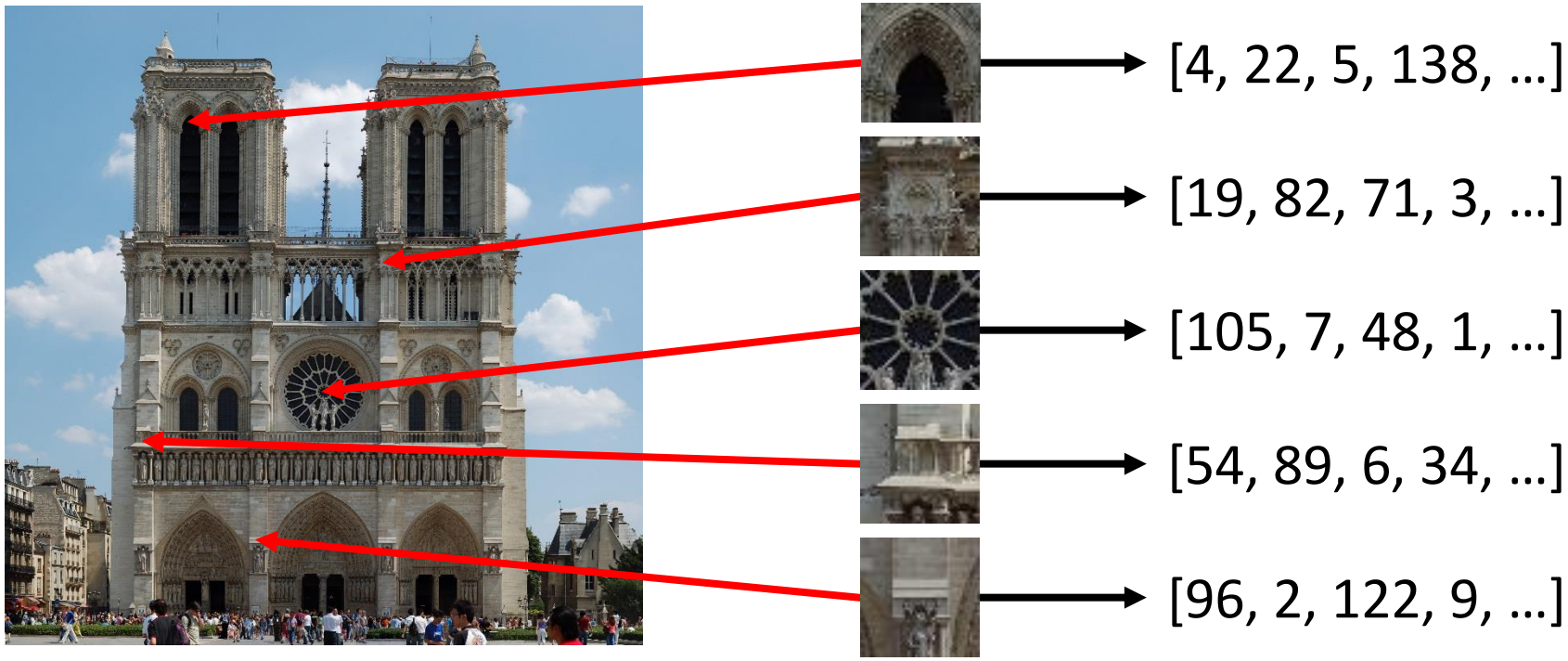
2D Features

- Feature detection
- Decompose an image into salient points



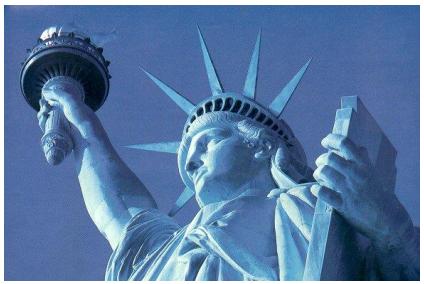
2D Features

- Feature description
- Summarize points with distinctive representations



Feature Invariance

- Rotation
- Scale
- Affine
- Illumination



Rotation Invariance

Image Patch

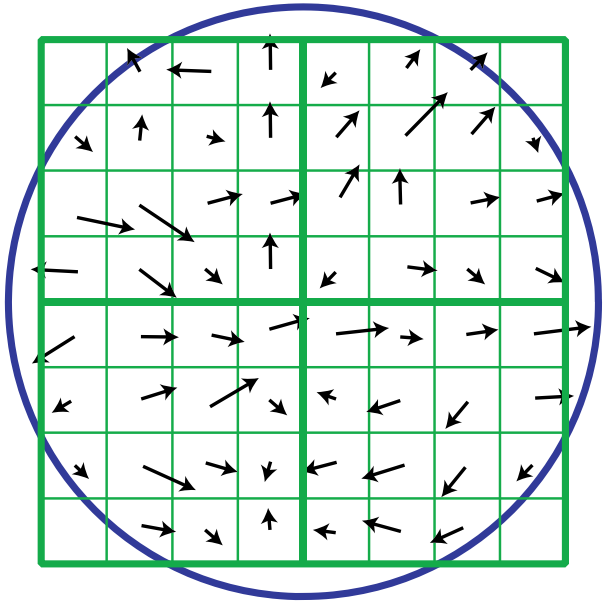


Image Gradients

Rotation Invariance

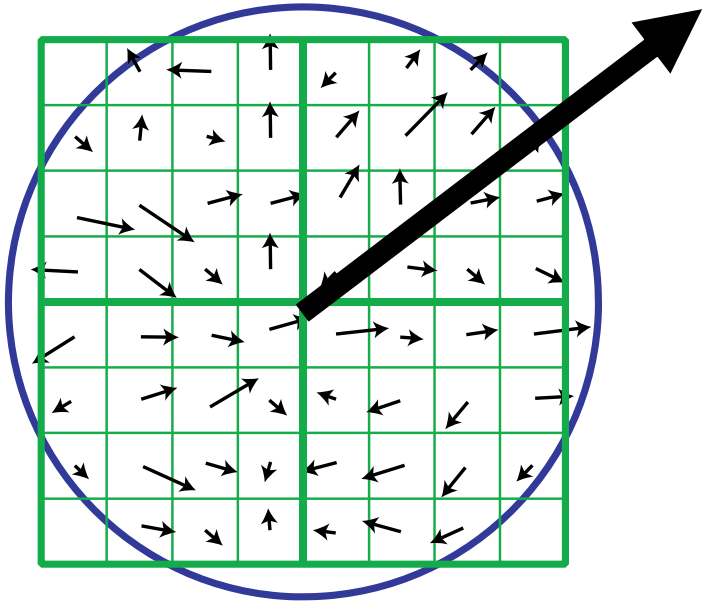
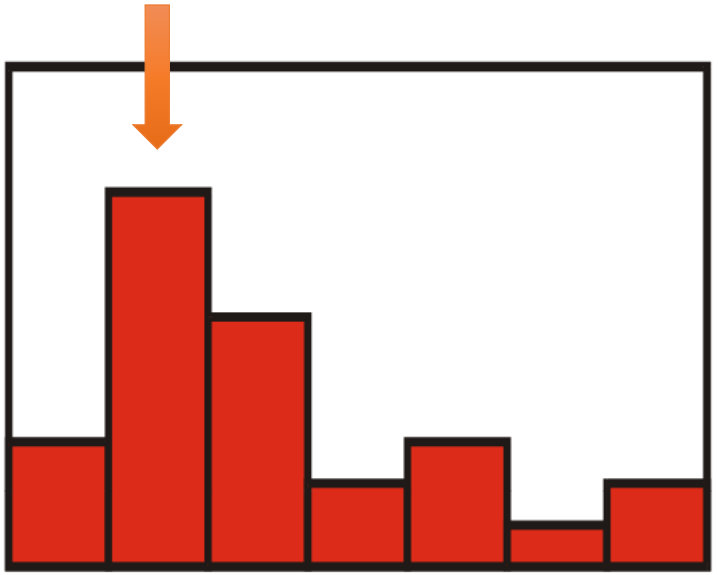


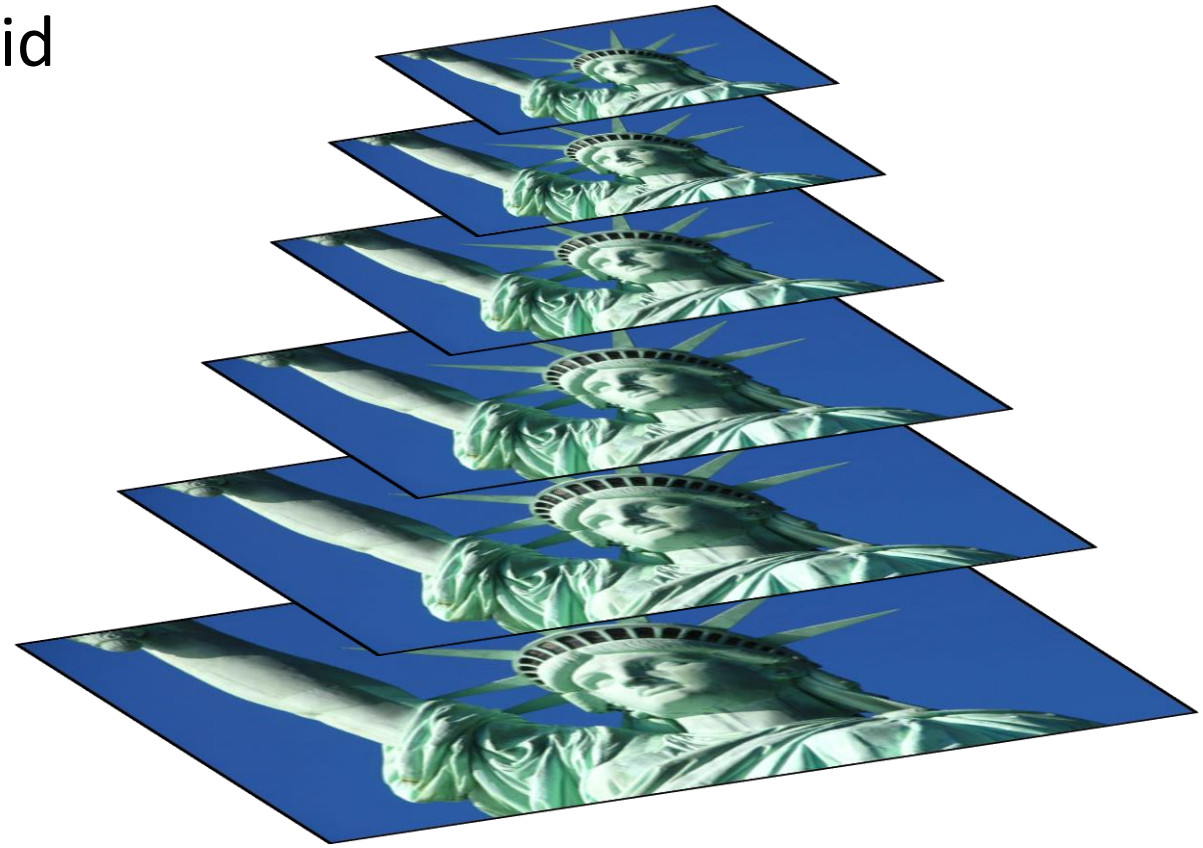
Image Gradients



Gradient Histogram

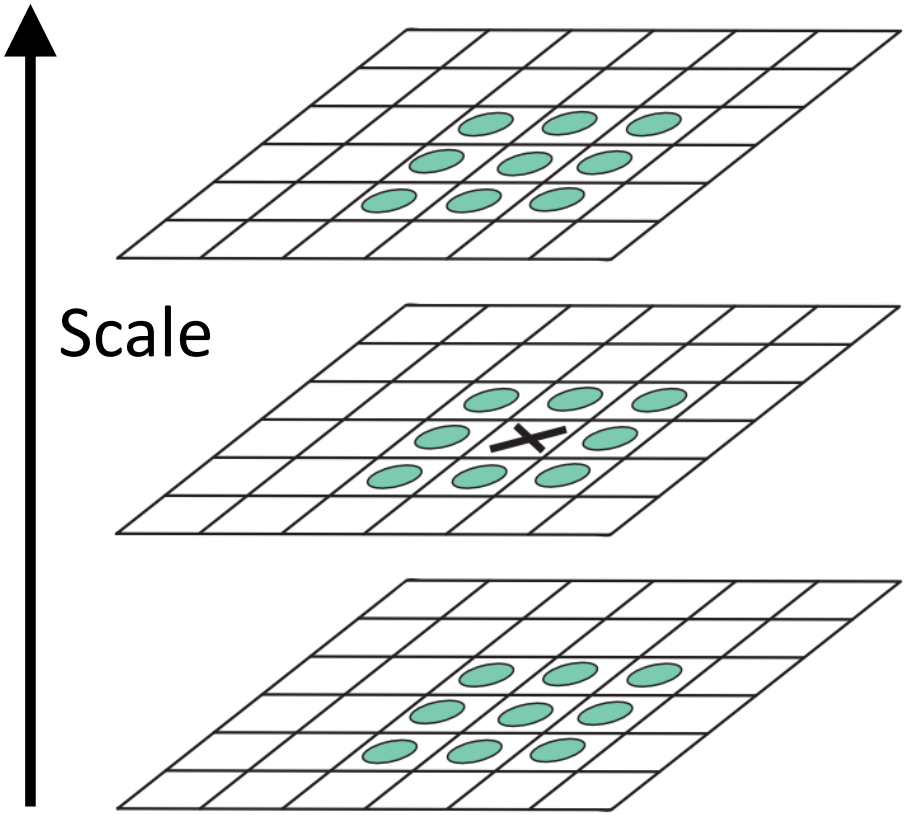
Scale Invariance

- Image pyramid

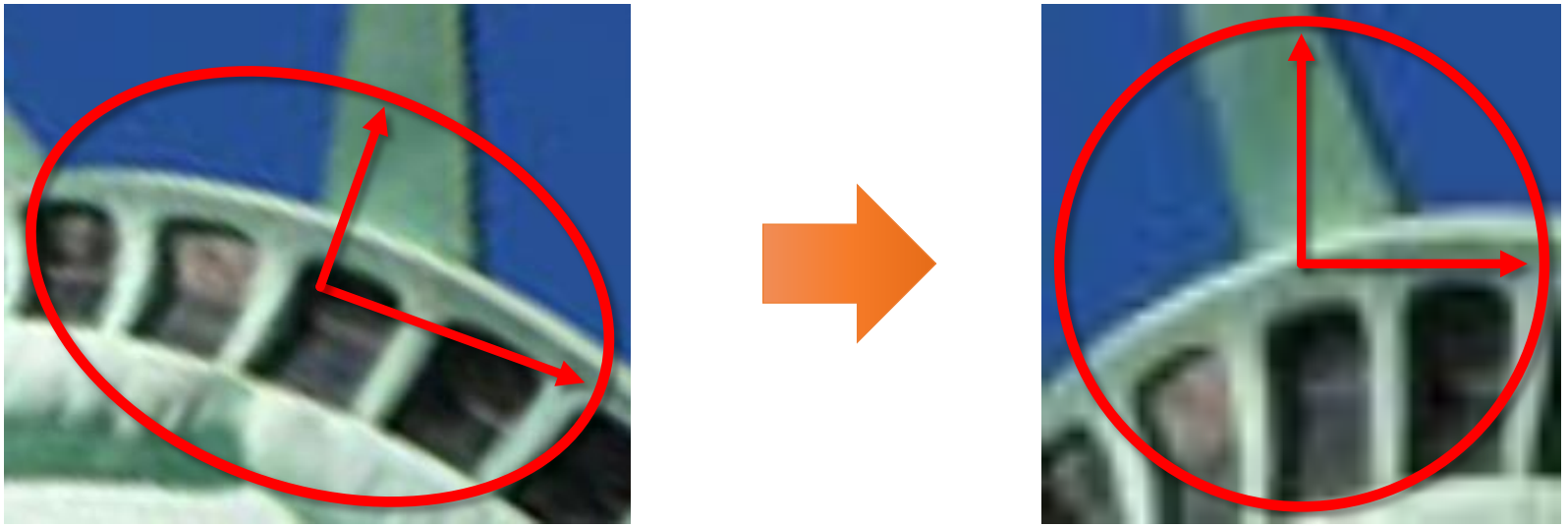


Scale Invariance

- Image pyramid
- Find maximum response across scales



Affine Invariance



Illumination Invariance

- Descriptor normalization

[4, 22, 5, 138, …] → [0.03, 0.15, 0.03, 0.92, …]

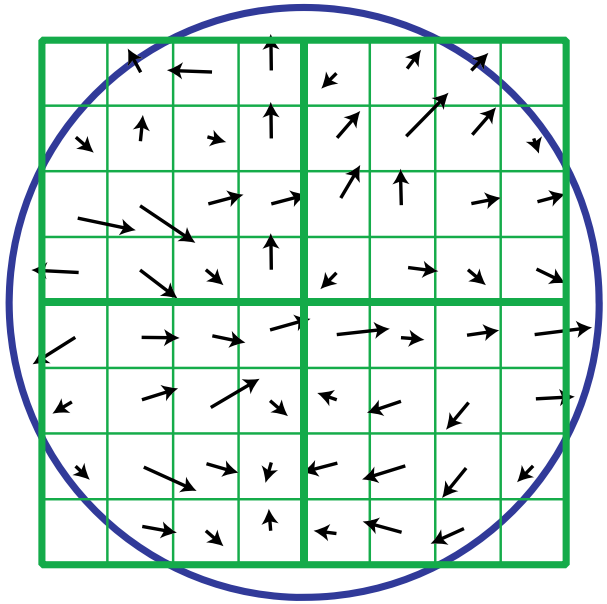
[19, 82, 71, 3, …] → [0.13, 0.55, 0.47, 0.02, …]

[105, 7, 48, 1, …] → [0.70, 0.05, 0.32, 0.01, …]

[54, 89, 6, 34, …] → [0.36, 0.59, 0.04, 0.23, …]

Illumination Invariance

- Gradient direction



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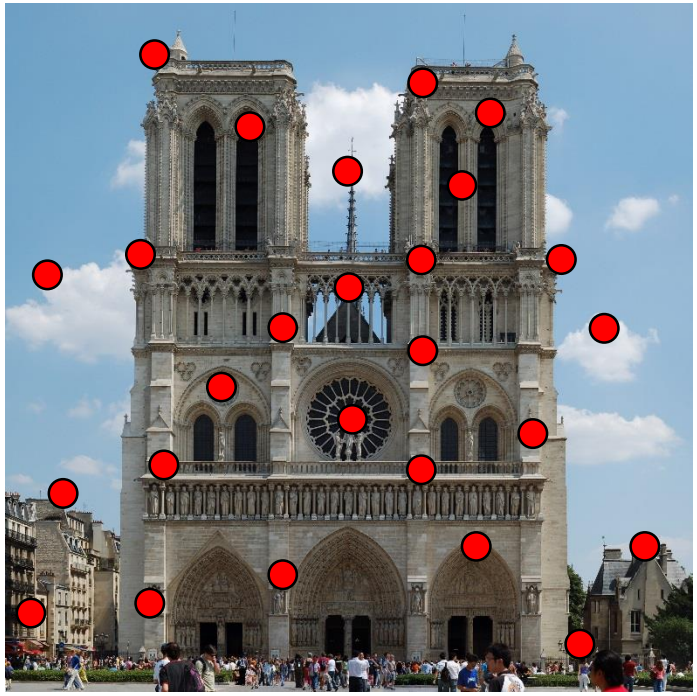
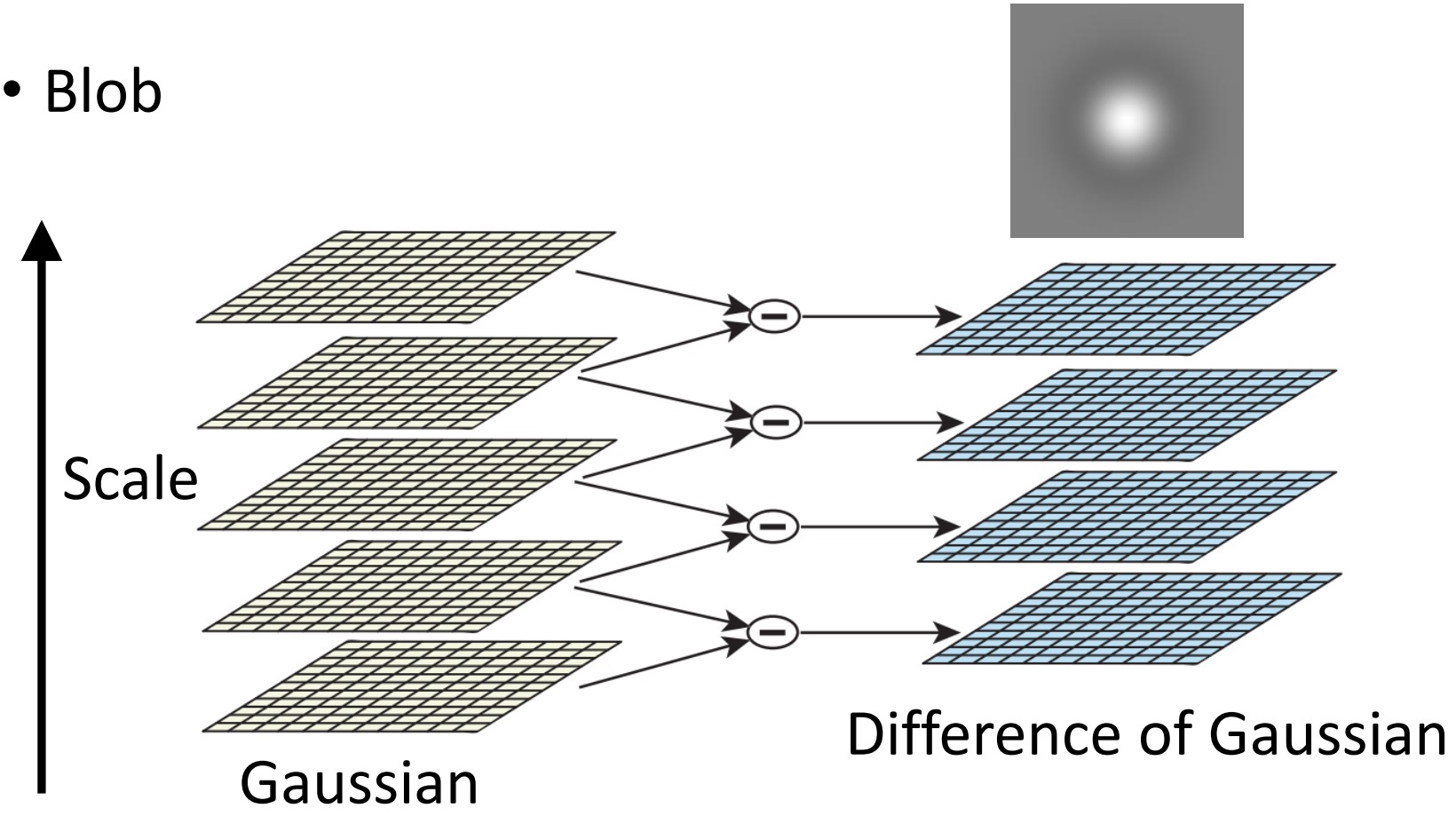


