



Large-scale 3D Modeling from Crowdsourced Data

Jan-Michael Frahm, UNC

Enrique Dunn, SIT

Marc Pollefeys, ETHZ, Microsoft

Jared Heinly, URCV

Johannes Schönberger, ETHZ



ETH zürich



Microsoft

URCV

Large-scale Modeling Pipeline

Jared Heinly

URCV
urcventures.com



ETH zürich



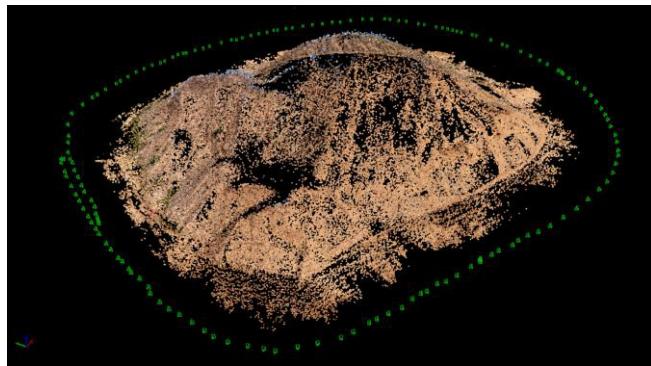
Microsoft

URCV

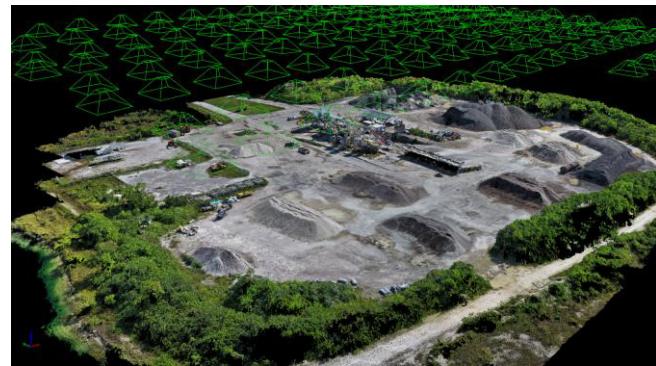
URCV

urcventures.com

Ground-Based



Aerial-Based



Stockpiles



Housing



Education



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

Challenges and Opportunities of Crowd-sourced Data



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

What is crowd-sourced data?

- User-driven



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

What is crowd-sourced data?

- User-driven



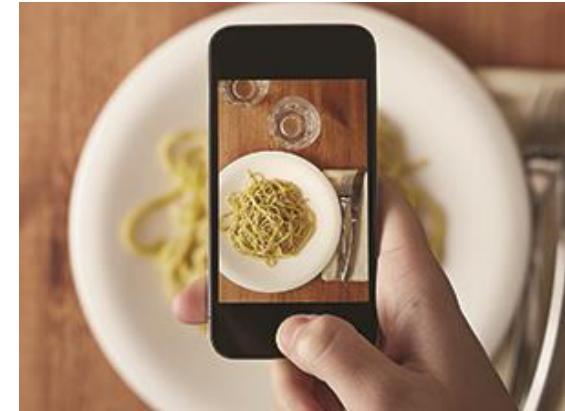
What is crowd-sourced data?

- User-driven



What is crowd-sourced data?

- User-driven



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

What is crowd-sourced data?

- User-driven



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

10

What is crowd-sourced data?