2D Feature Detectors

- Blob
  - SIFT, SURF

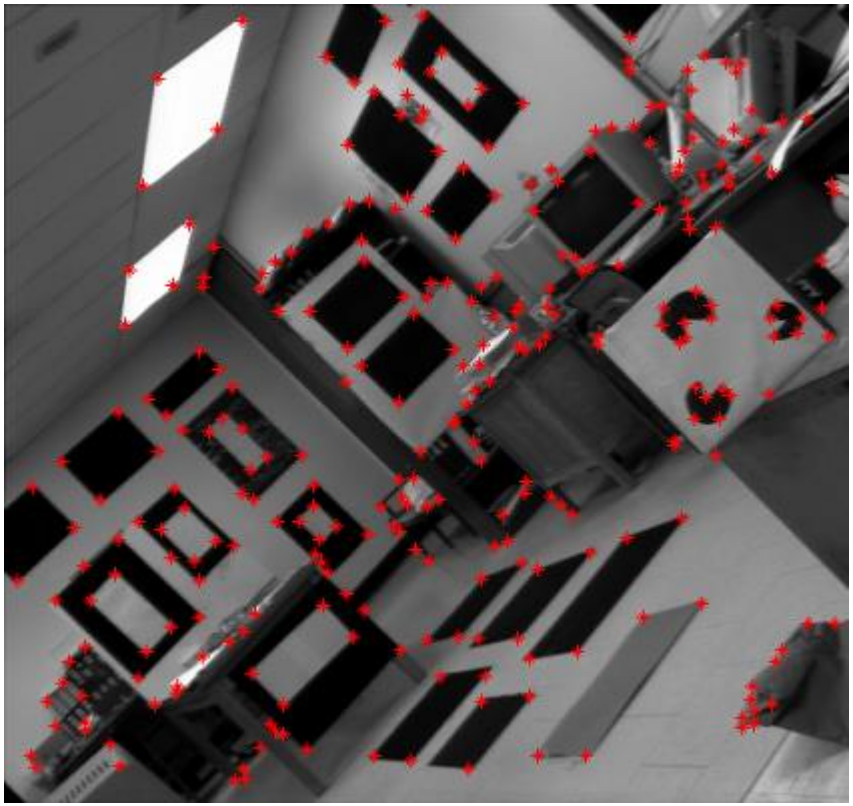
2D Feature Detectors

- Blob



2D Feature Detectors

- Corner
  - Harris, FAST



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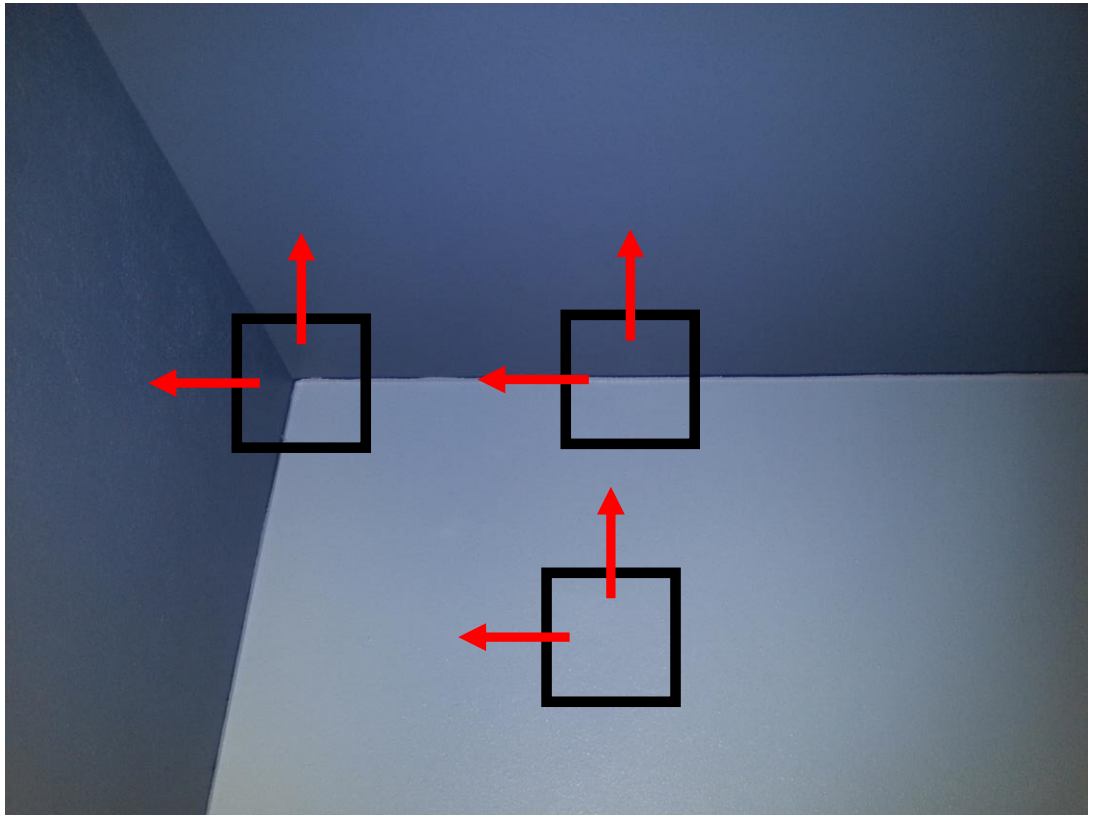

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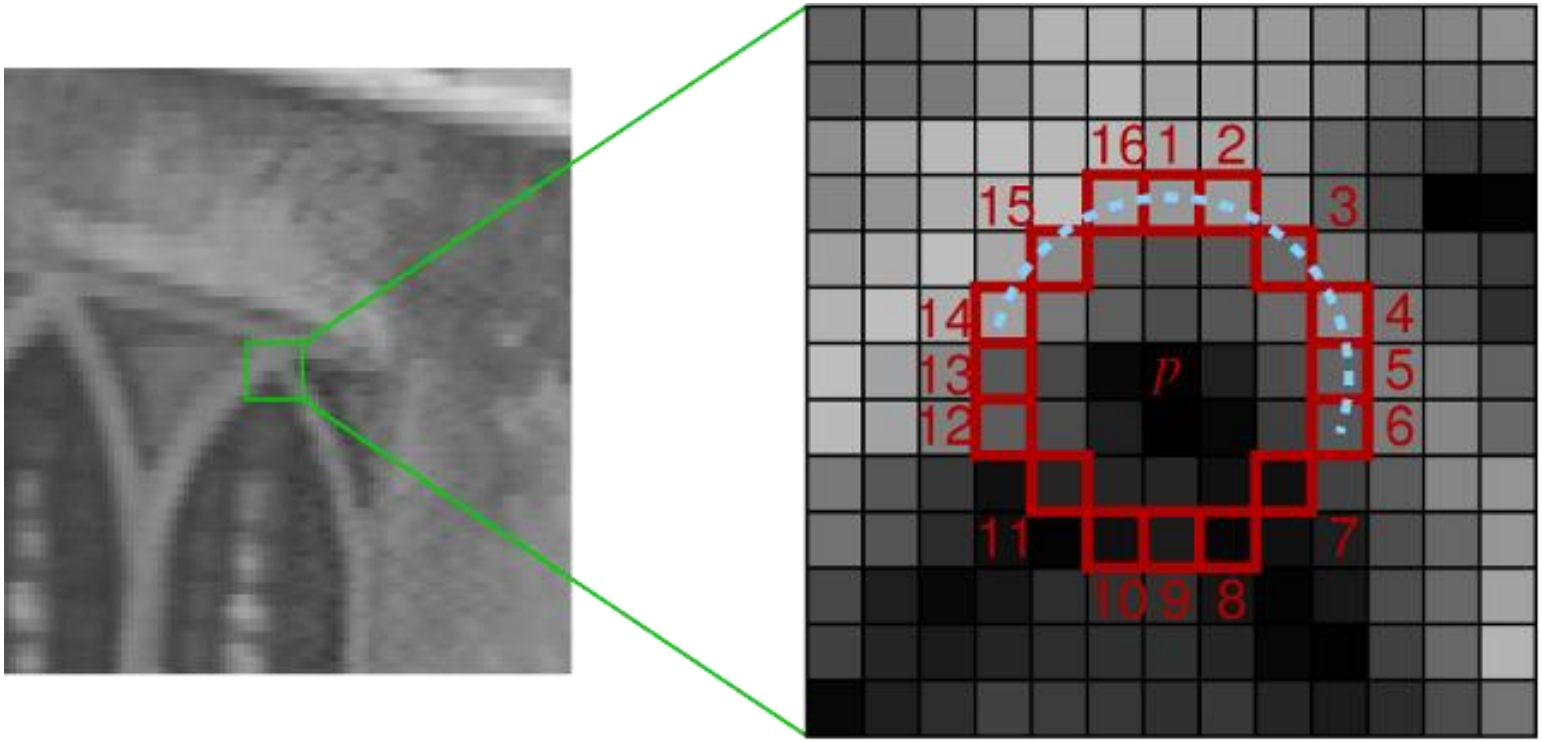

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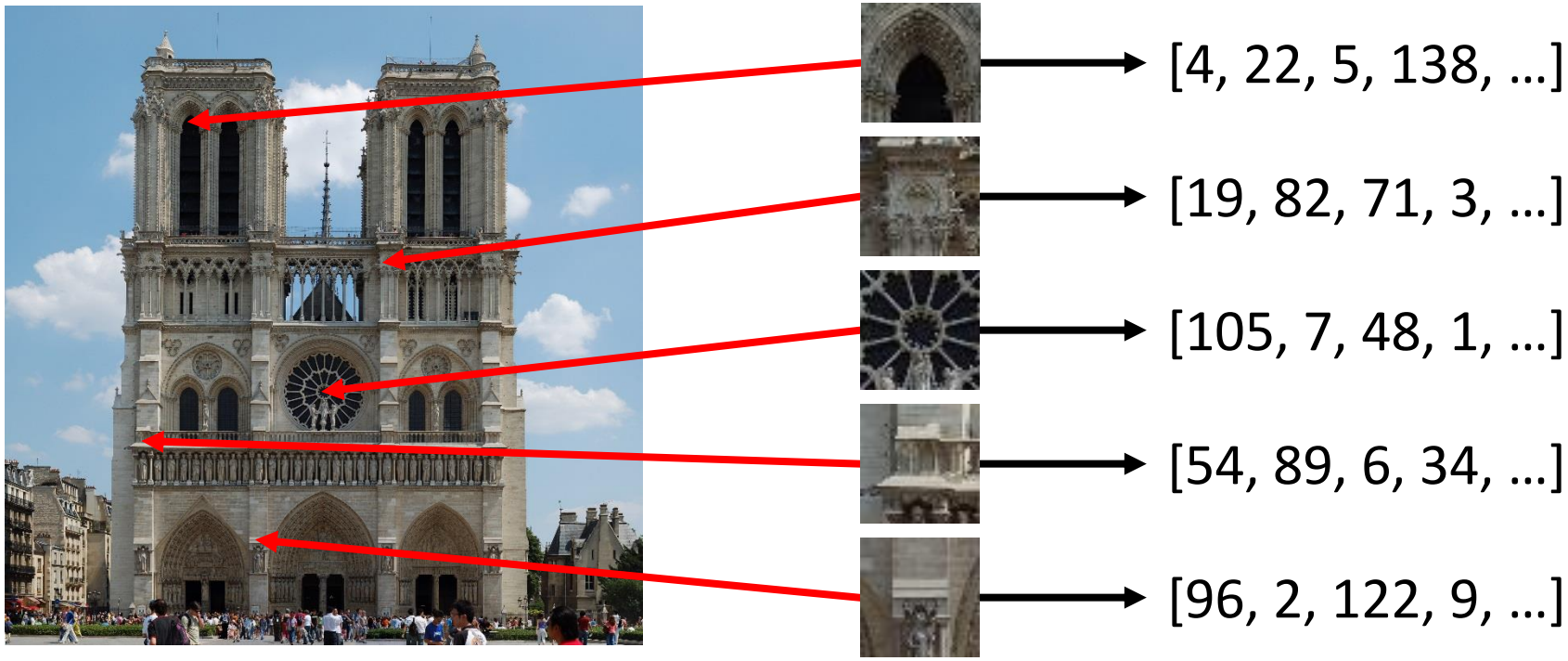


2D Feature Descriptors

- Gradients
  - SIFT, SURF

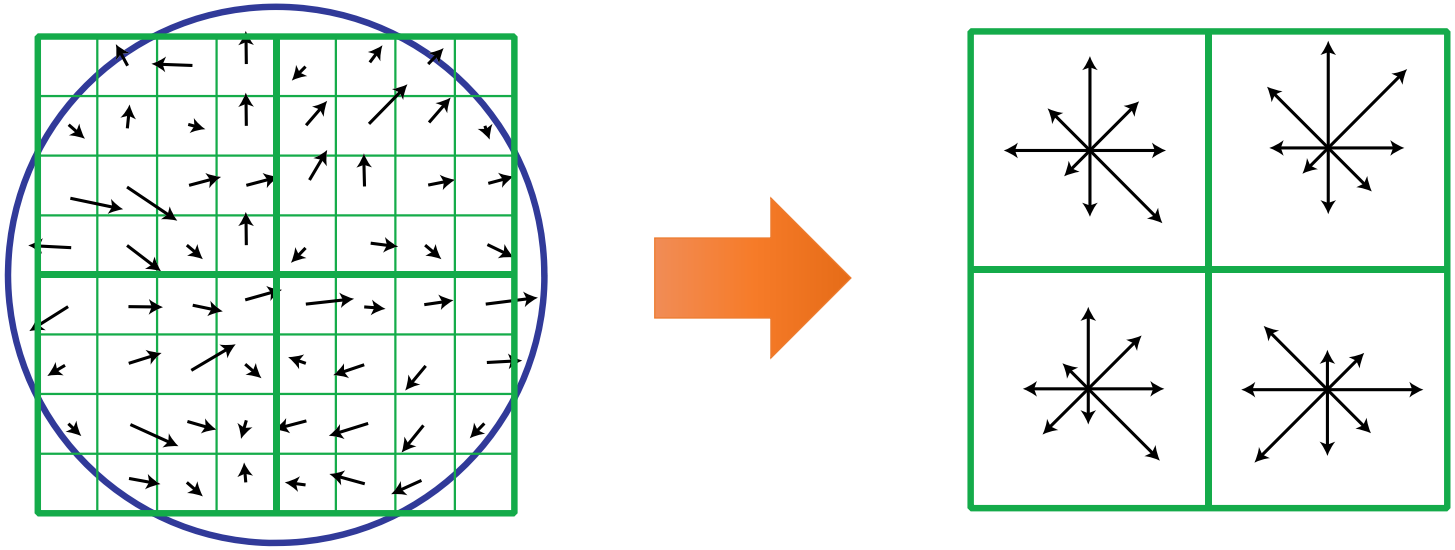
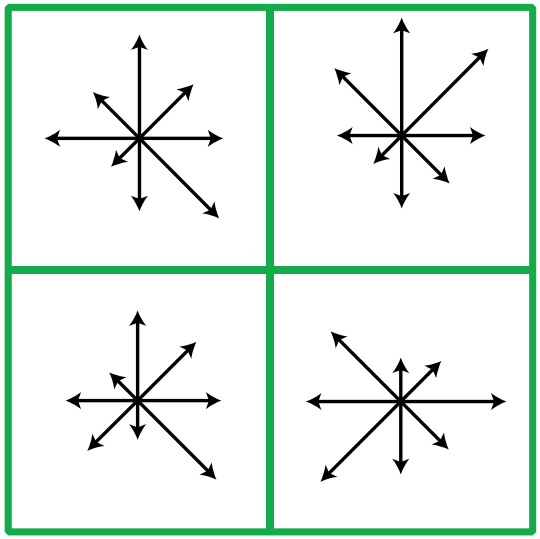


Image Gradients

2D Feature Descriptors

- Gradients
  - SIFT, SURF

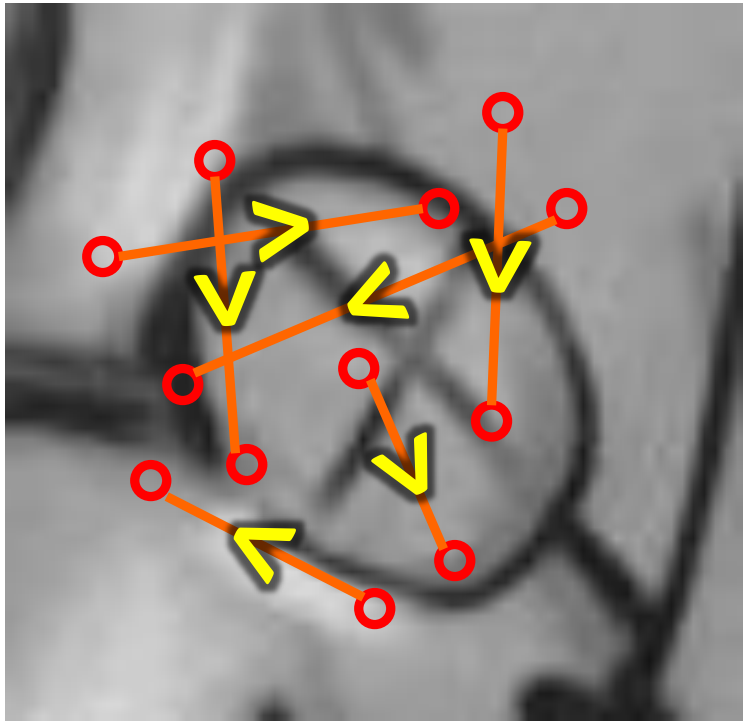


[0.012, 0.492, 0.187,
0.618, 0.741, 0.305, …]

Feature Descriptor

2D Feature Descriptors

- Binary comparisons
  - BRIEF, ORB, BRISK



Descriptor: **0 1 1 0 1 0 …**

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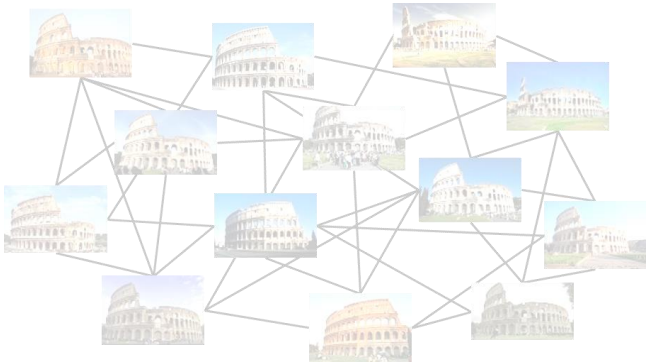

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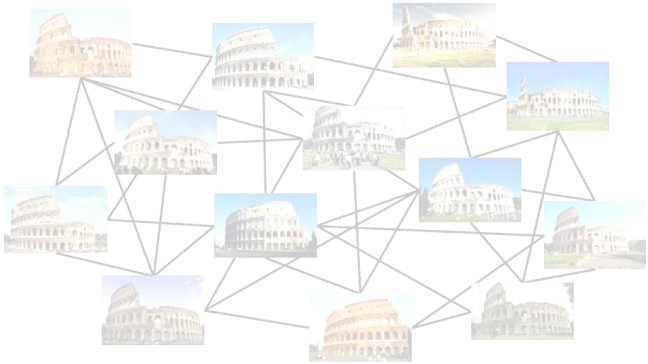
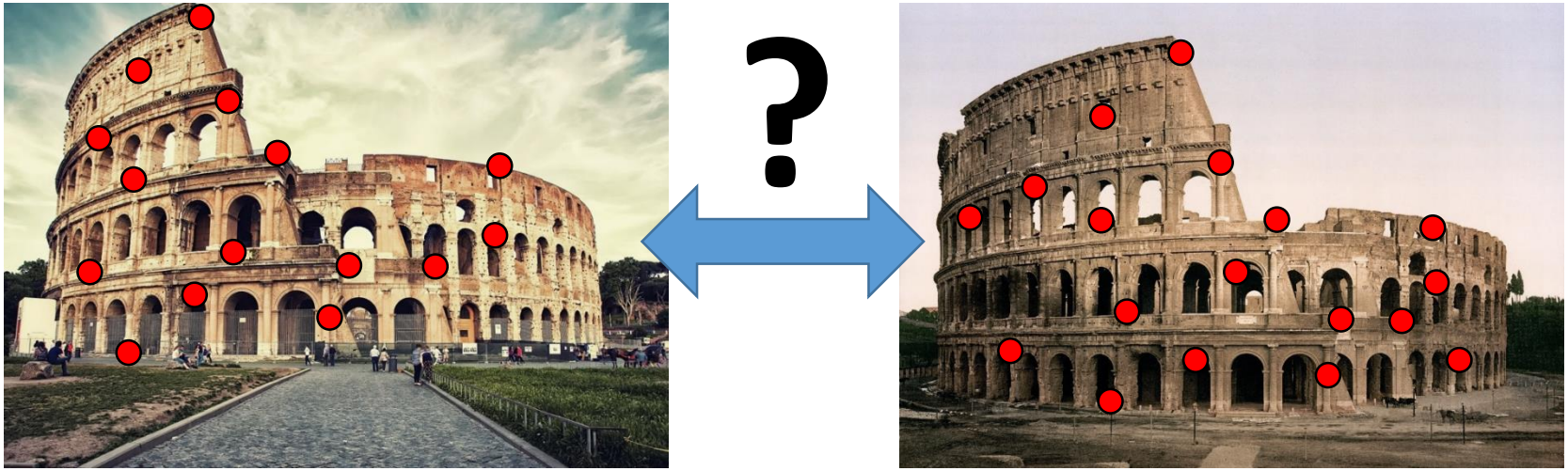
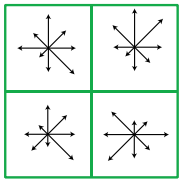


Feature Matching

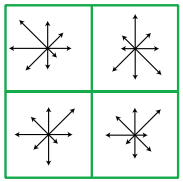


Feature Matching

- Distance metrics (real-valued)
  - Euclidean
  - Dot product



[0.012, 0.492, 0.187, 0.618, 0.741, …]



[0.913, 0.102, 0.003, 0.015, 0.120, …]

Feature Matching

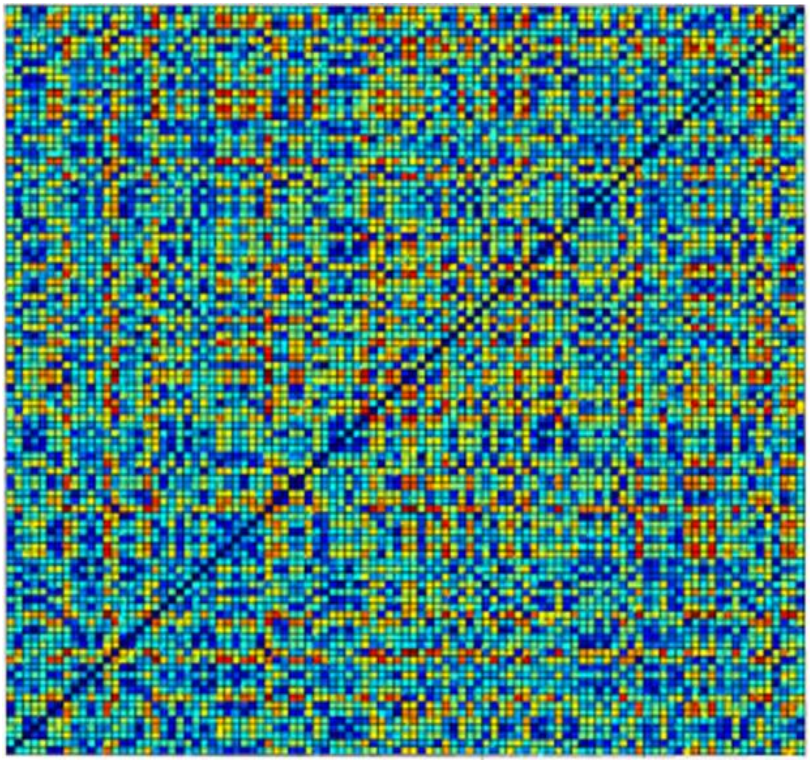
- Distance metrics (binary)
  - Hamming

[0, 0, 1, 0, 1, 1, 1, 0, 1, 1, 0, 1, …]

[0, 1, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1, …]

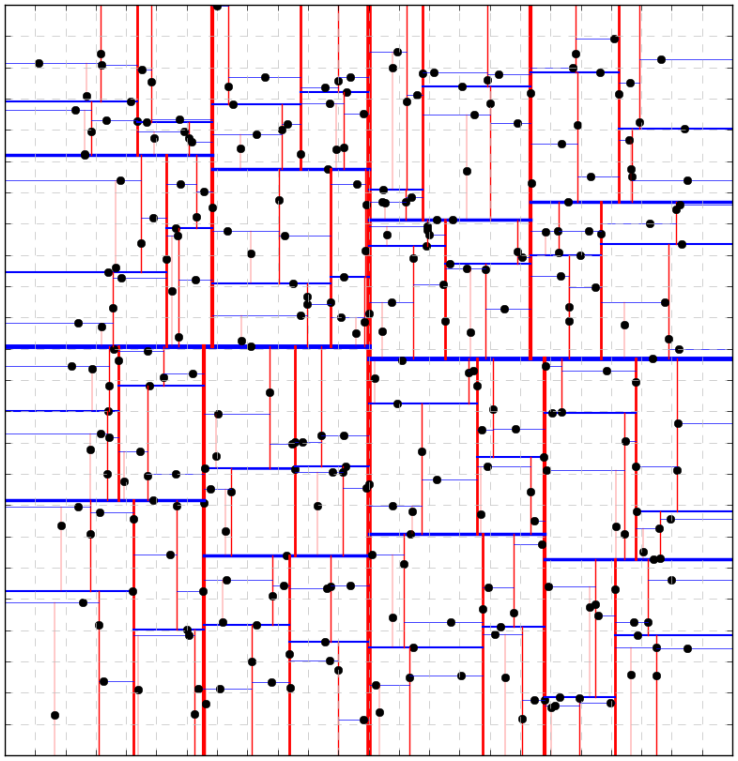
Feature Matching

- Which features to match
  - Exhaustive

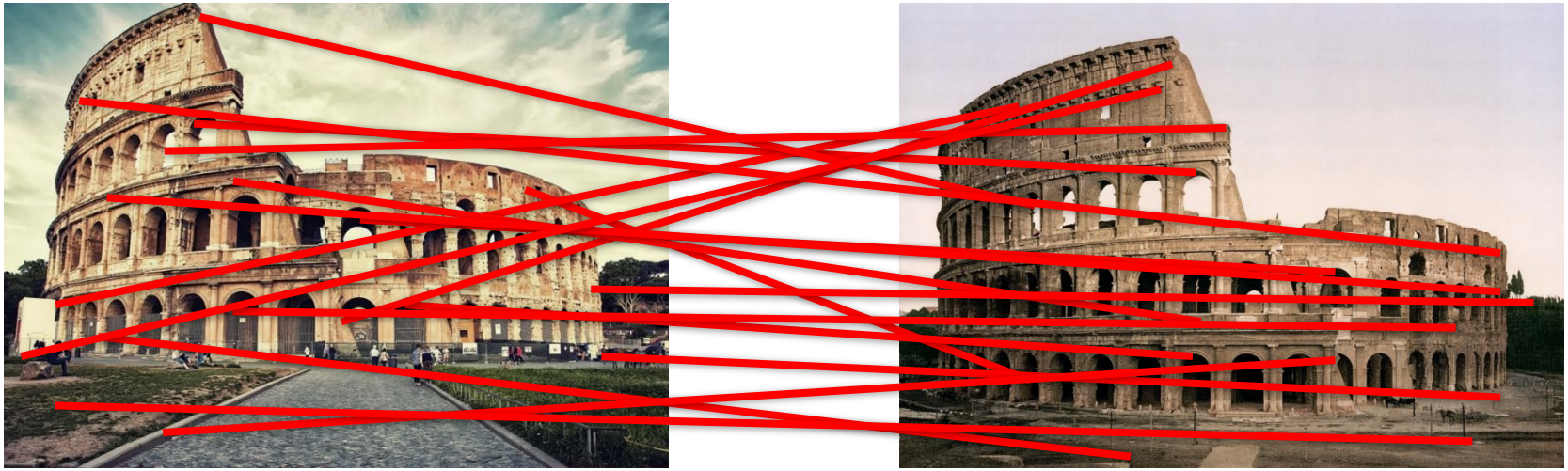


Feature Matching

- Which features to match
  - Exhaustive
  - Approximate

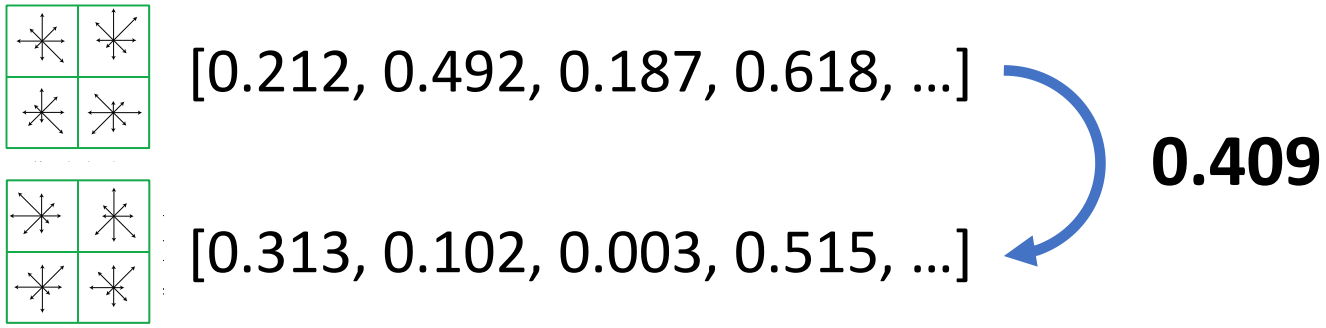


Feature Matching



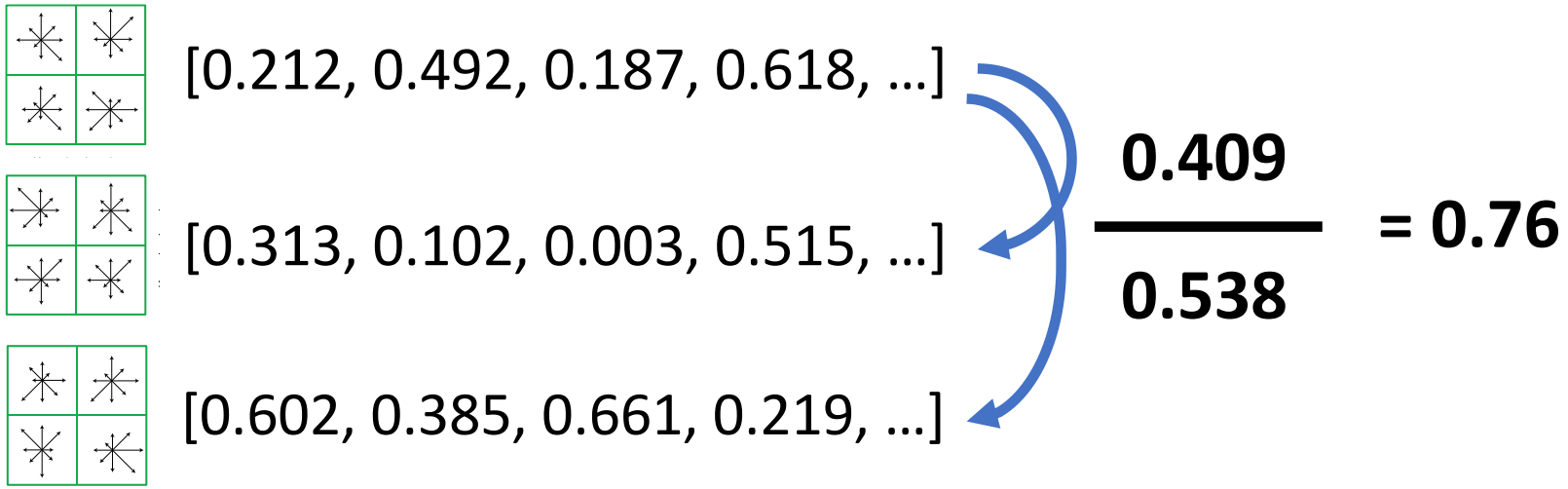
Feature Matching

- Match criteria
  - 1st nearest neighbor
  - Distance threshold



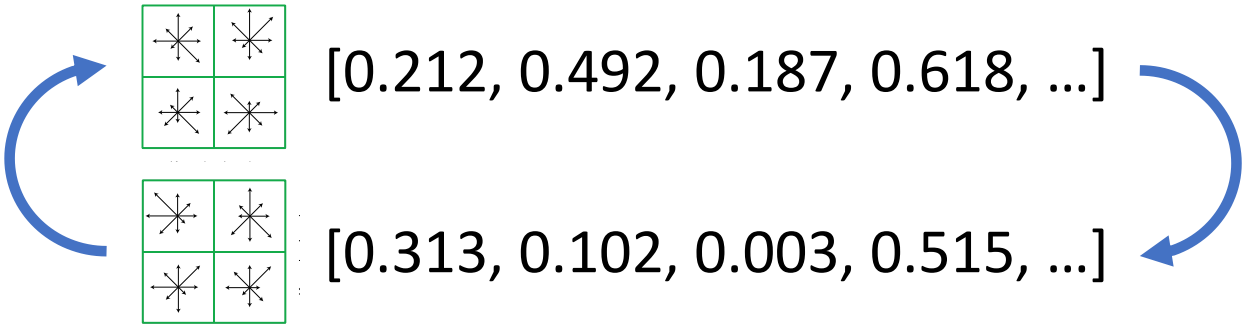
Feature Matching

- Match criteria
  - 1st nearest neighbor
  - Distance threshold
  - Ratio test



Feature Matching

- Match criteria
  - Cross-check
  - One-to-one



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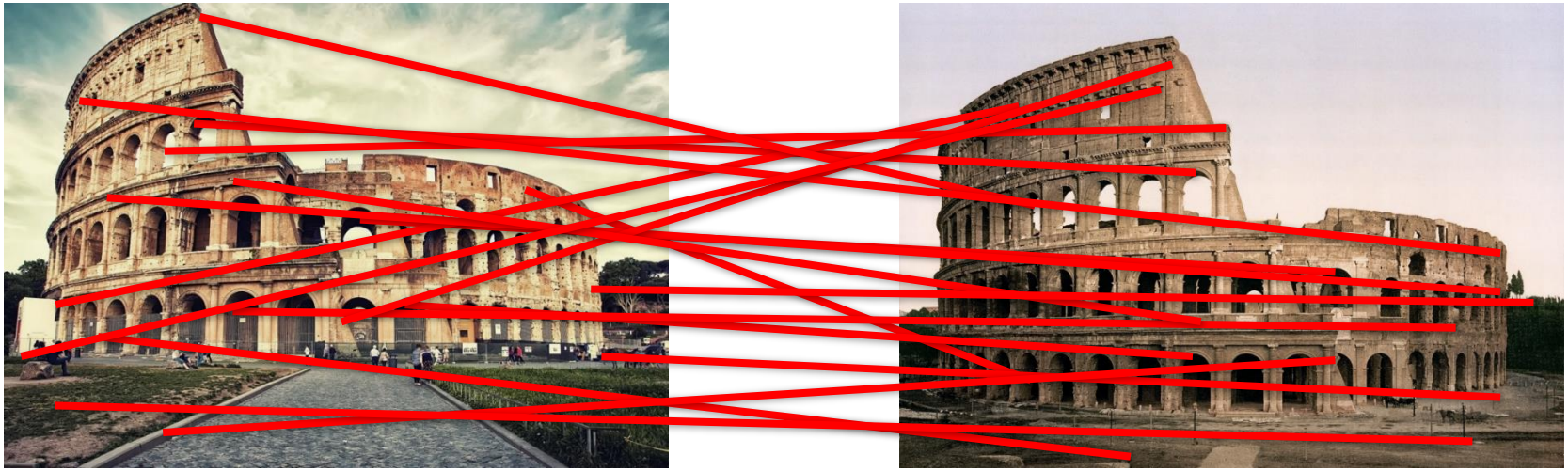

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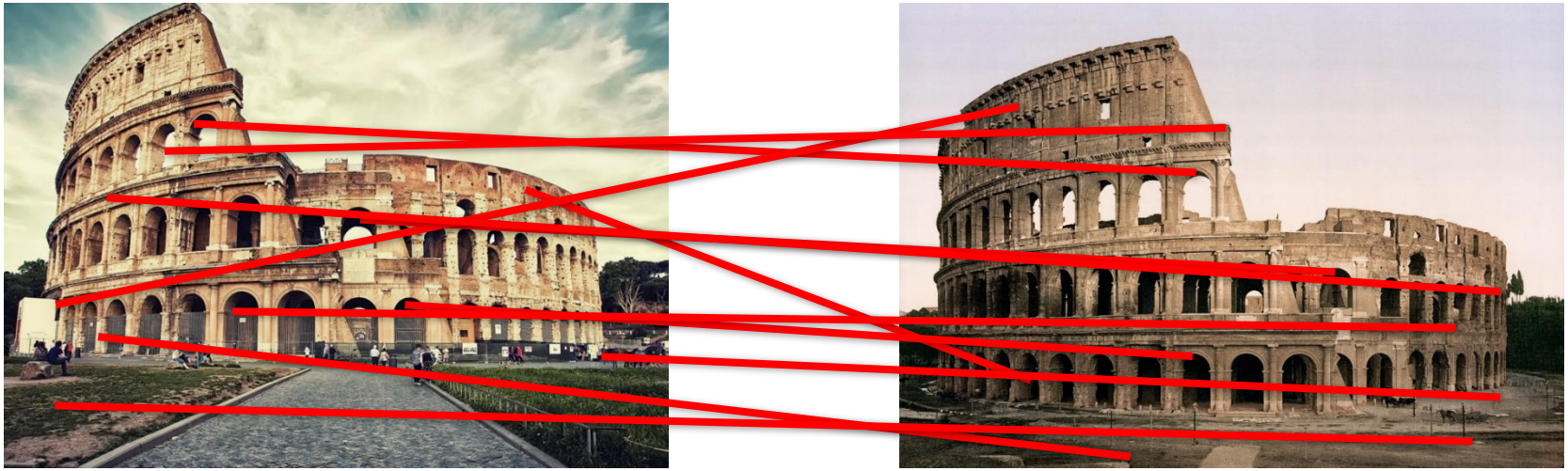

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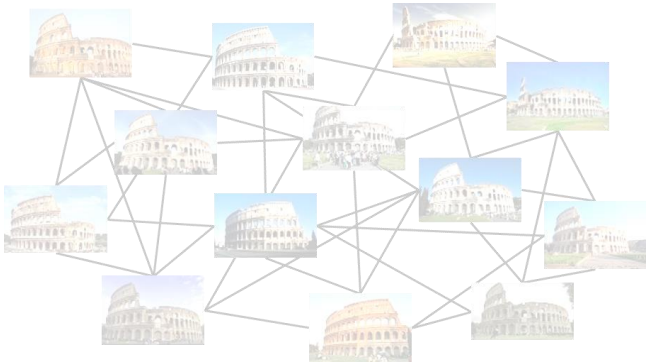

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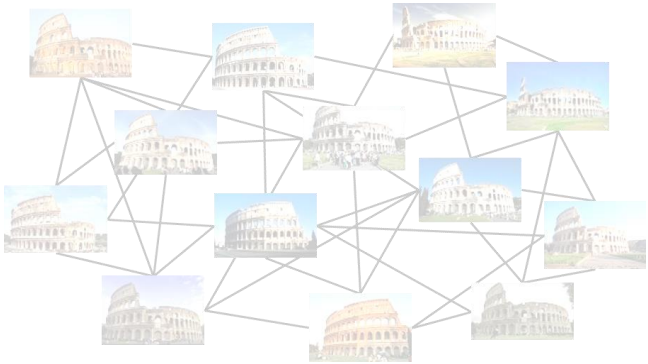
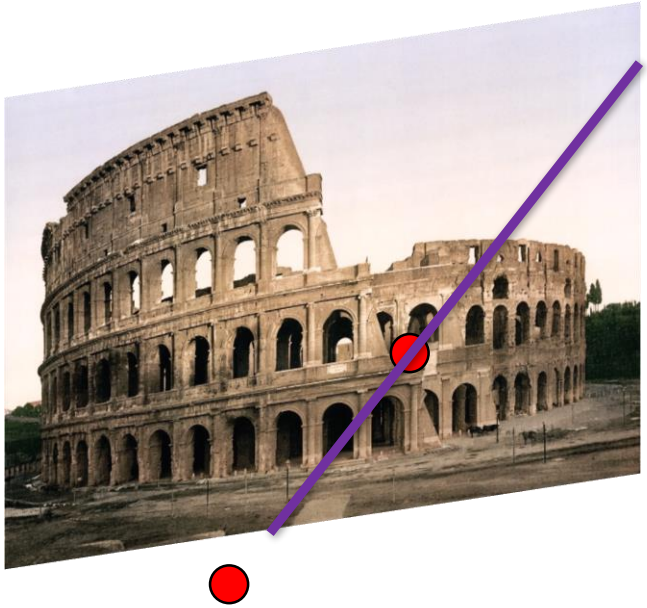


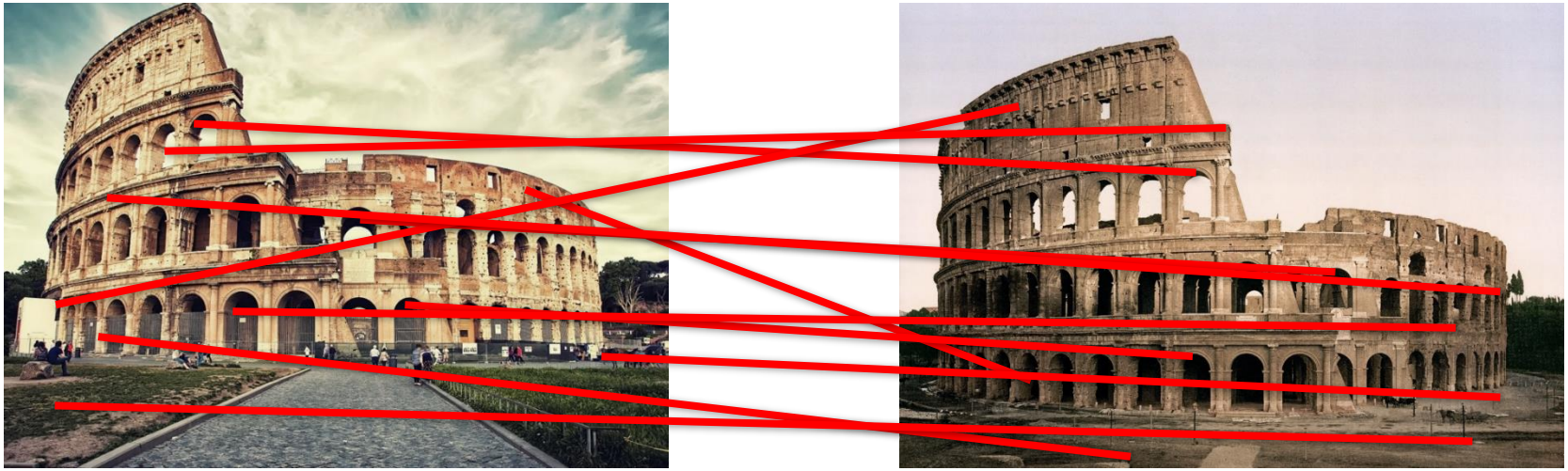
Epipolar Geometry



Epipolar Geometry

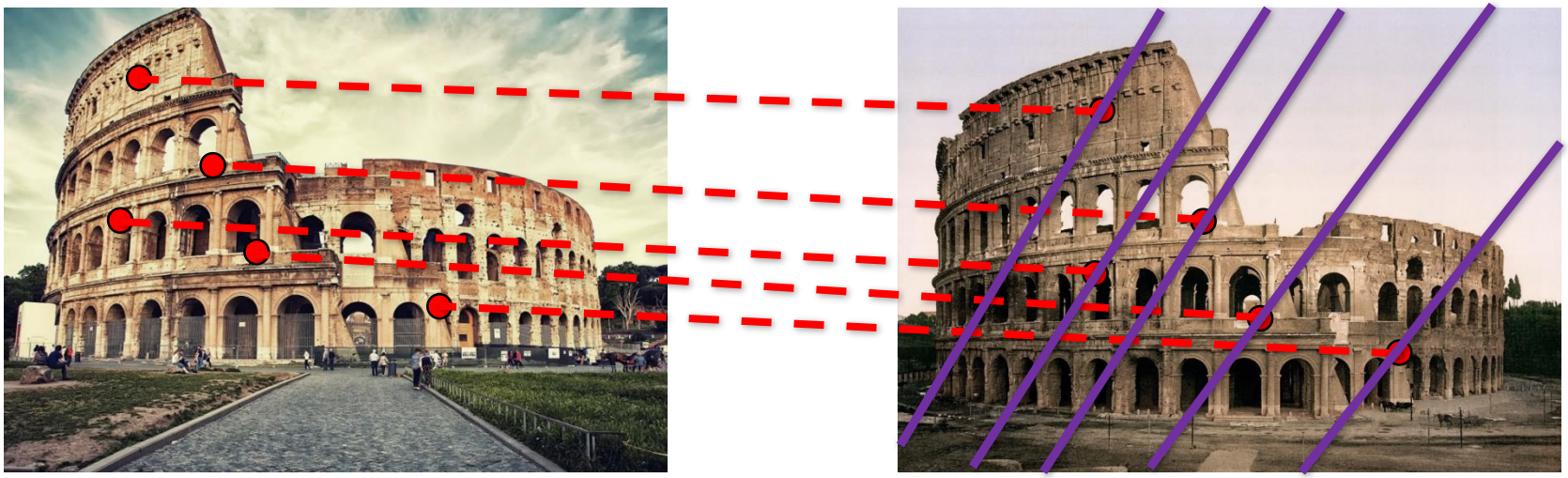
Epipolar Line

Feature Matching



Geometric Verification

- RANSAC (random sample consensus)



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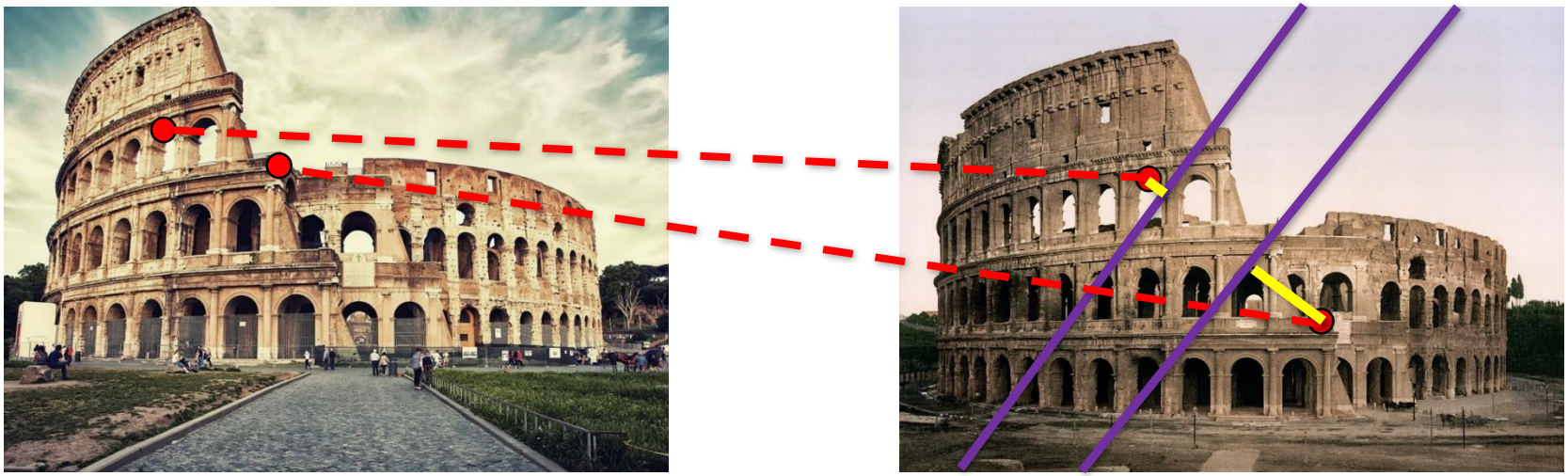
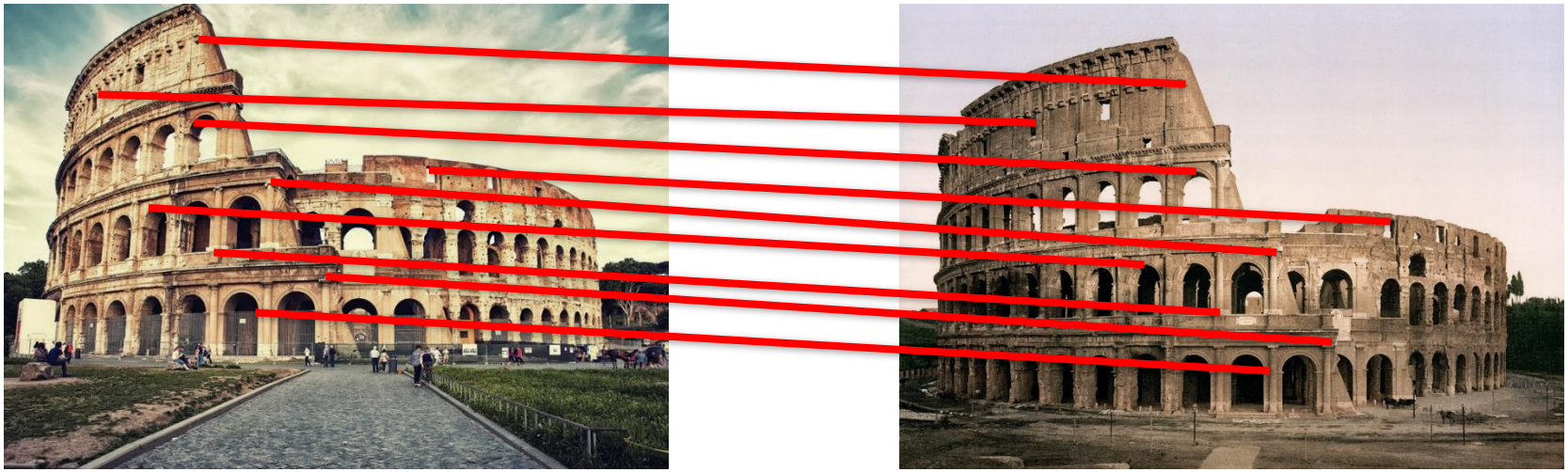


Geometric Verification

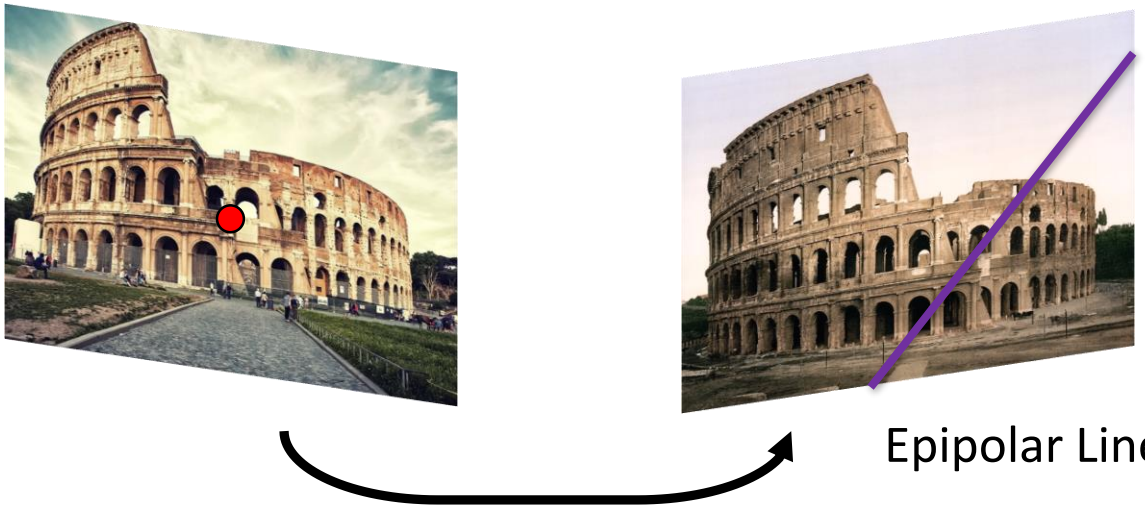
- RANSAC (random sample consensus)
  - Solution with most inliers



Epipolar Geometry

- Camera intrinsics known
  - Essential matrix, **E** (5 points)
- Camera intrinsics unknown
  - Fundamental matrix, **F** (7 points)

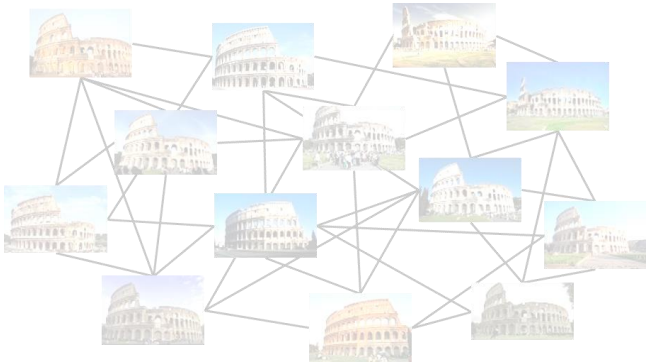
$$\mathbf{K} = \begin{bmatrix} f_x & & c_x \\ & f_y & c_y \\ & & 1 \end{bmatrix}$$