- User-driven



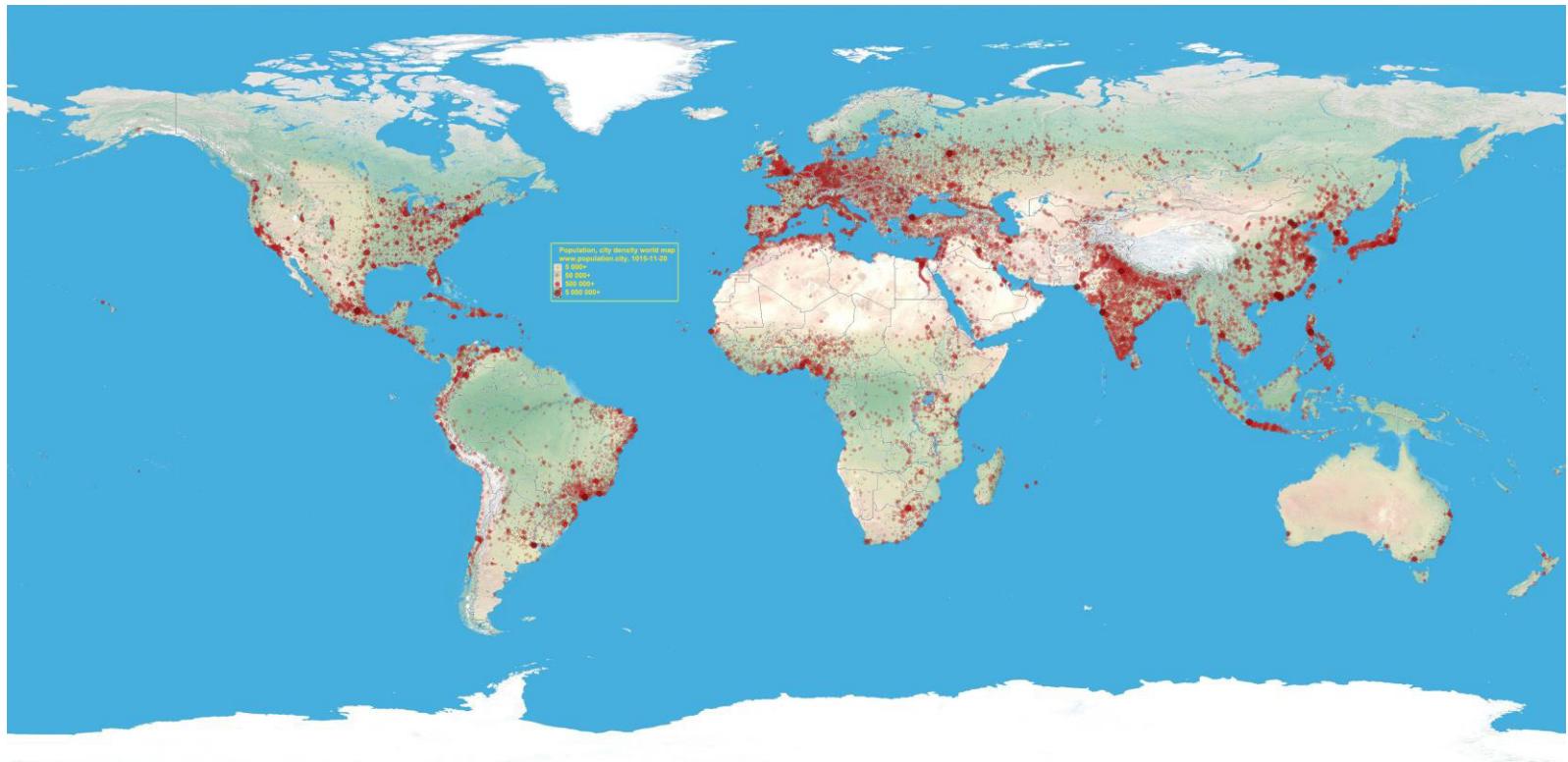
What is crowd-sourced data?

- Diverse



What is crowd-sourced data?