Outline – Data Association

- 2D features → Image registration
  - Features
  - Matching
  - Verification

- Image registration → Connected components
  - Exhaustive
  - Image retrieval
  - Clustering
  - Streaming



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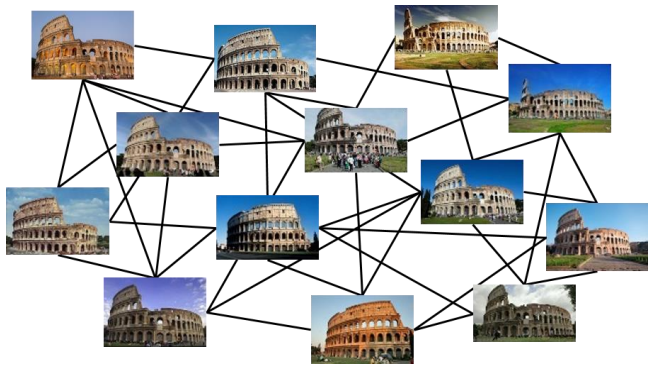

Connected Component Discovery

- How to discover related images?
- Exhaustive matching
- Nearest neighbors
  - Clustering and streaming are based off of this

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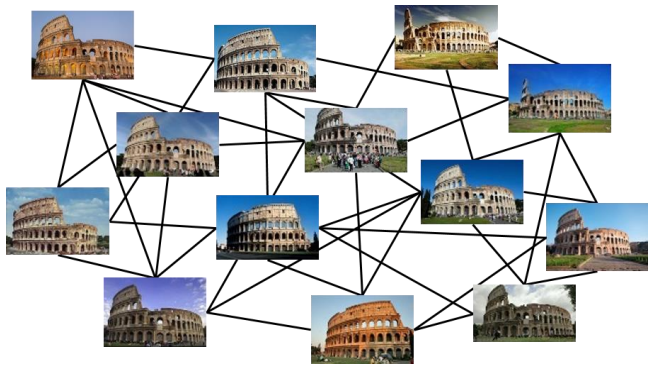
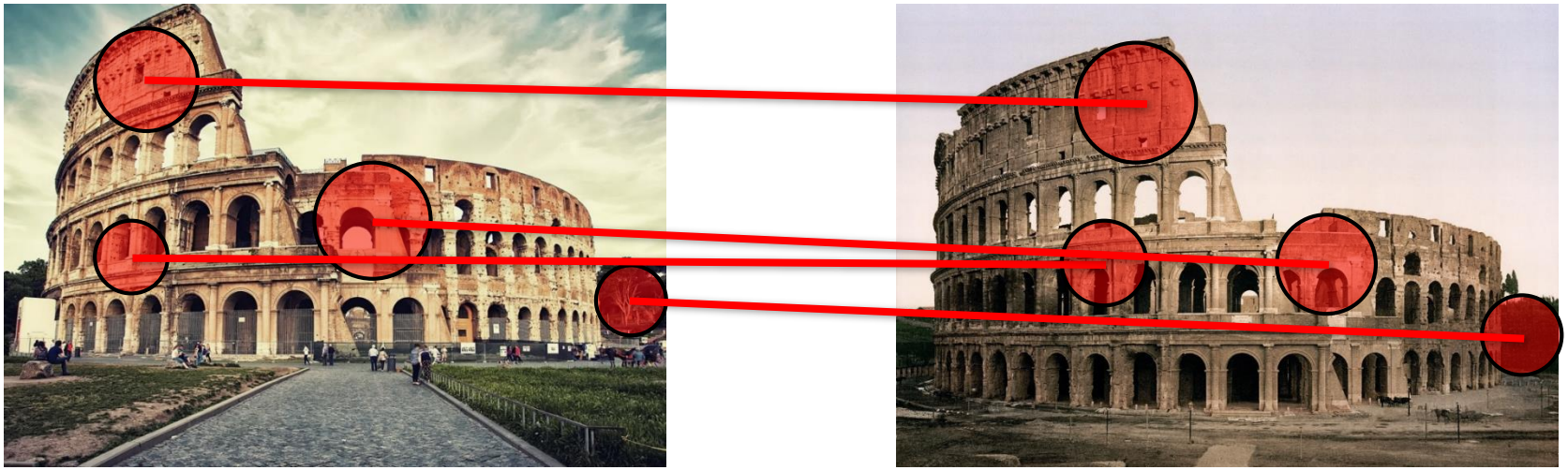


Exhaustive Matching

- Preemptive matching
  - Wu, 3DV 2013
- Determine candidate image pairs to verify



Exhaustive Matching

- Two-view geometry classification
  - Schönberger, CVPR 2015, GCPR 2015
- Determine candidate image pairs to verify
  - Image pair descriptor

Exhaustive Matching

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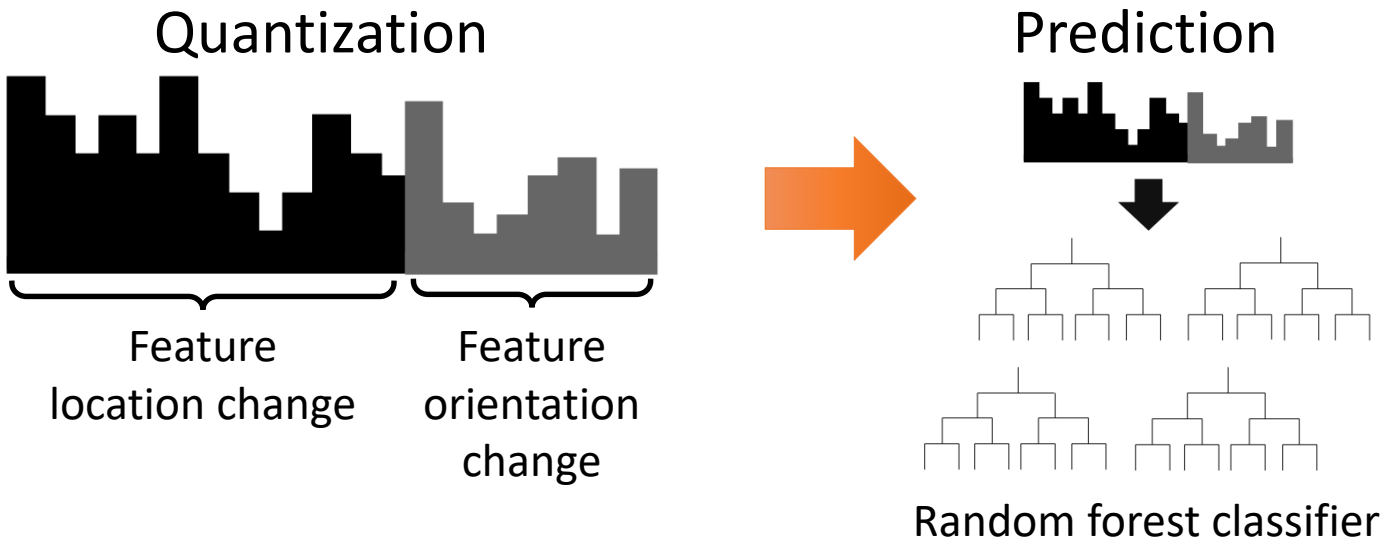

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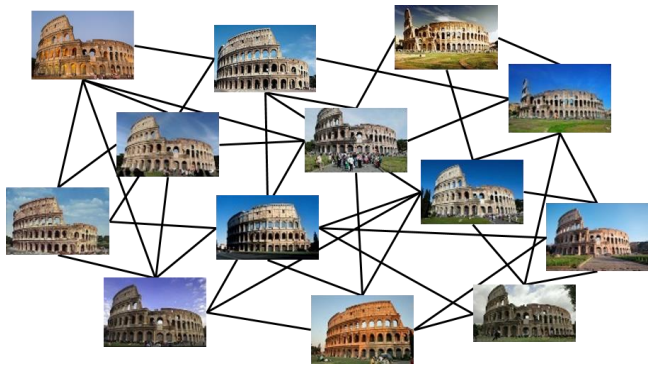

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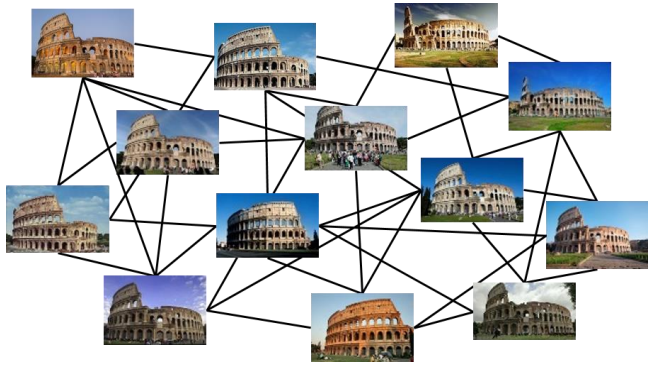
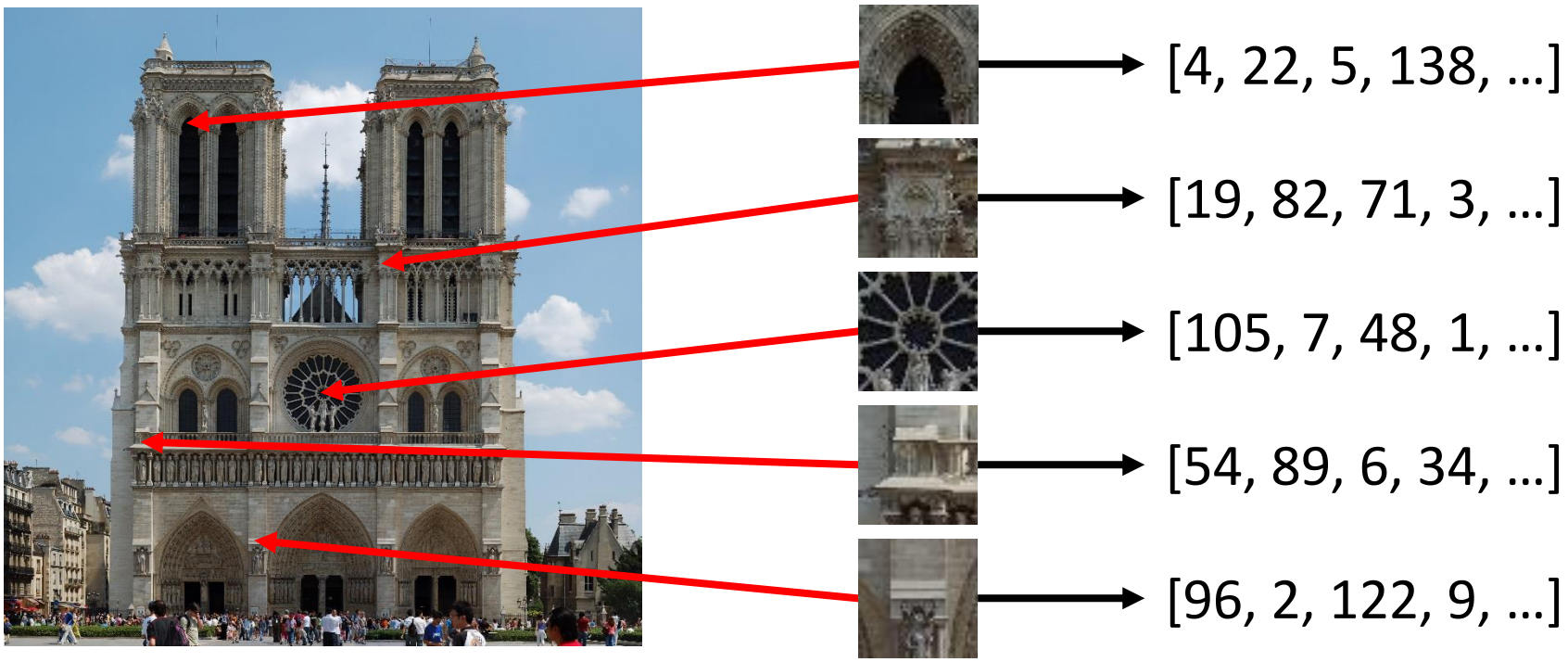


Image Retrieval

- Bag of words



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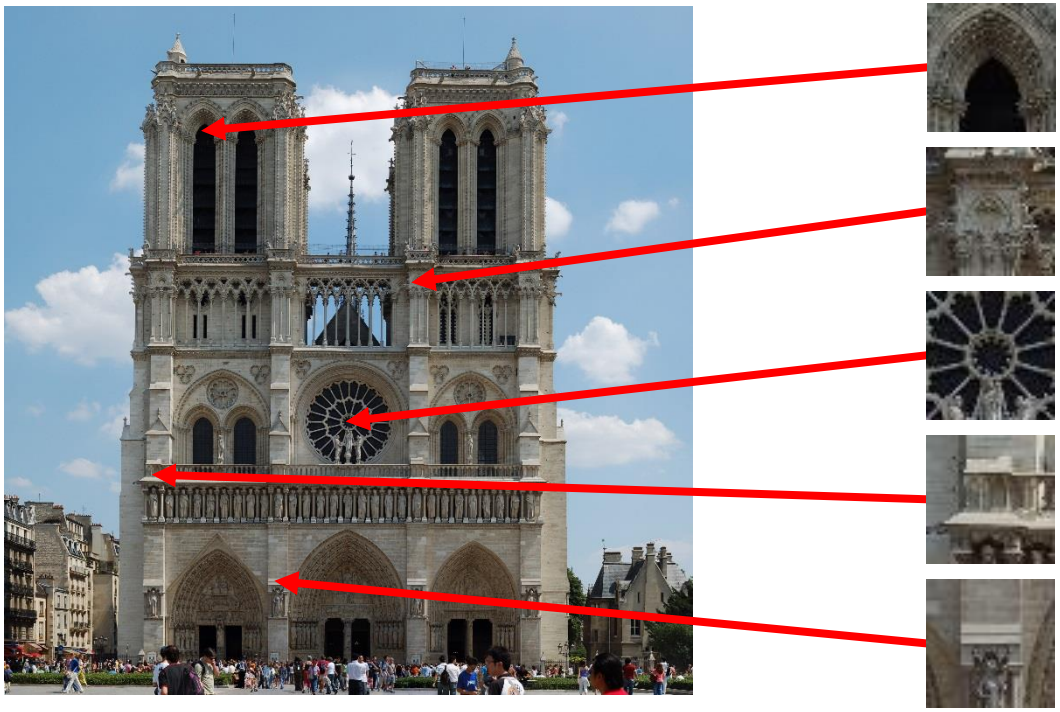

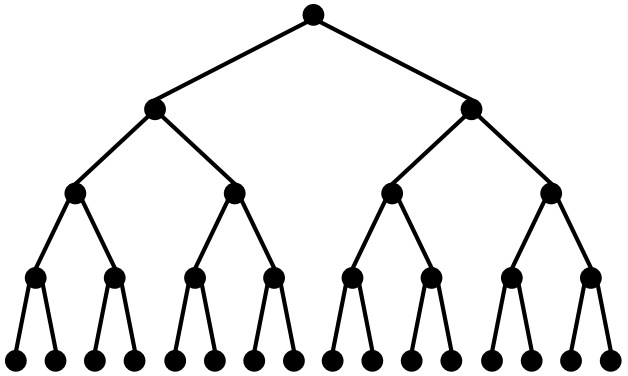

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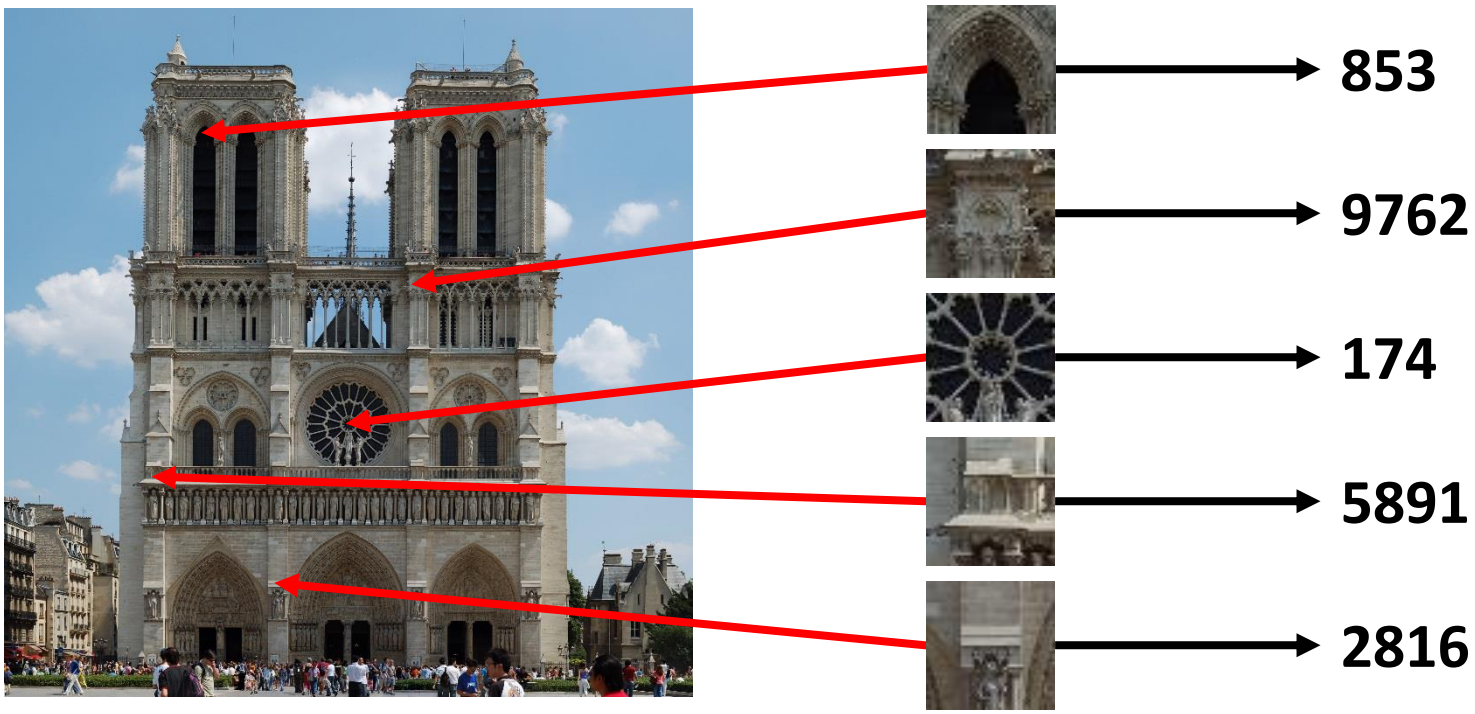

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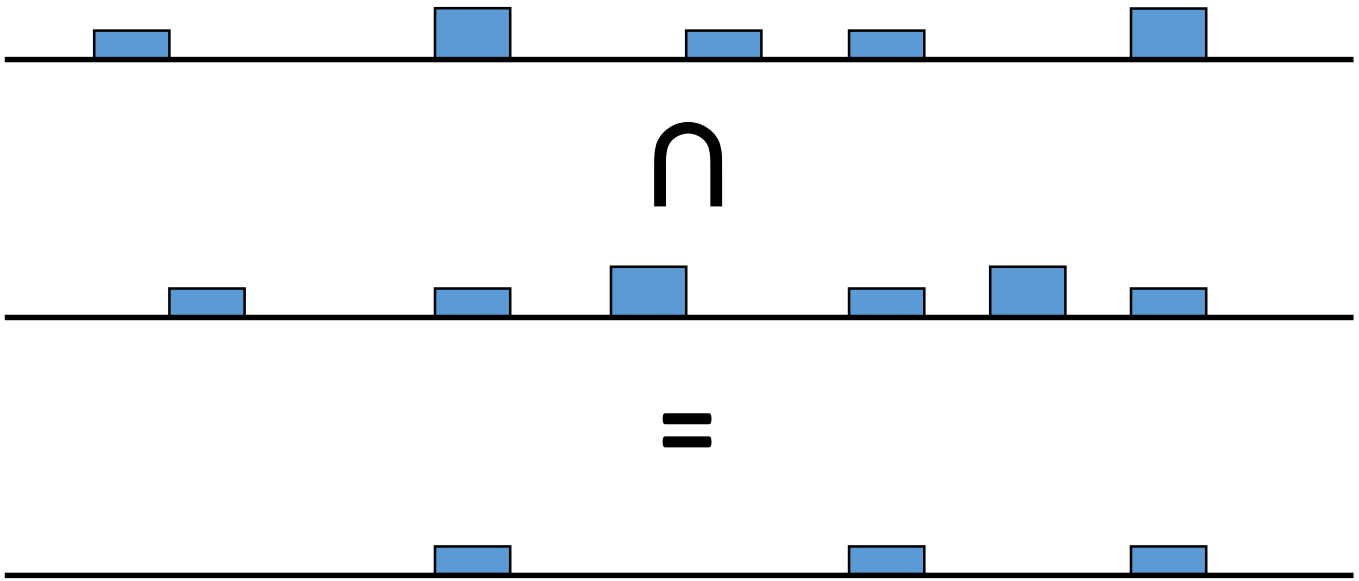
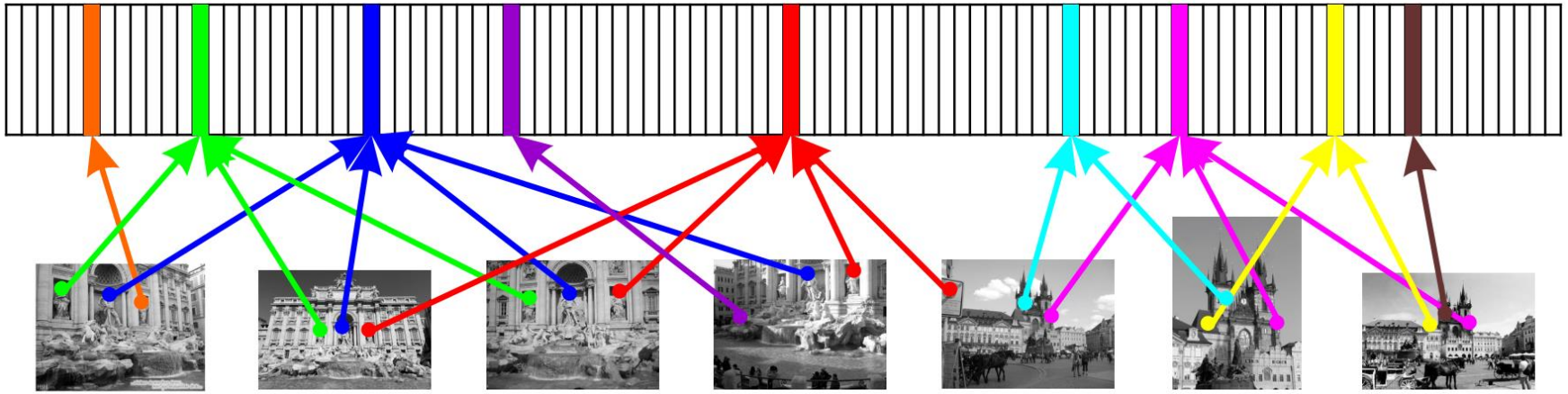


Image Retrieval

- VocMatch
  - Havlena and Schindler, ECCV 2014



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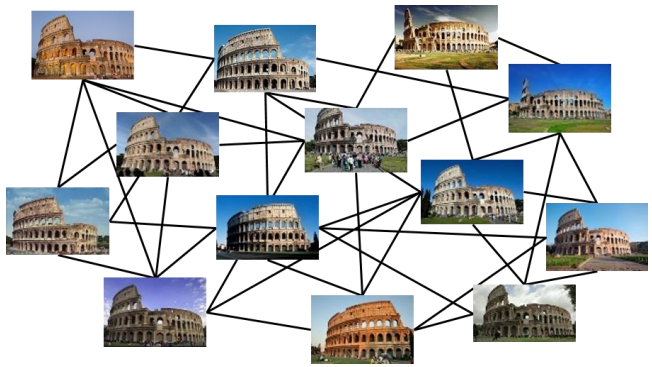

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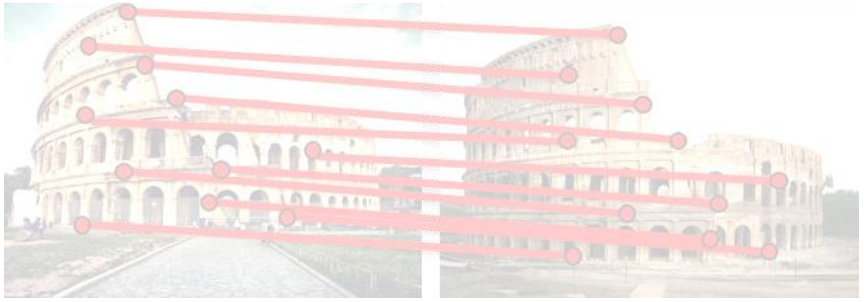

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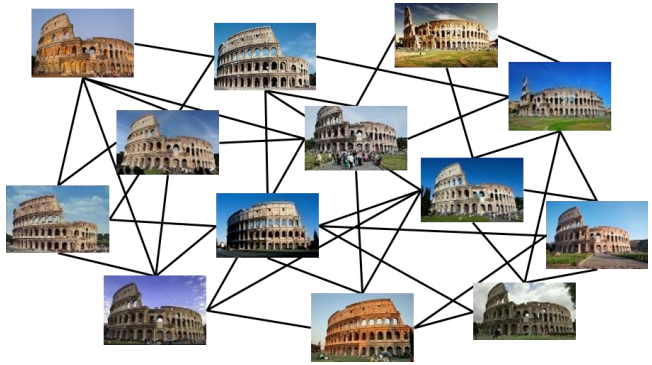
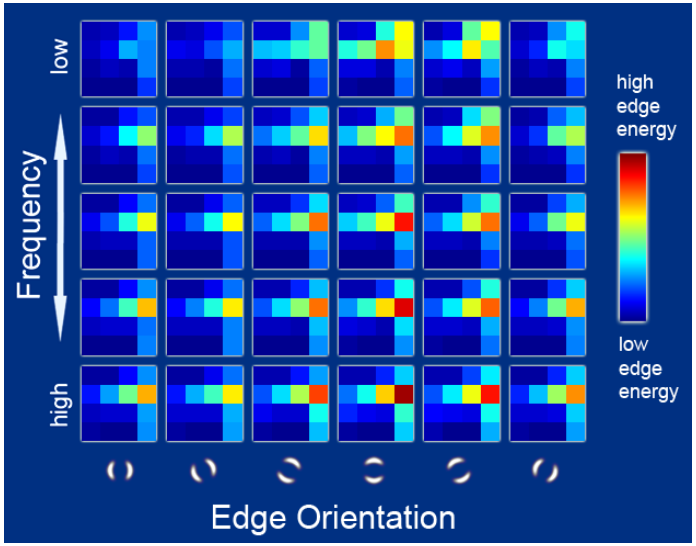


Clustering

- Frahm et al, ECCV 2010
- GIST



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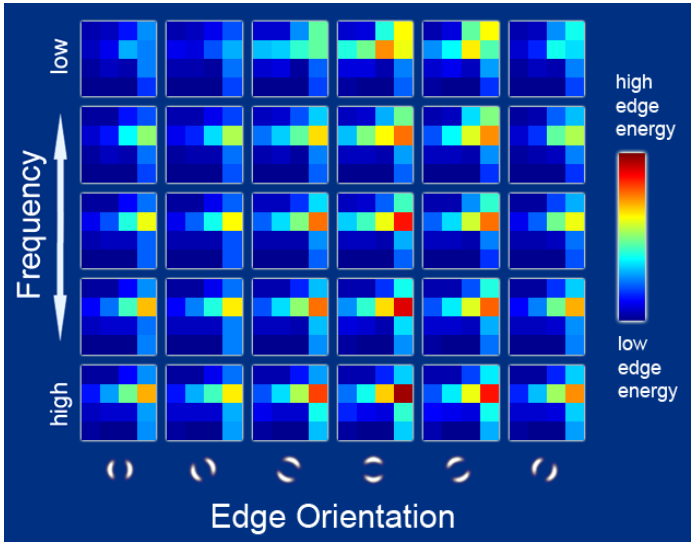
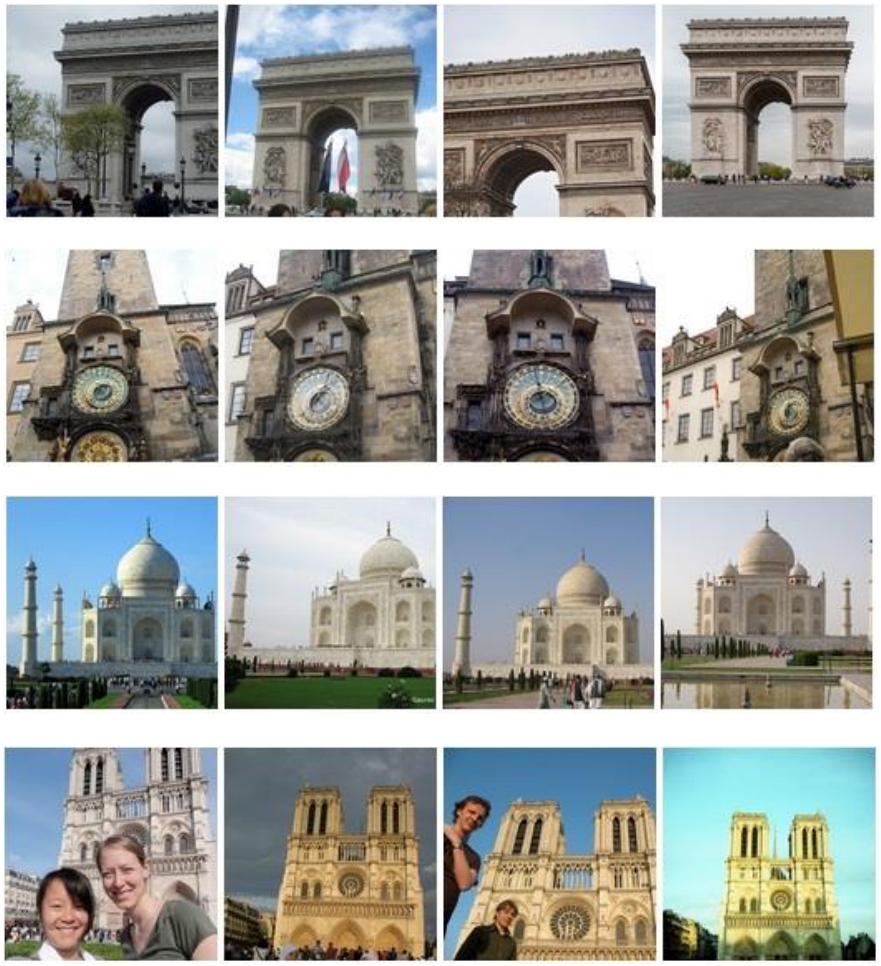
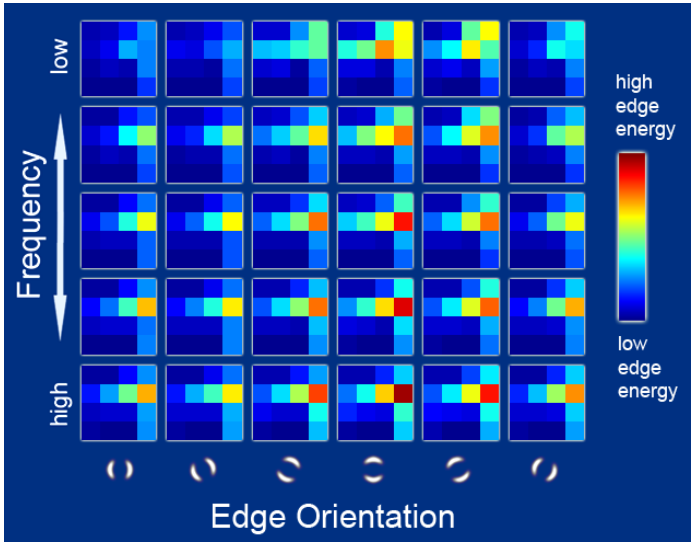
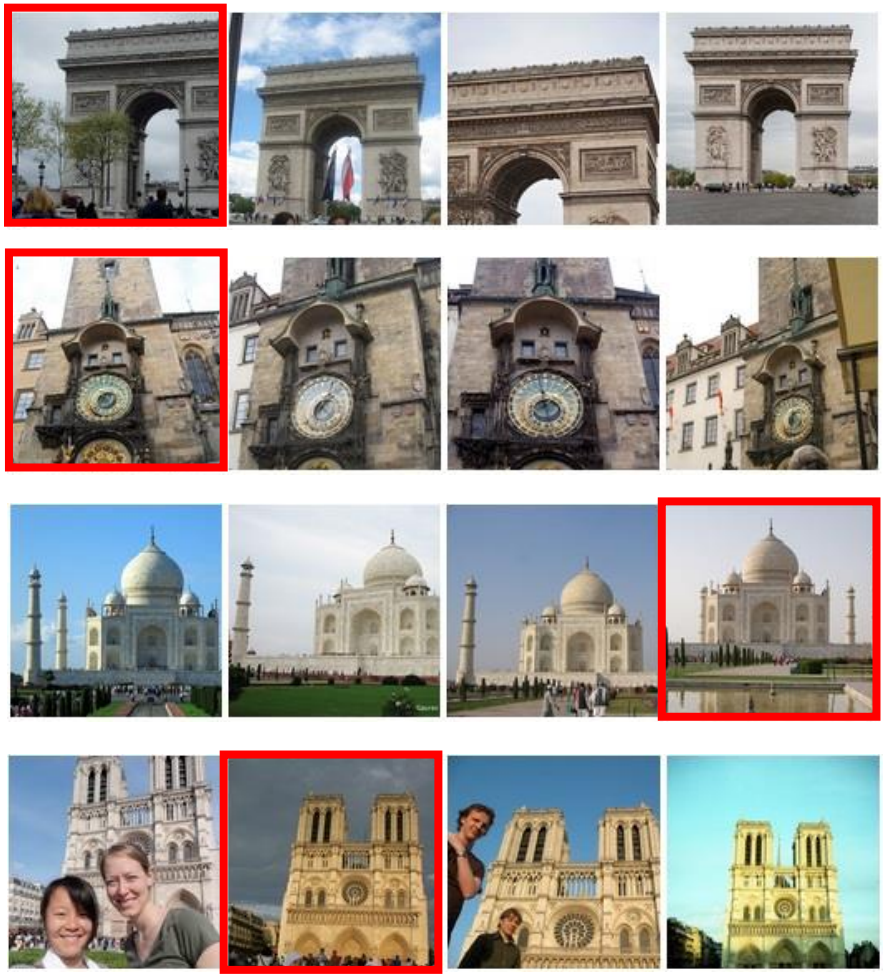




GIST Clustering

- Frahm et al, ECCV 2010
- GIST





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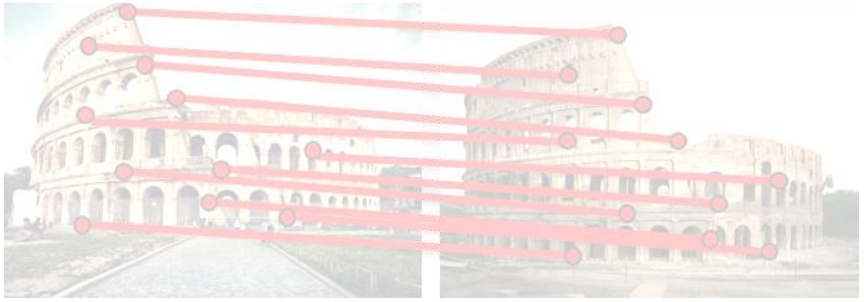

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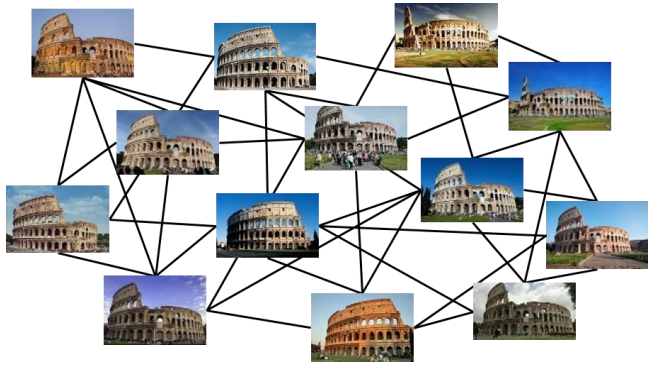
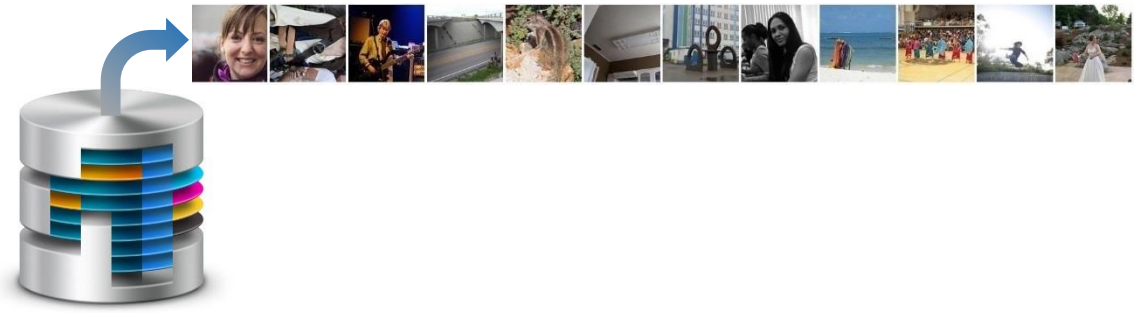


Streaming

- Limited memory budget
- Limited compute budget
- Handle very large datasets

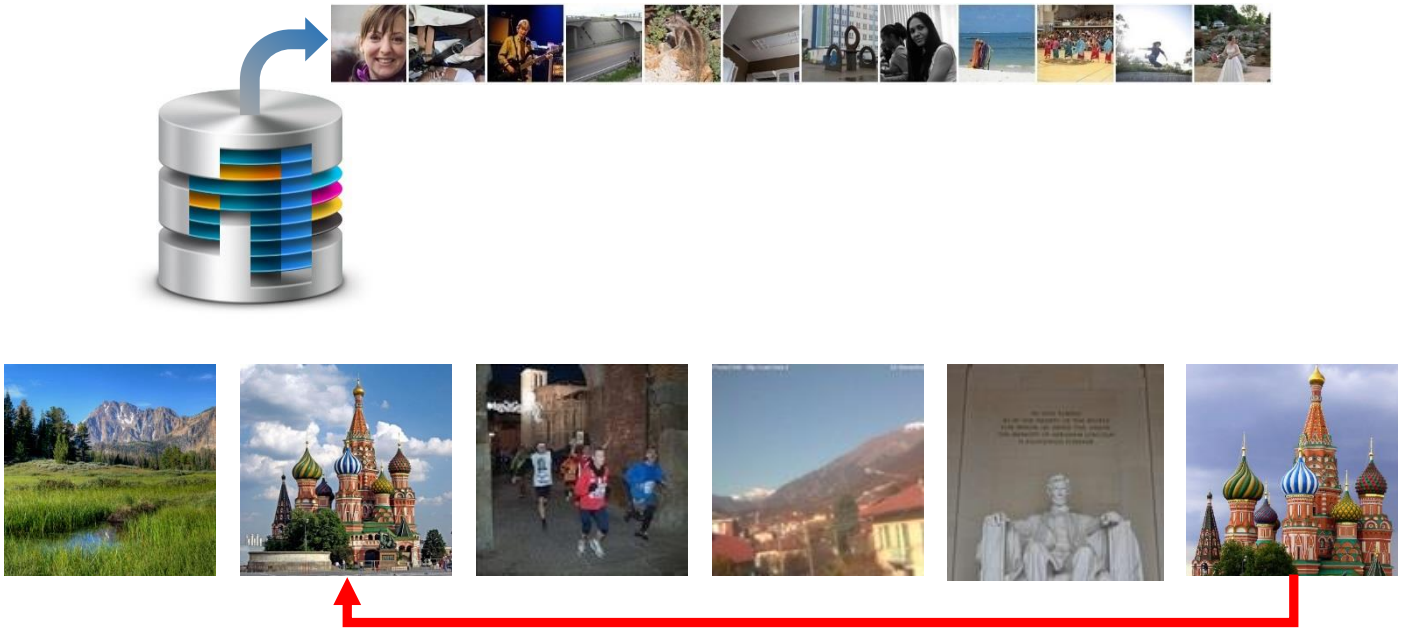
Streaming

- Read images sequentially from disk
- Read each image only once
- Keep images in memory only as long as necessary

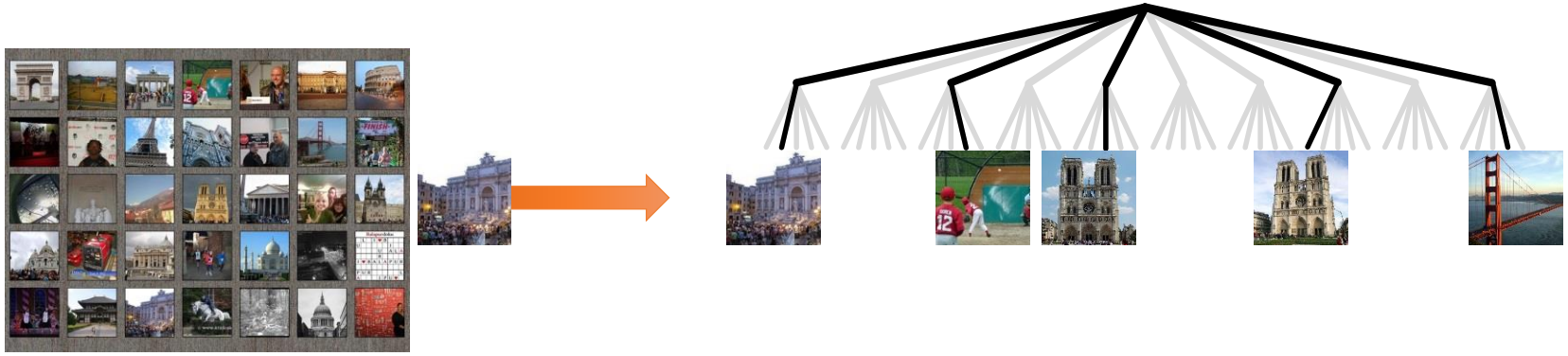


Challenges of Streaming

- Limited window in which to perform association
- No control over image order



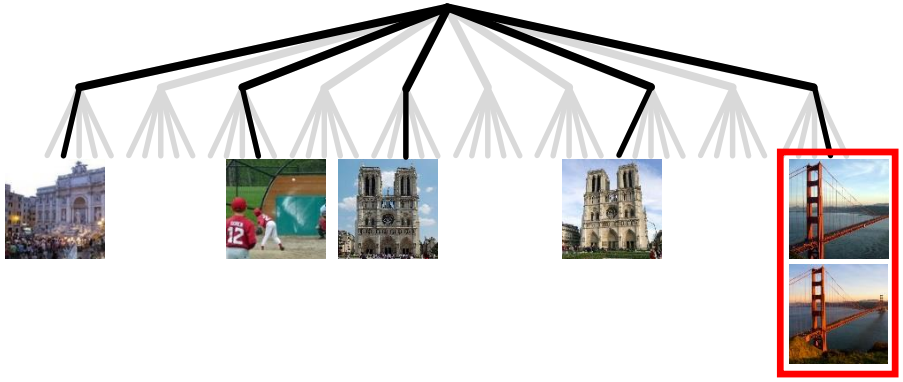
Streaming Data Association



100M Images

Streaming Data Association

100M Images



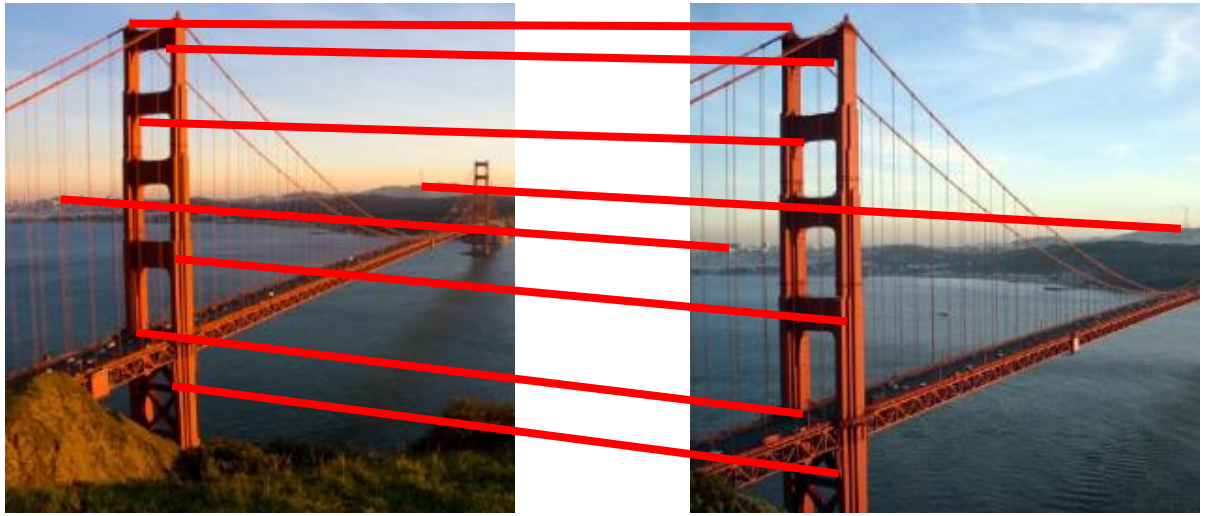
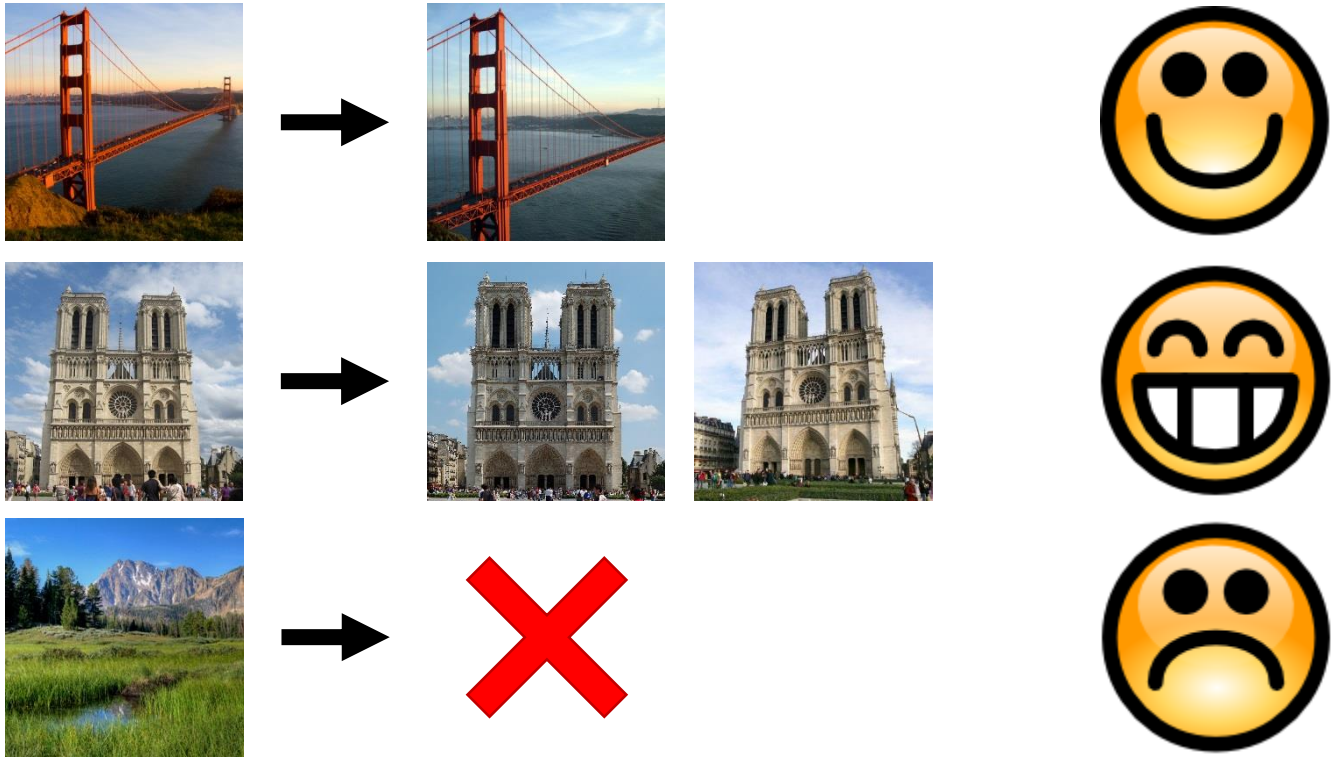


Image Registration



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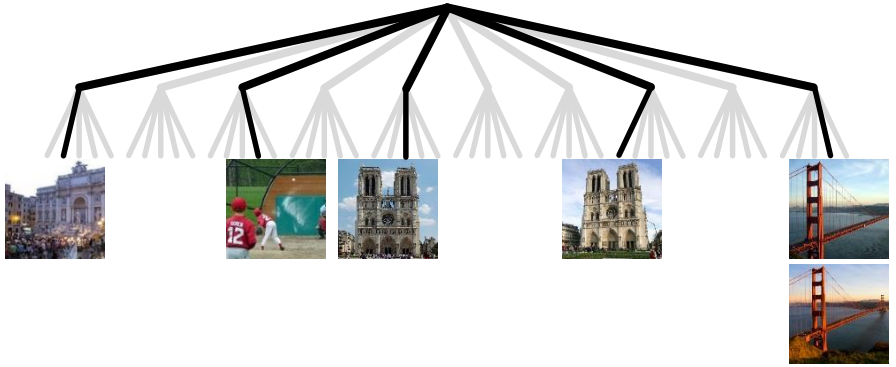