- Diverse



ETH zürich



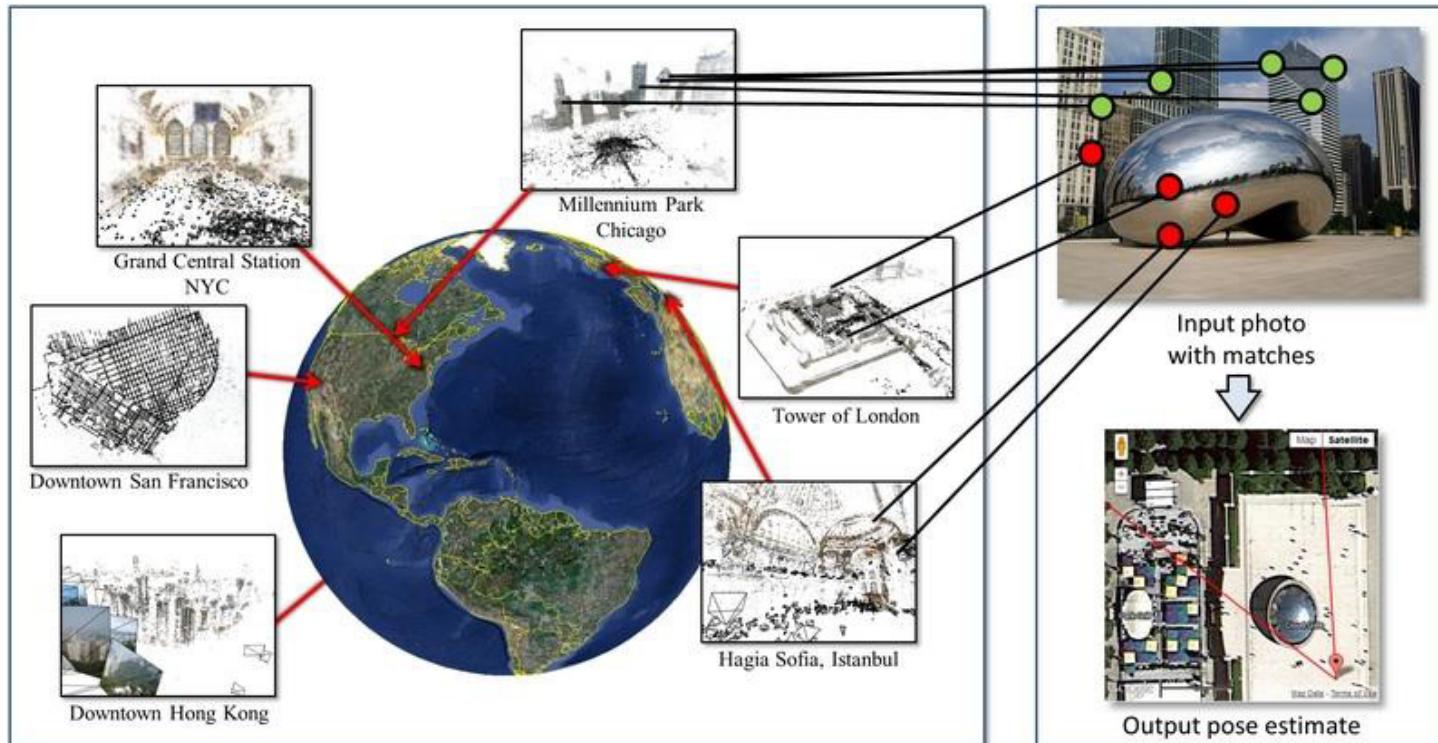
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Opportunities