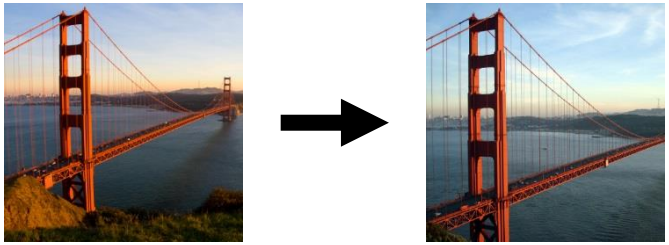

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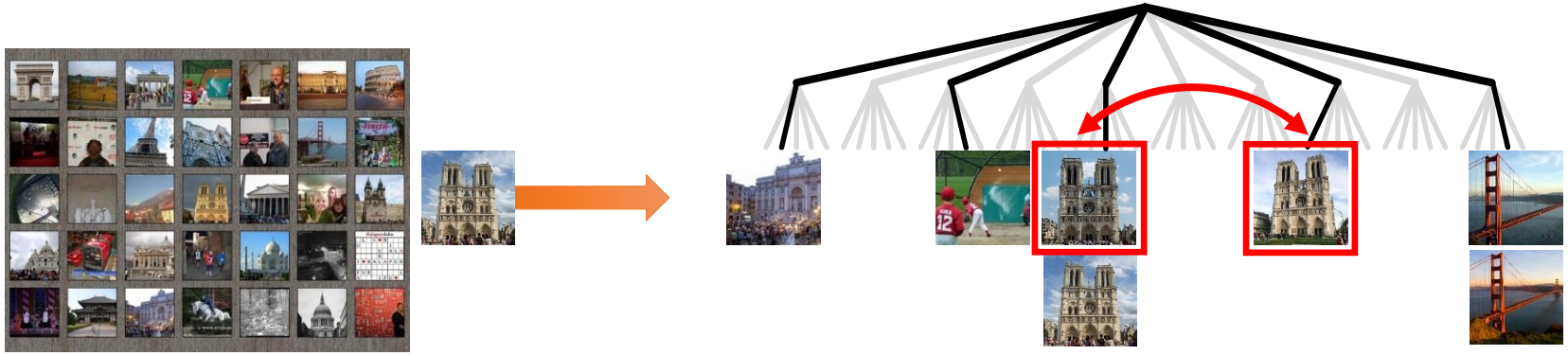

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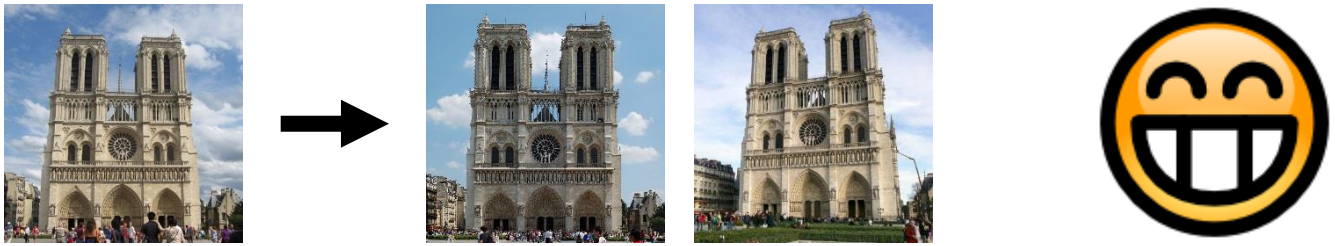

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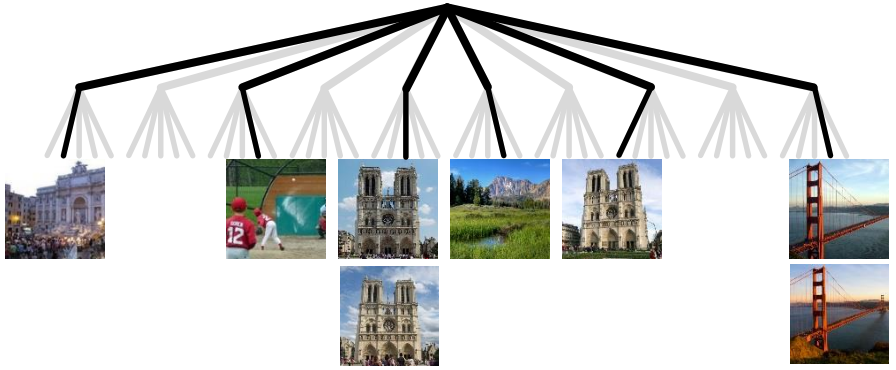
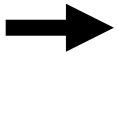
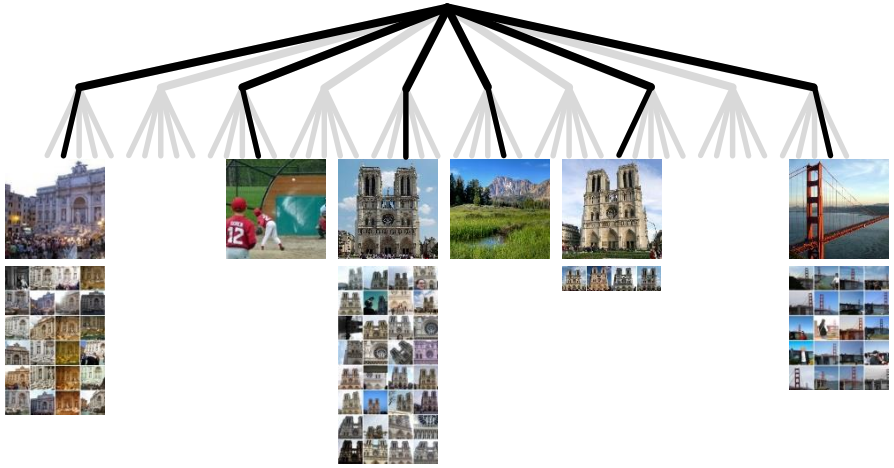




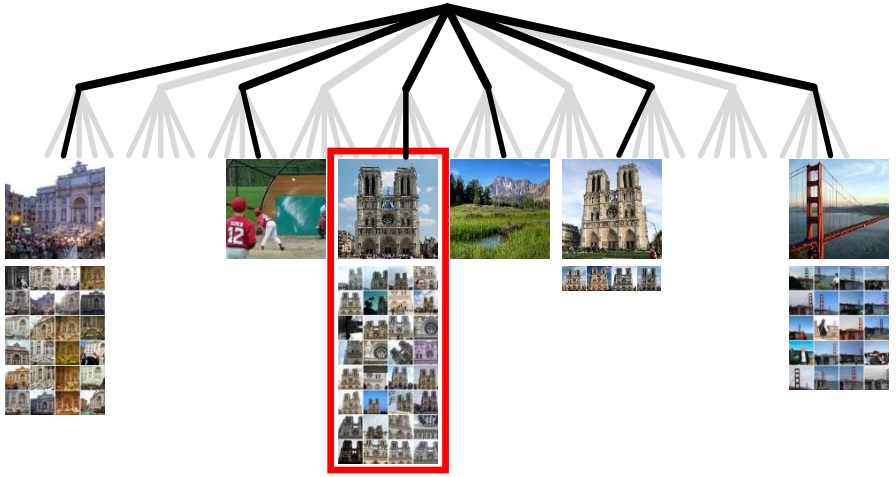
Streaming Data Association

100M Images

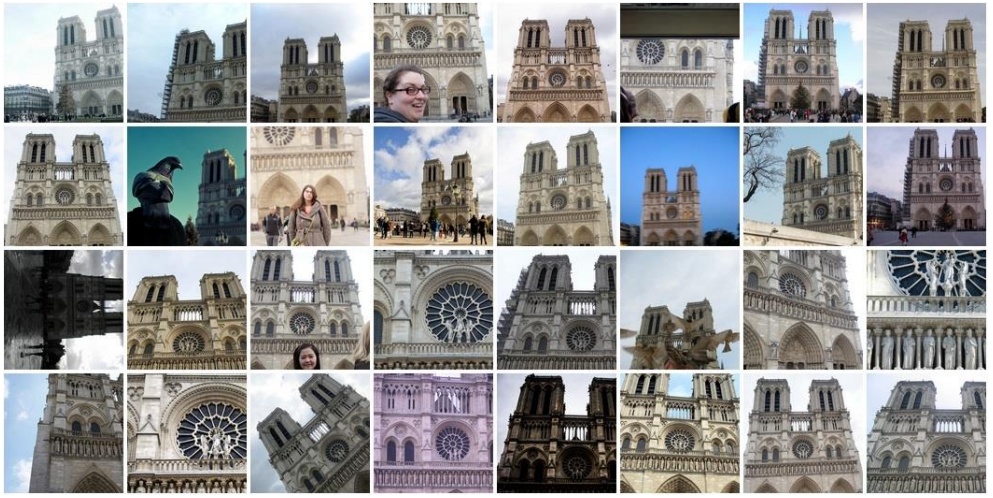


Cluster Formation

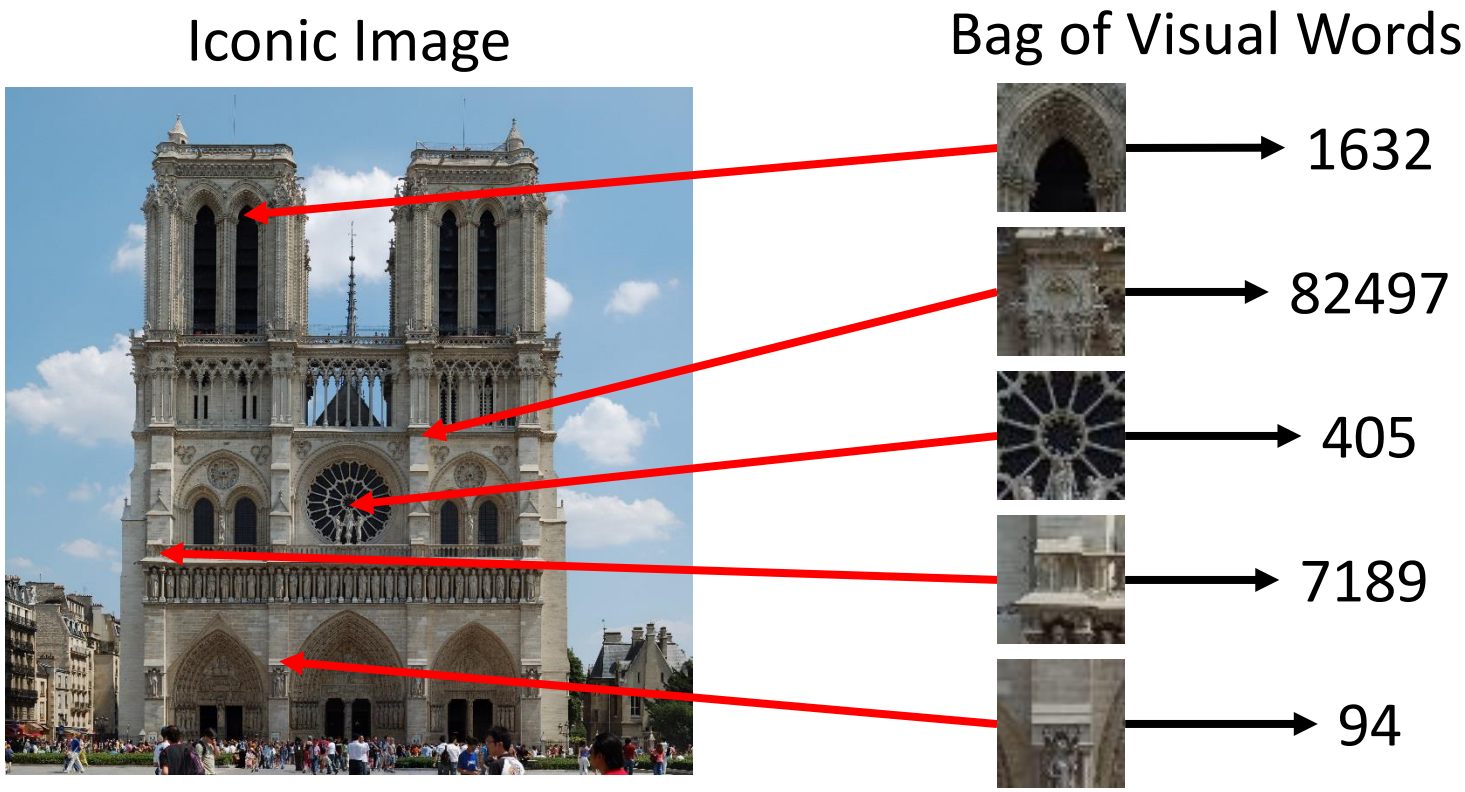
100M Images



Iconic Image



Cluster Representation

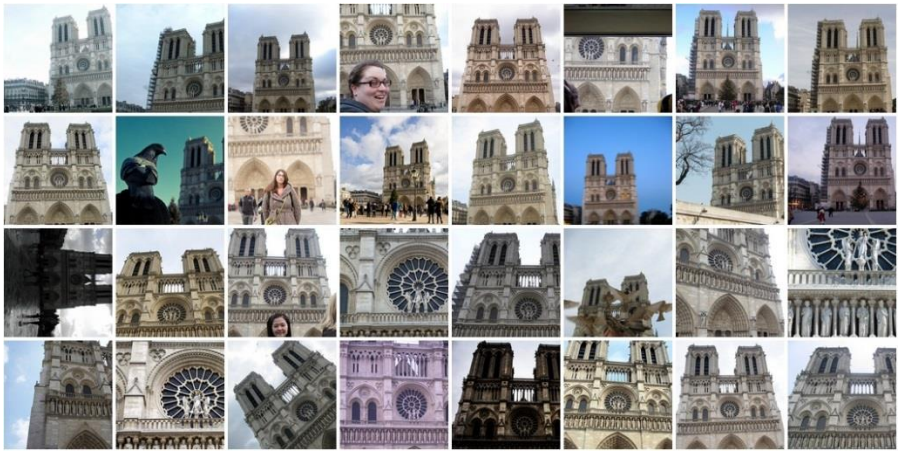


Cluster Representation

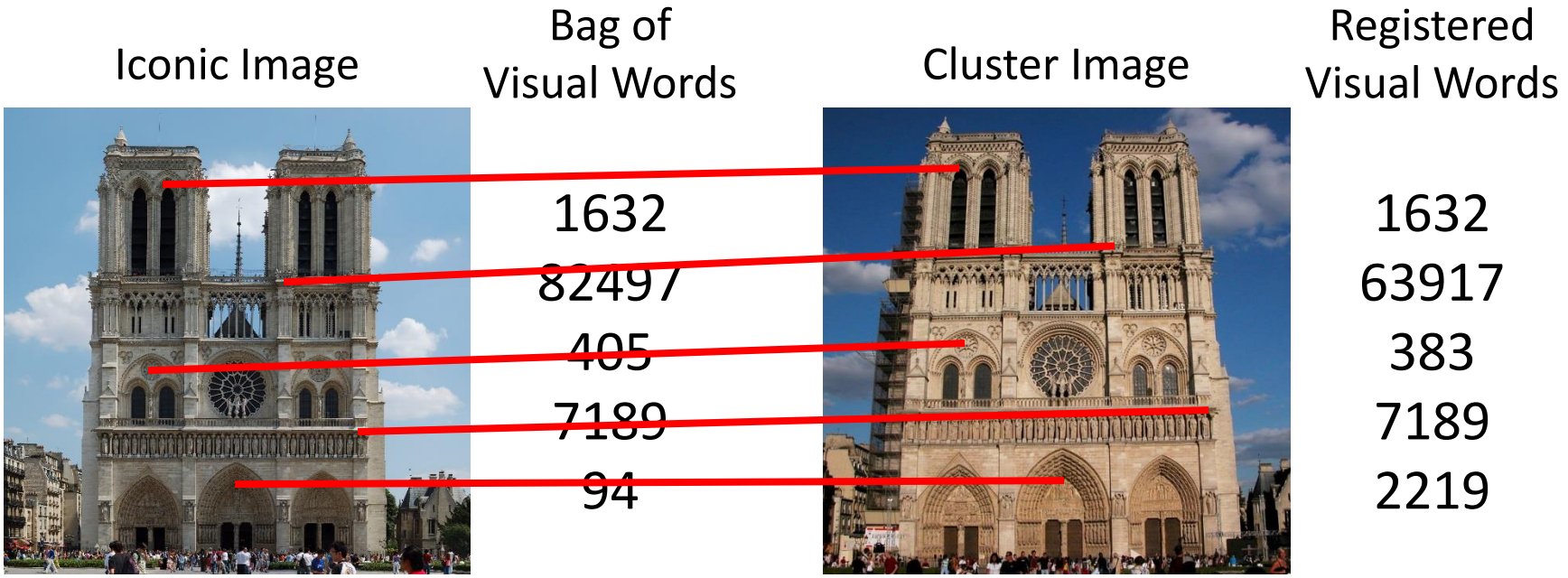
Iconic Image

Bag of
Visual Words

1632
82497
405
7189
94



Cluster Representation



Cluster Representation

Iconic Image	Bag of Visual Words	Cluster Image	Registered Visual Words
	1632		1632
	82497		**63917**
	405		**383**
	7189		7189
	94		**2219**

Cluster Representation

Iconic Image

Bag of Visual Words

1632
82497
405
7189
94
63917
383
2219

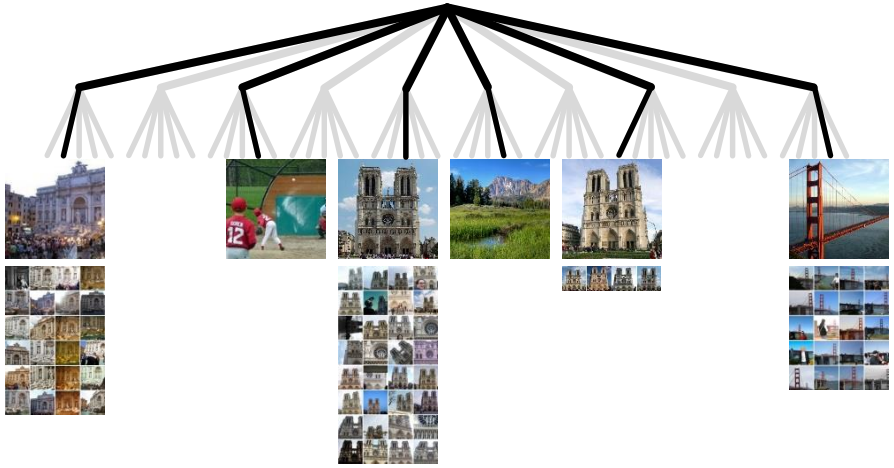
Cluster Image

Registered Visual Words

1632
63917
383
7189
2219

Streaming Data Association

100M Images



Streaming Data Association

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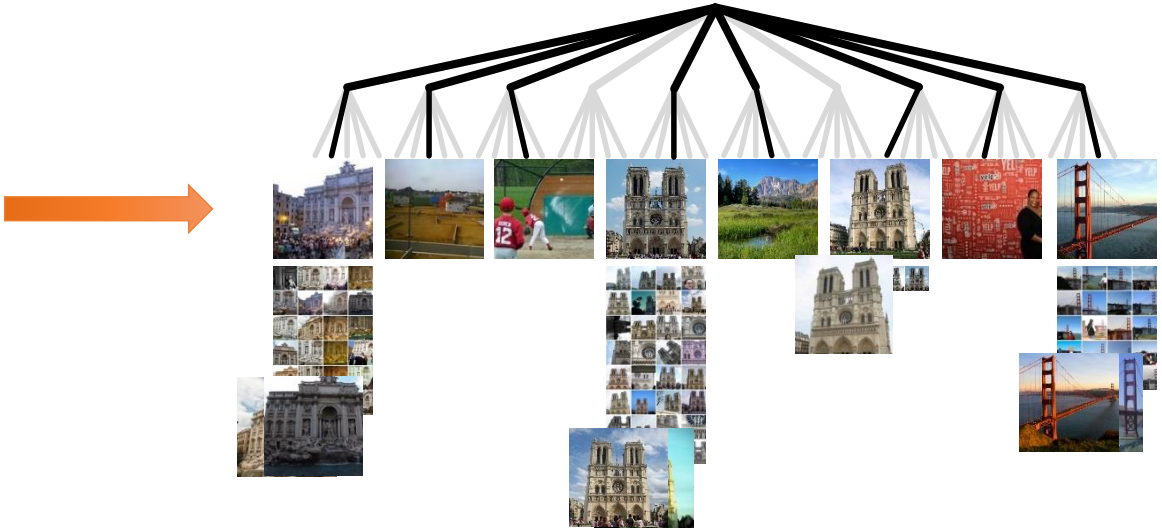

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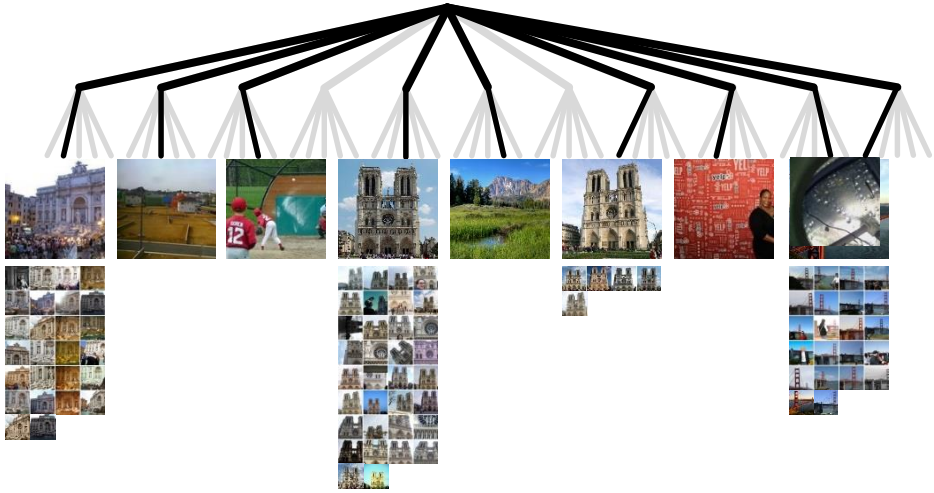

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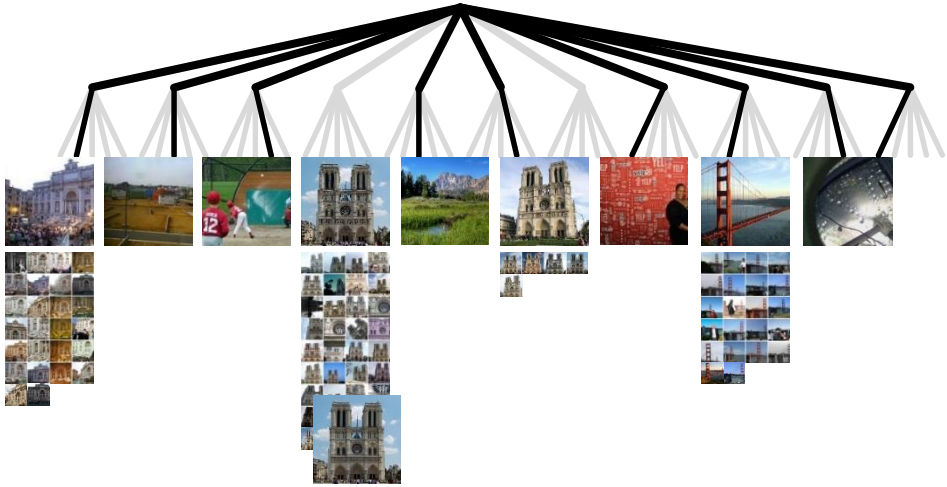

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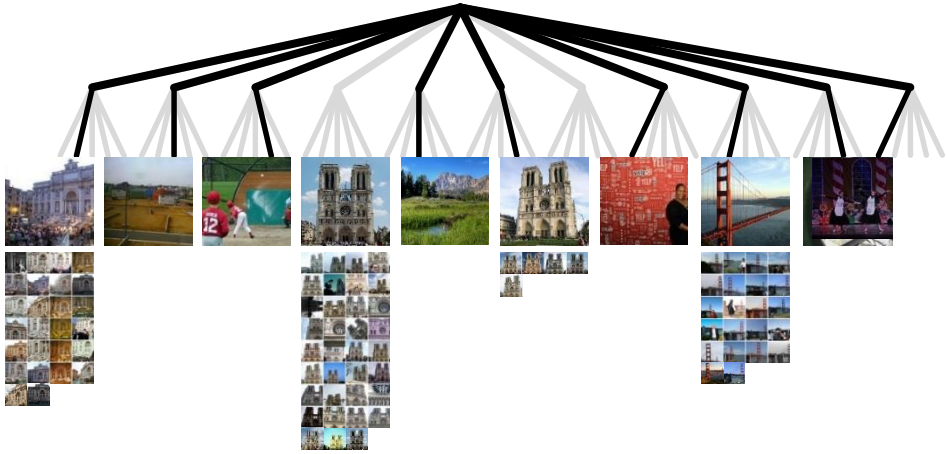
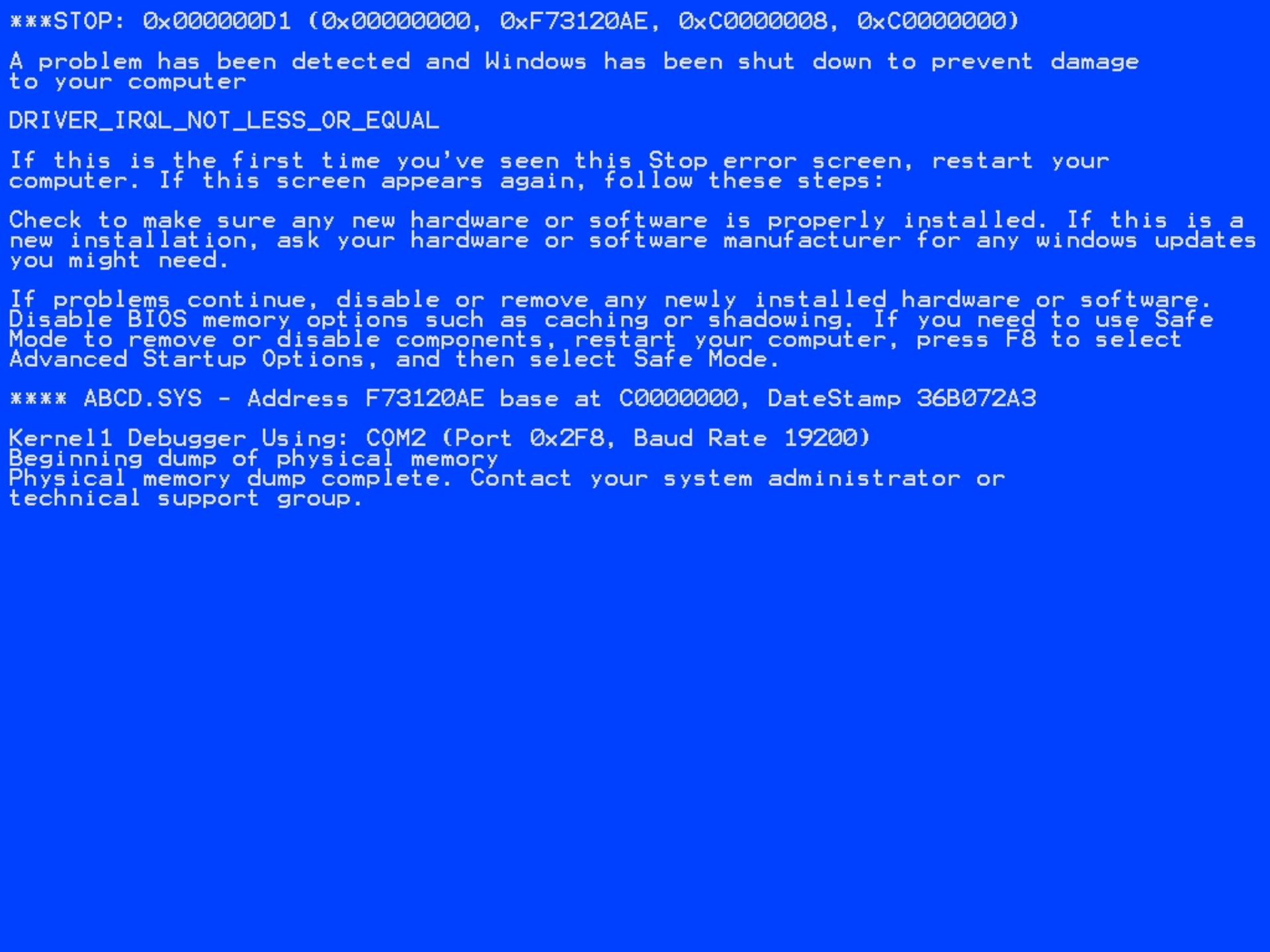
100M Images



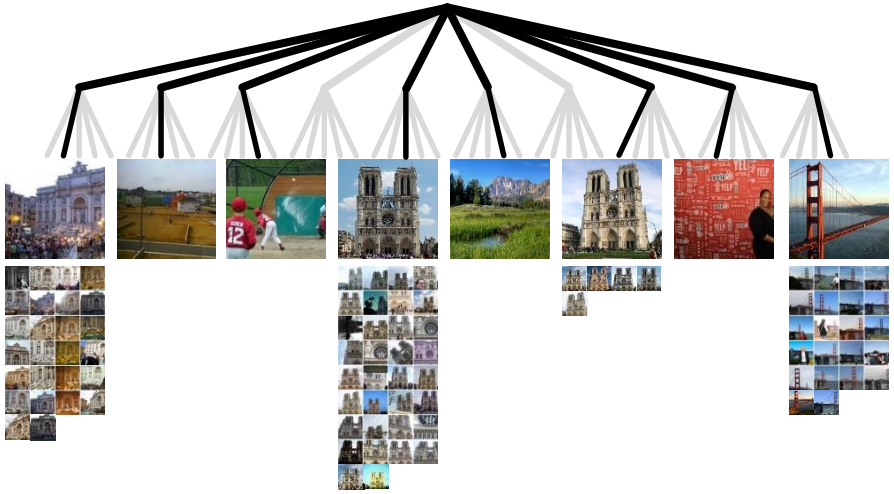
Streaming Data Association

100M Images


***STOP: 0x000000D1 (0x00000000, 0xF73120AE, 0xC0000008, 0xC0000000)
A problem has been detected and Windows has been shut down to prevent damage to your computer
DRIVER_IRQL_NOT_LESS_OR_EQUAL
If this is the first time you've seen this Stop error screen, restart your computer. If this screen appears again, follow these steps:
Check to make sure any new hardware or software is properly installed. If this is a new installation, ask your hardware or software manufacturer for any windows updates you might need.
If problems continue, disable or remove any newly installed hardware or software. Disable BIOS memory options such as caching or shadowing. If you need to use Safe Mode to remove or disable components, restart your computer, press F8 to select Advanced Startup Options, and then select Safe Mode.
**** ABCD.SYS - Address F73120AE base at C0000000, DateStamp 36B072A3
Kernel1 Debugger Using: COM2 (Port 0x2F8, Baud Rate 19200)
Beginning dump of physical memory
Physical memory dump complete. Contact your system administrator or technical support group.