- Diversity – Space



Li, Snavley, Huttenlocher, Fua, *ECCV 2012*



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Opportunities

- Diversity – Time



Matzen, Snavley, *ECCV 2014*



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Opportunities

- Real-time



Google



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Opportunities

- Real-time



ETH zürich

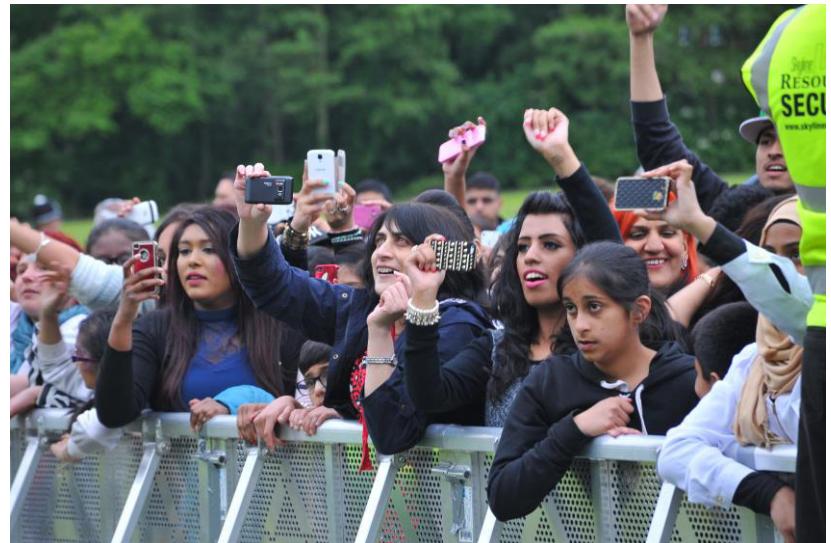


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Opportunities

- Representation of interests of camera/internet-enabled humanity



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Challenges

- Diversity – Viewpoint



ETH zürich



Microsoft

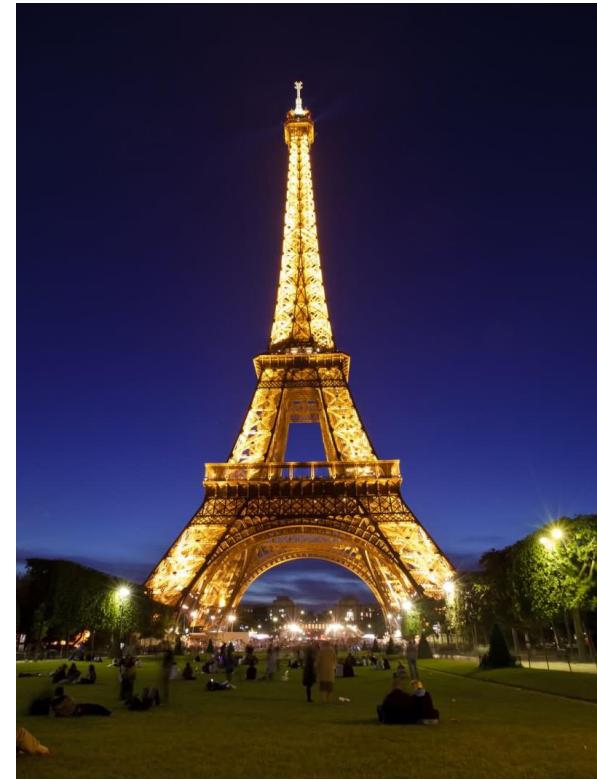
URCV

Large-scale 3D Modeling from Crowdsourced Data

19

Challenges

- Diversity – Illumination



ETH zürich



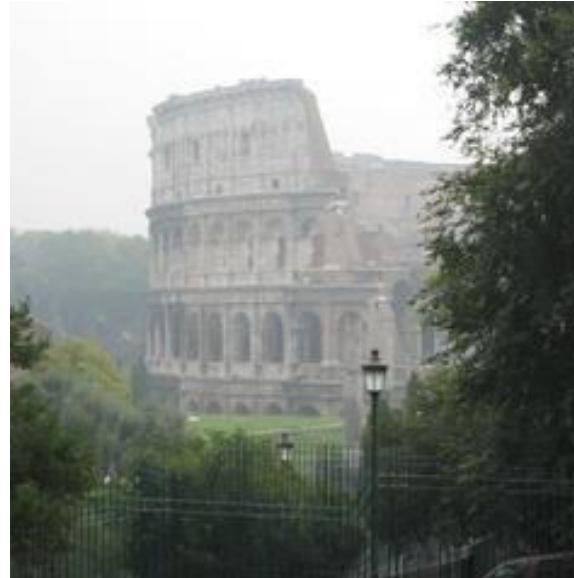
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