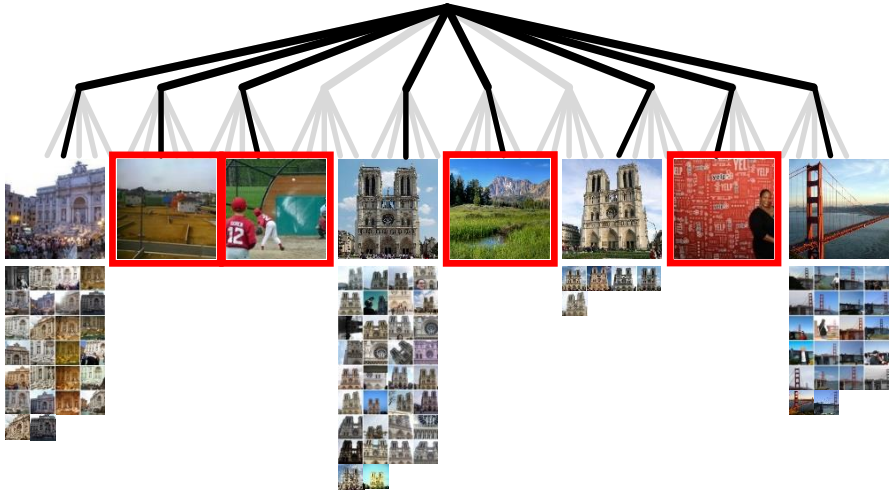
Streaming Data Association

100M Images

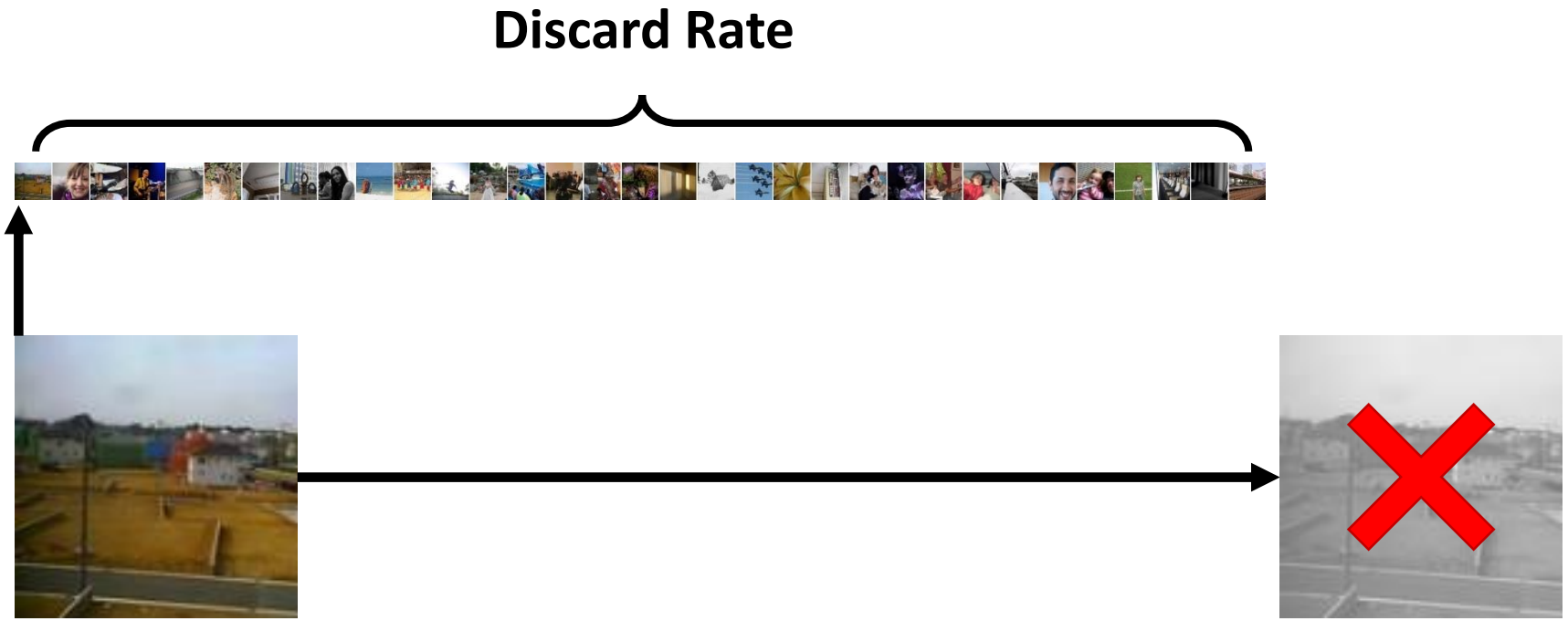


Streaming Data Association

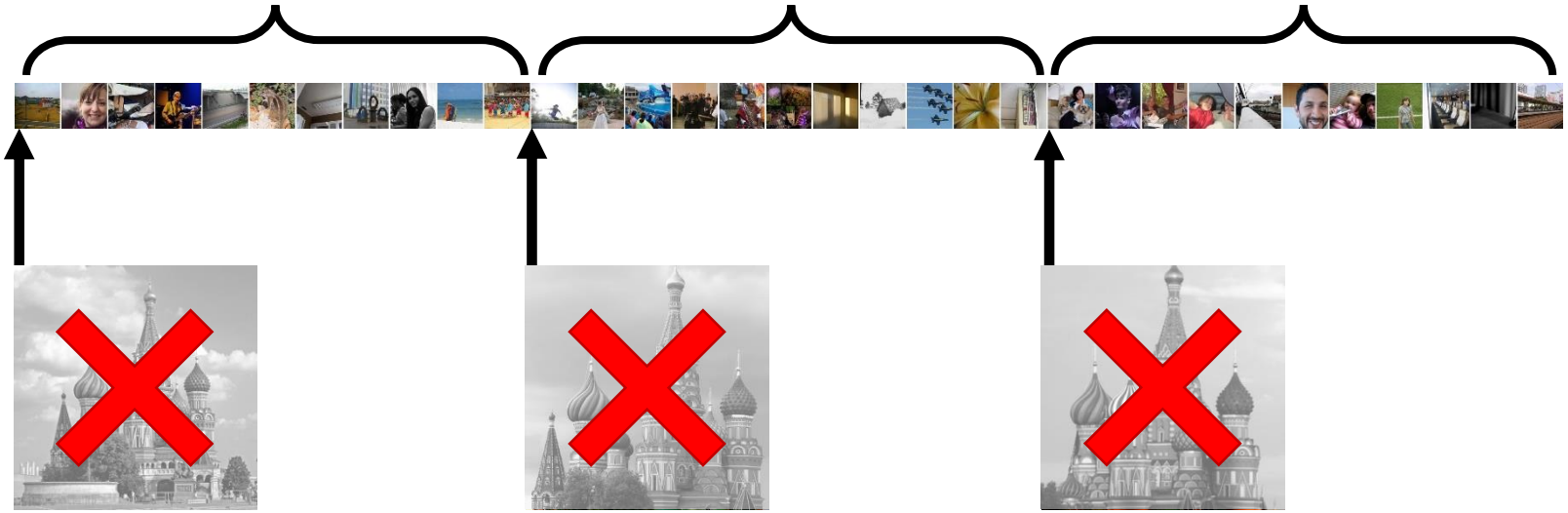
100M Images



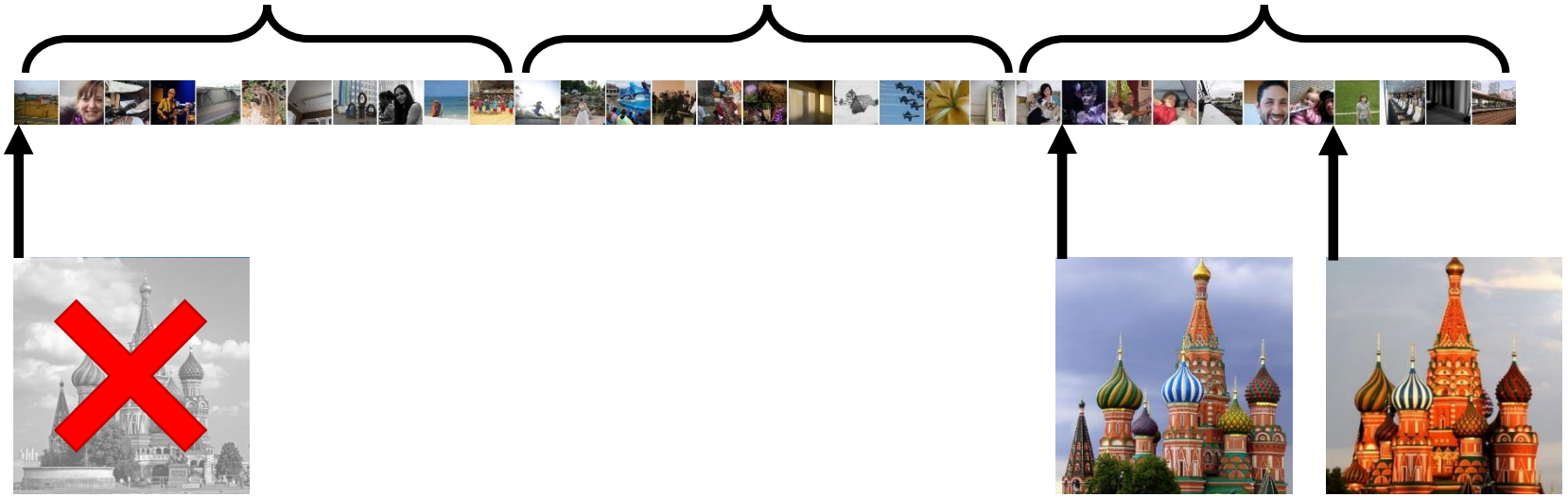
Cluster Discarding



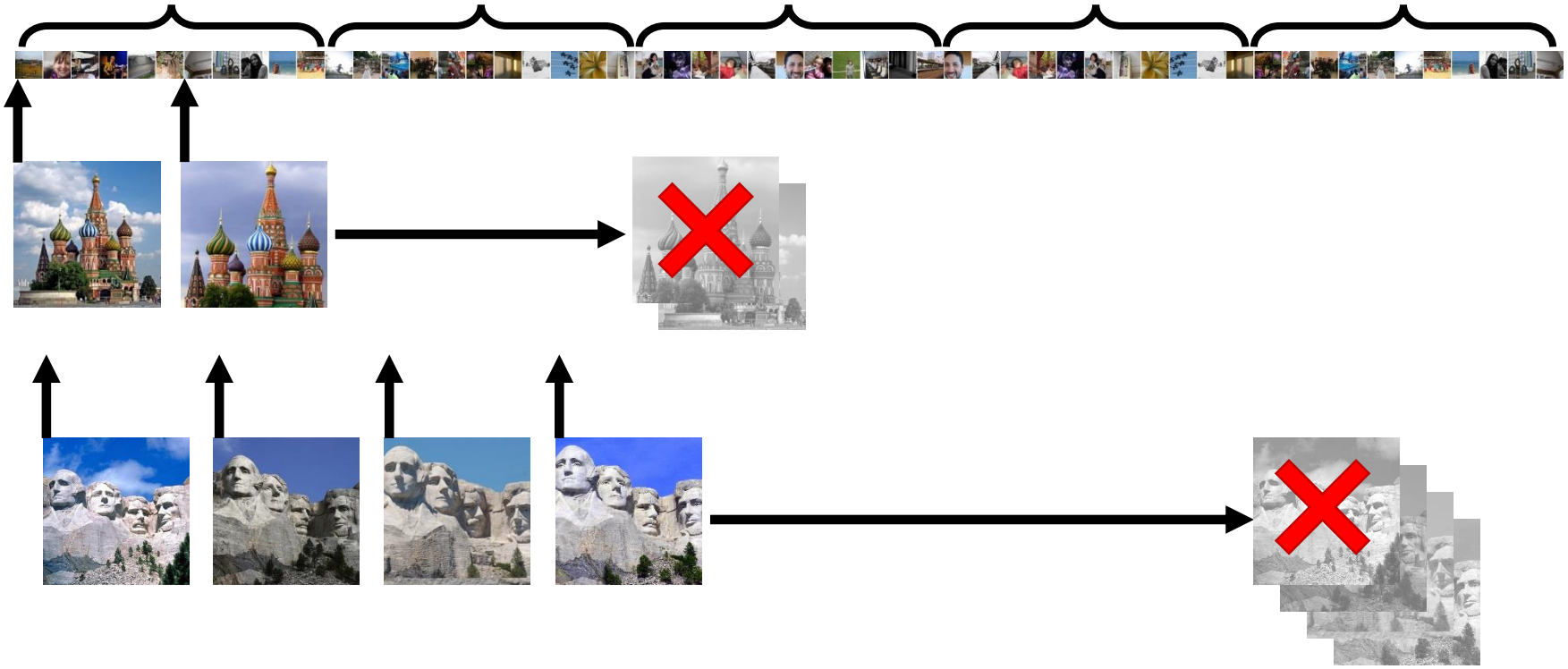
Cluster Discarding



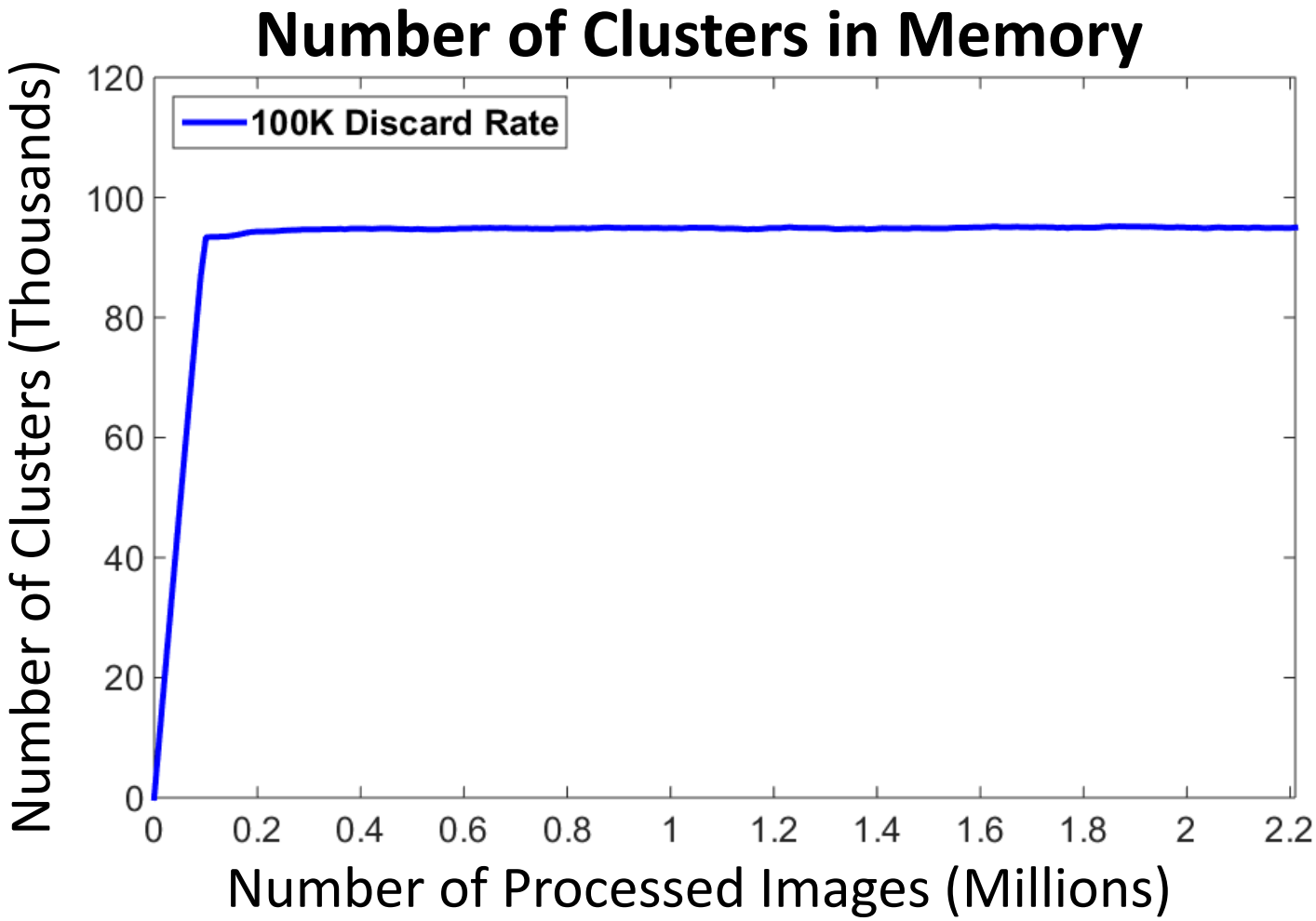
Cluster Discarding



Cluster Discarding

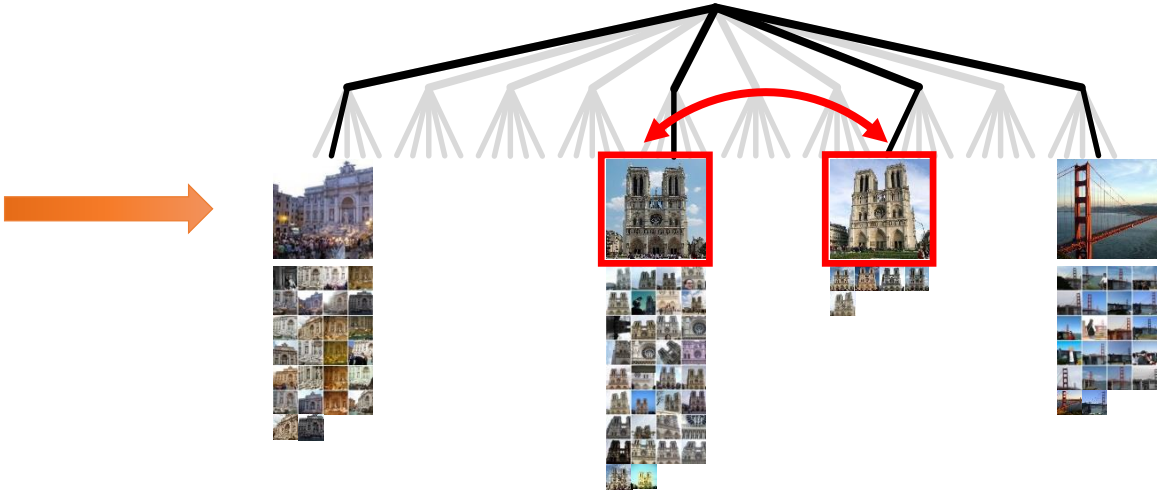


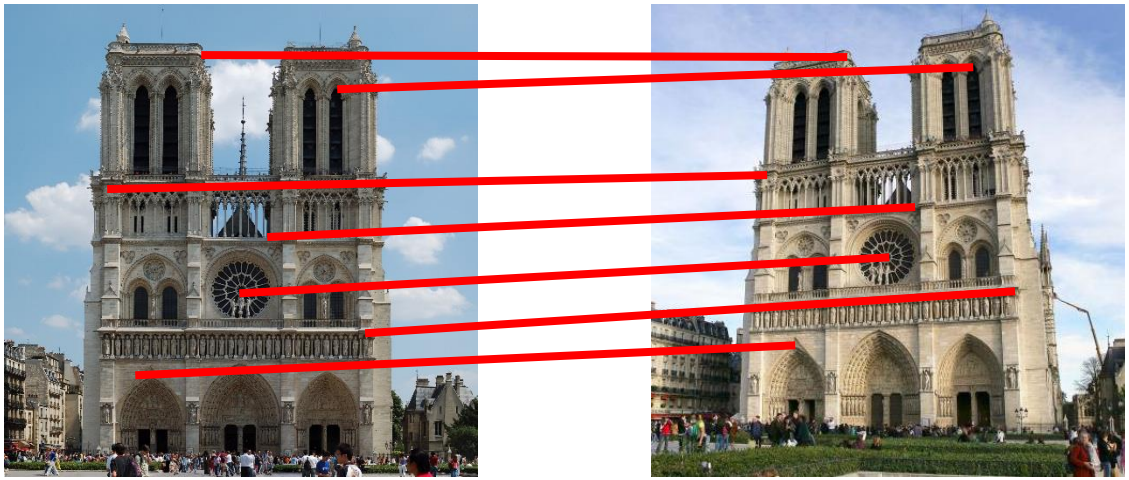
Memory Consumption



Streaming Data Association

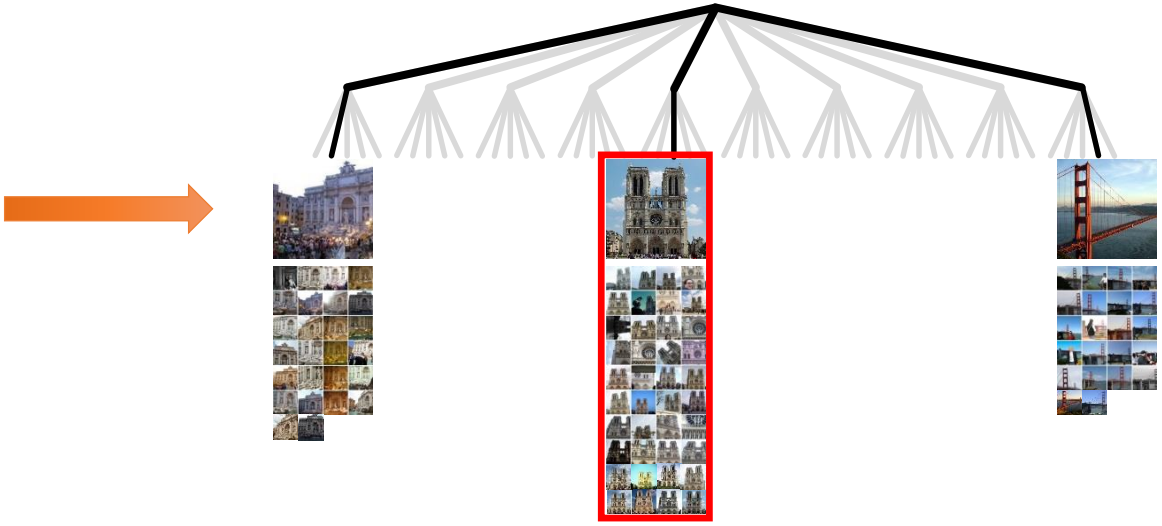
100M Images





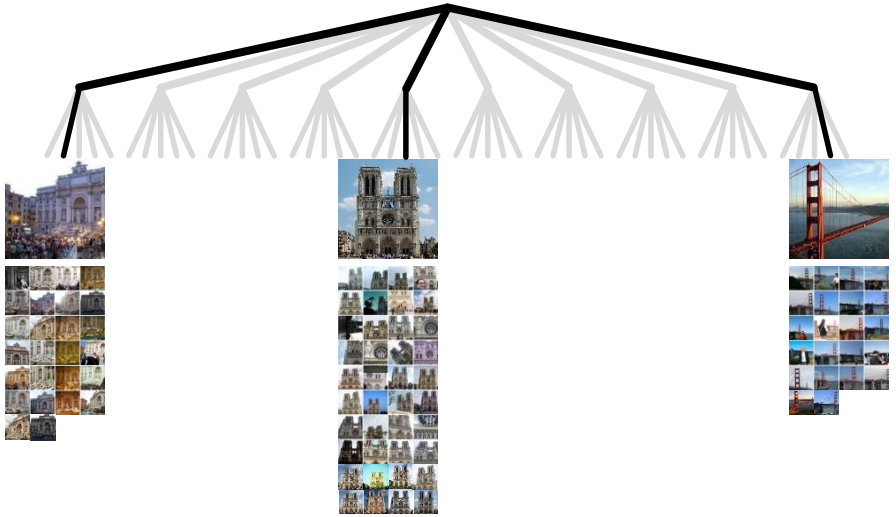
Streaming Data Association

100M Images

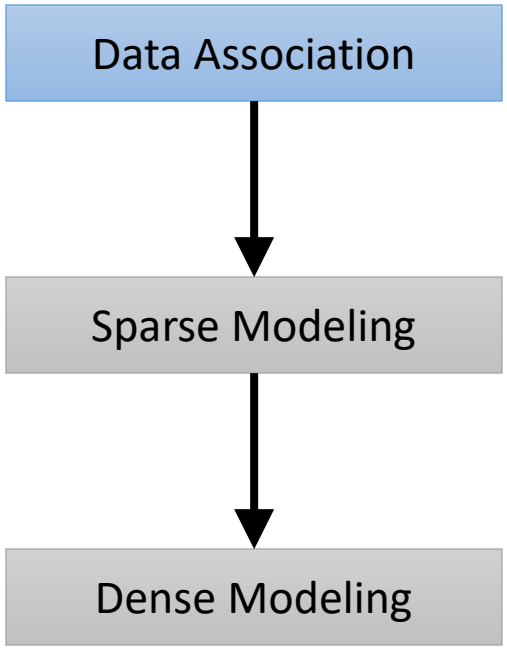


Streaming Data Association

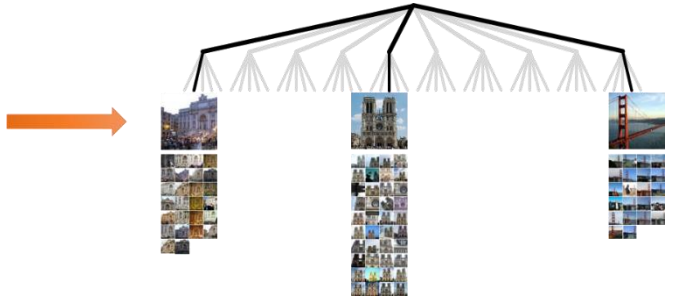
100M Images



Reconstruction Pipeline



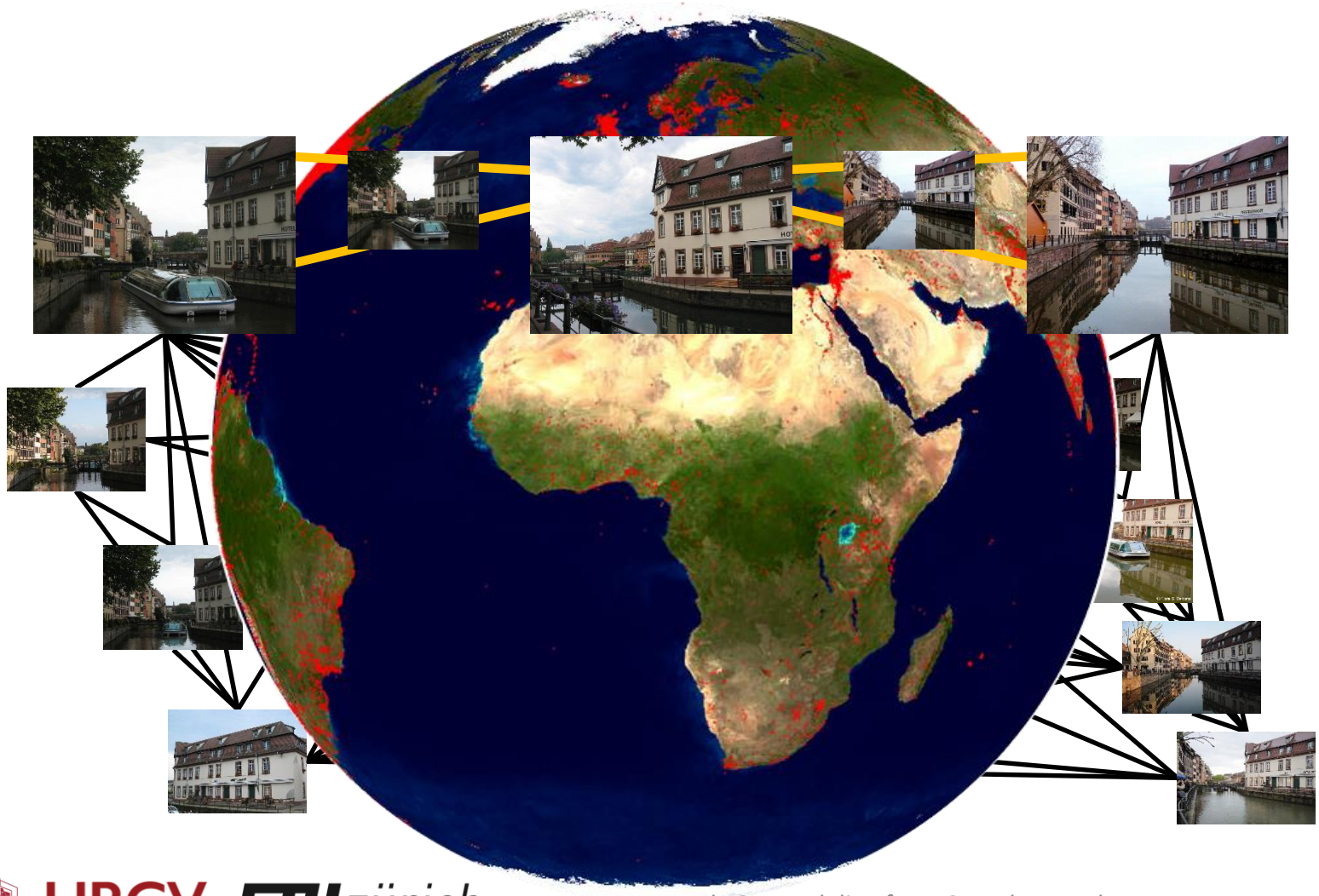
100M Images



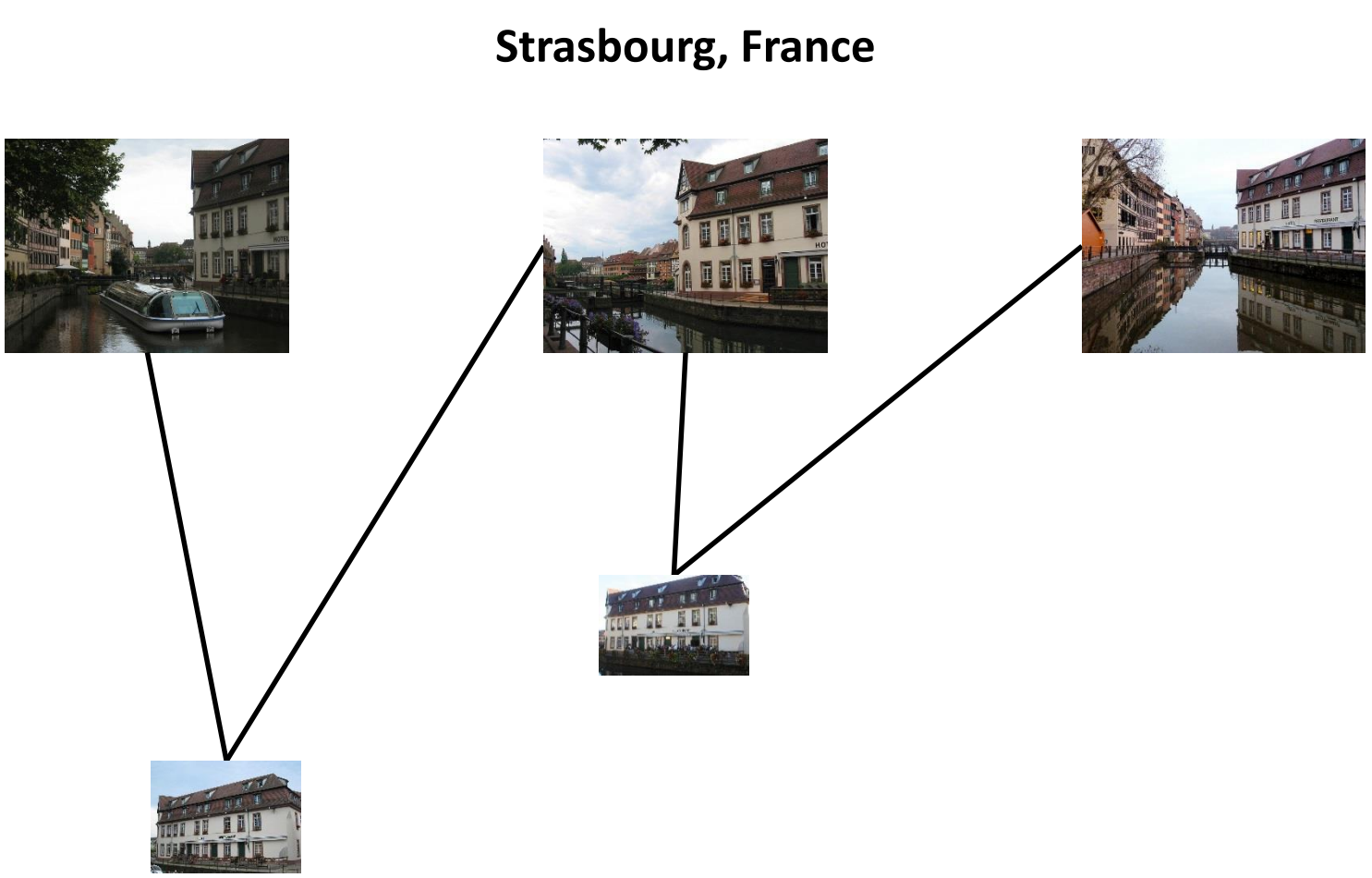
Registered Images

1.5 Million Registered
105 Hours

Scene Graph

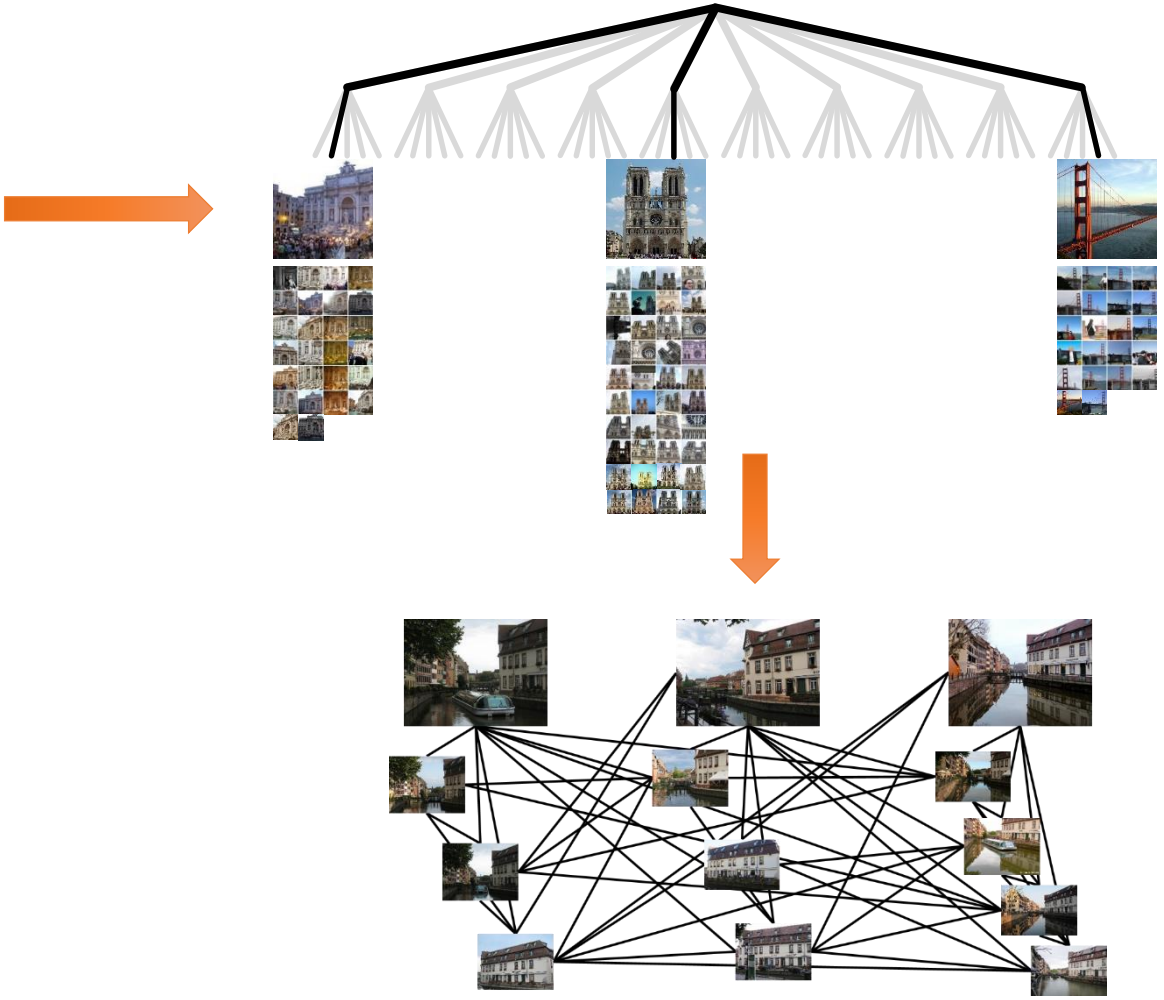


Scene Graph



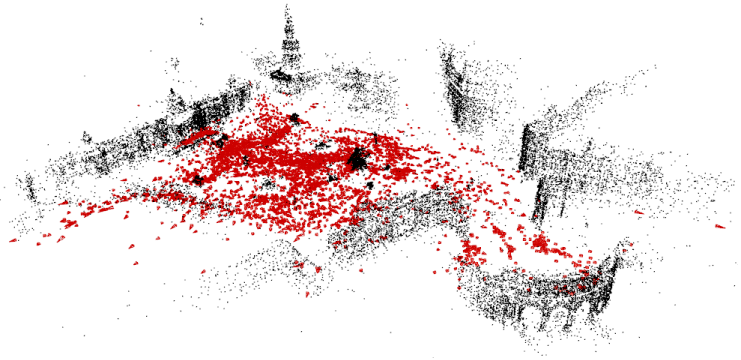
Streaming Data Association

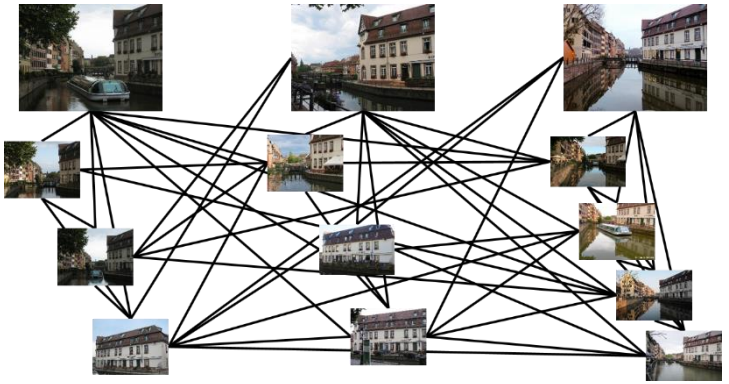
100M Images



Streaming Data Association

100M Images





Buckingham Palace, London, England

Golden Gate Bridge, San Francisco, California

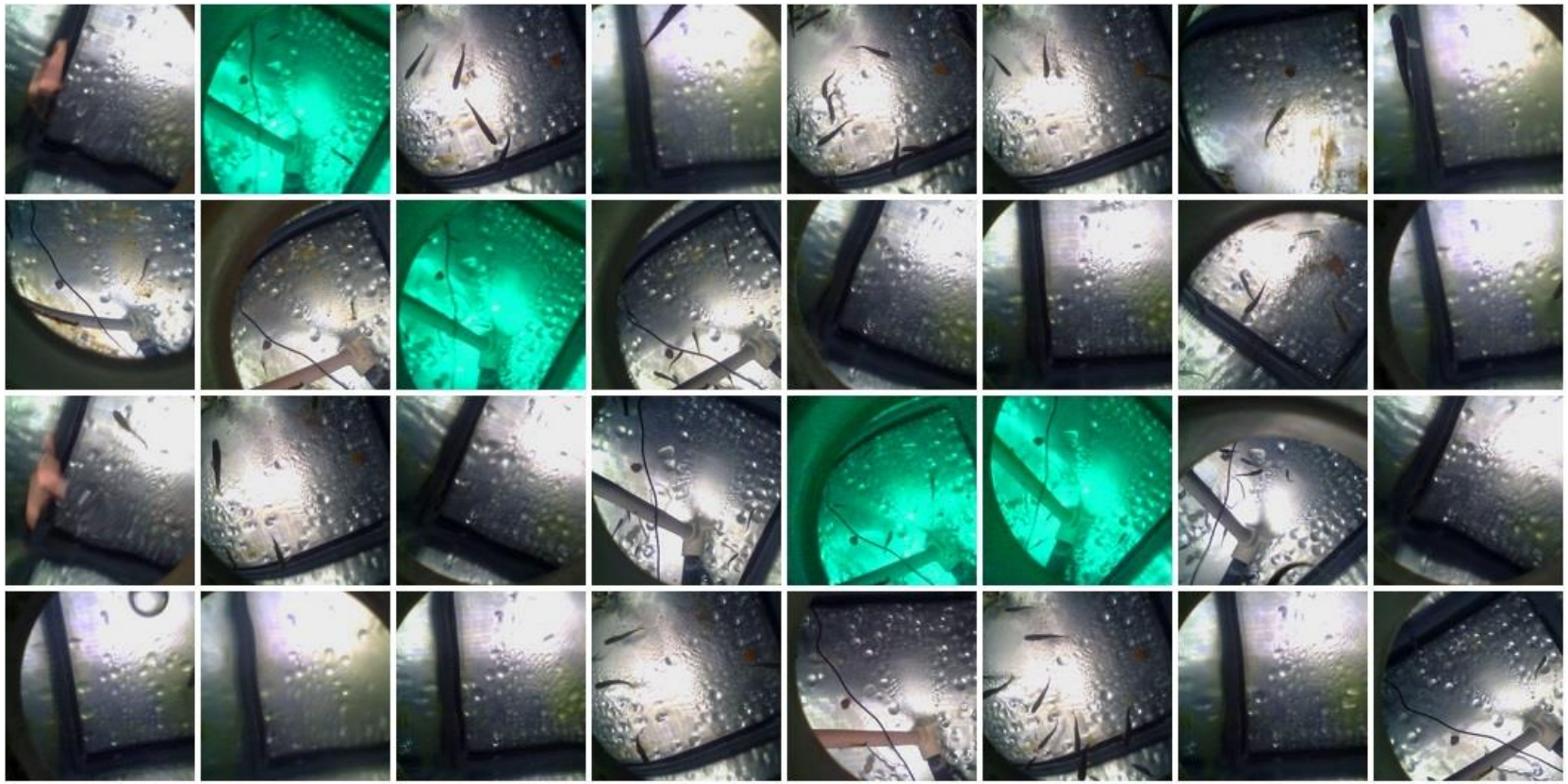
Eiffel Tower, Paris, France

Taj Mahal, Agra, Uttar Pradesh, India

Other Connected Components

Other Connected Components

Other Connected Components



Other Connected Components

Results

Berlin, Germany (2.7M images)

	Frahm et al, 2010	Heinly et al, 2015
Registered	4.6%	26%
Data Association Time*	13.3 Hours	7.9 Hours

*Identical Hardware Configuration

Results

Berlin, Germany (2.7M images)

Data Association Strategy	Match Attempts	Registered
Frahm et al, 2010 GIST	**1**	4.6%
Streaming GIST	**2**	8.9%

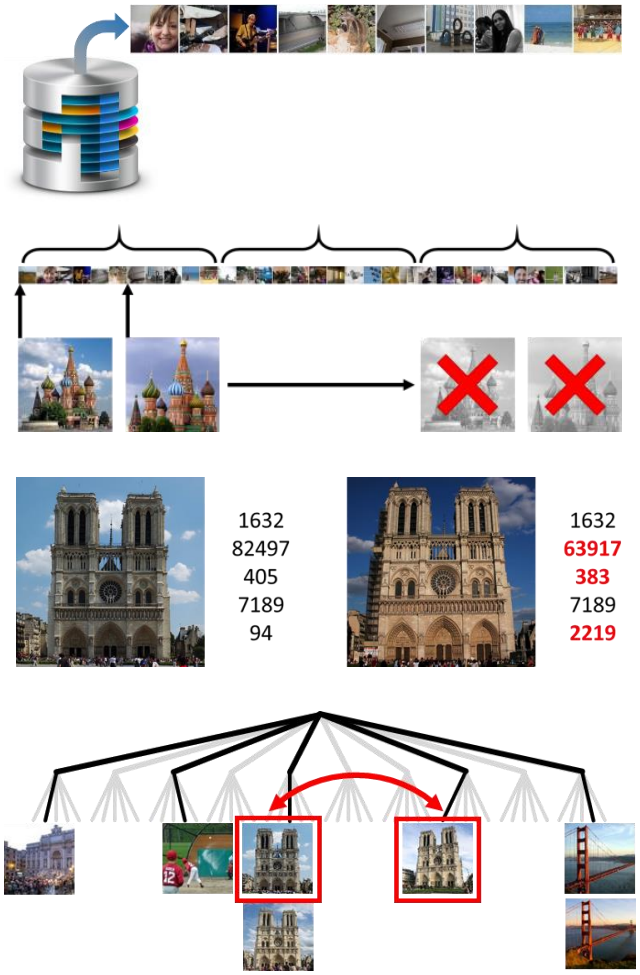
Results

Berlin, Germany (2.7M images)

Data Association Strategy	Match Attempts	Registered
Frahm et al, 2010 GIST	**1**	4.6%
Streaming GIST	**2**	8.9%
Streaming Bag-of-Words	**1**	25%
Streaming Bag-of-Words	**2**	26%

Challenges - Revisited

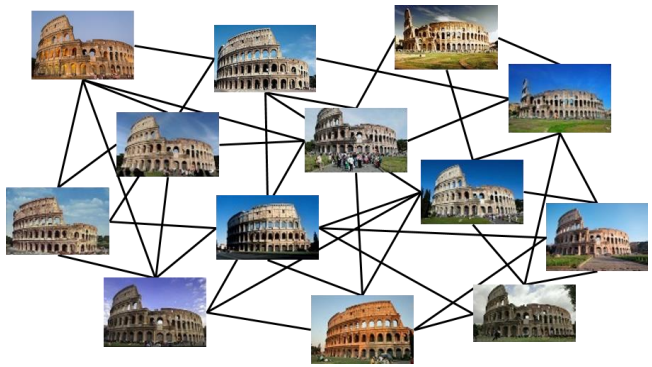
- Scalability
  - Streaming paradigm
  - Compact memory representation
- Completeness
  - Adaptive cluster representation
  - Favor diverse connections during streaming



Outline – Data Association

- 2D features → Image registration
  - Features
  - Matching
  - Verification

- Image registration → Connected components
  - Exhaustive
  - Image retrieval
  - Clustering
  - Streaming



Open-Source

github.com/jheinly

jaredheinly.com