20

Challenges

- Diversity – Weather



Challenges

- Diversity – Quality



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Challenges

- Diversity – Appearance



Challenges

- Diversity – Ambiguity



Challenges

- Sparsity – Space



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

25

Challenges

- Sparsity – Time



ETH zürich

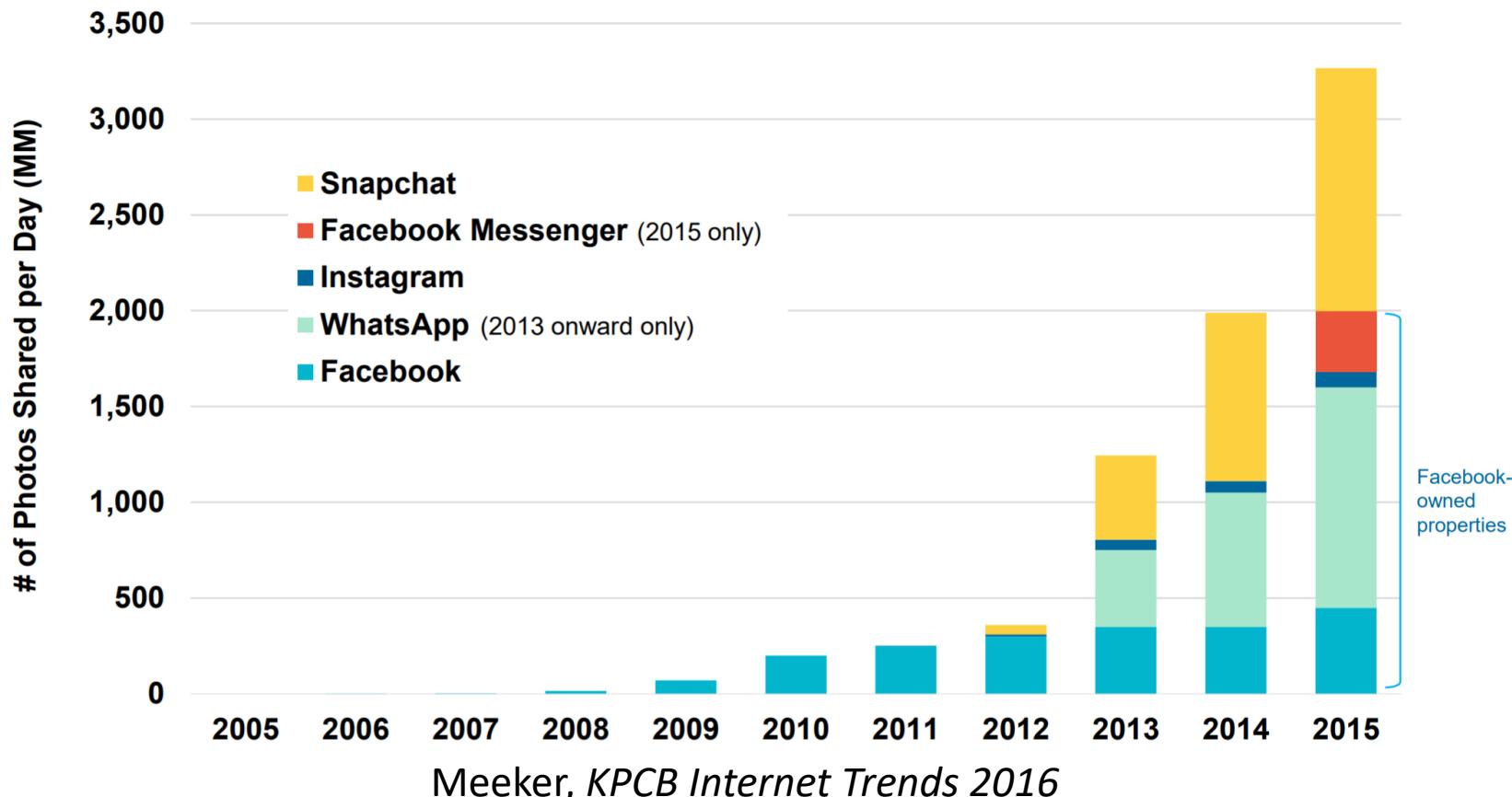


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Challenges

Daily Number of Photos Shared on Select Platforms, Global, 2005 – 2015



Meeker, KPCB Internet Trends 2016



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Where can we get the data?

flickr

 Mapillary

twitter 

Google



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

What are some sample datasets?

- Yahoo Flickr Creative Commons 100M
 - 14 TB
 - 640x480 resolution
 - Half have geotags



ETH zürich

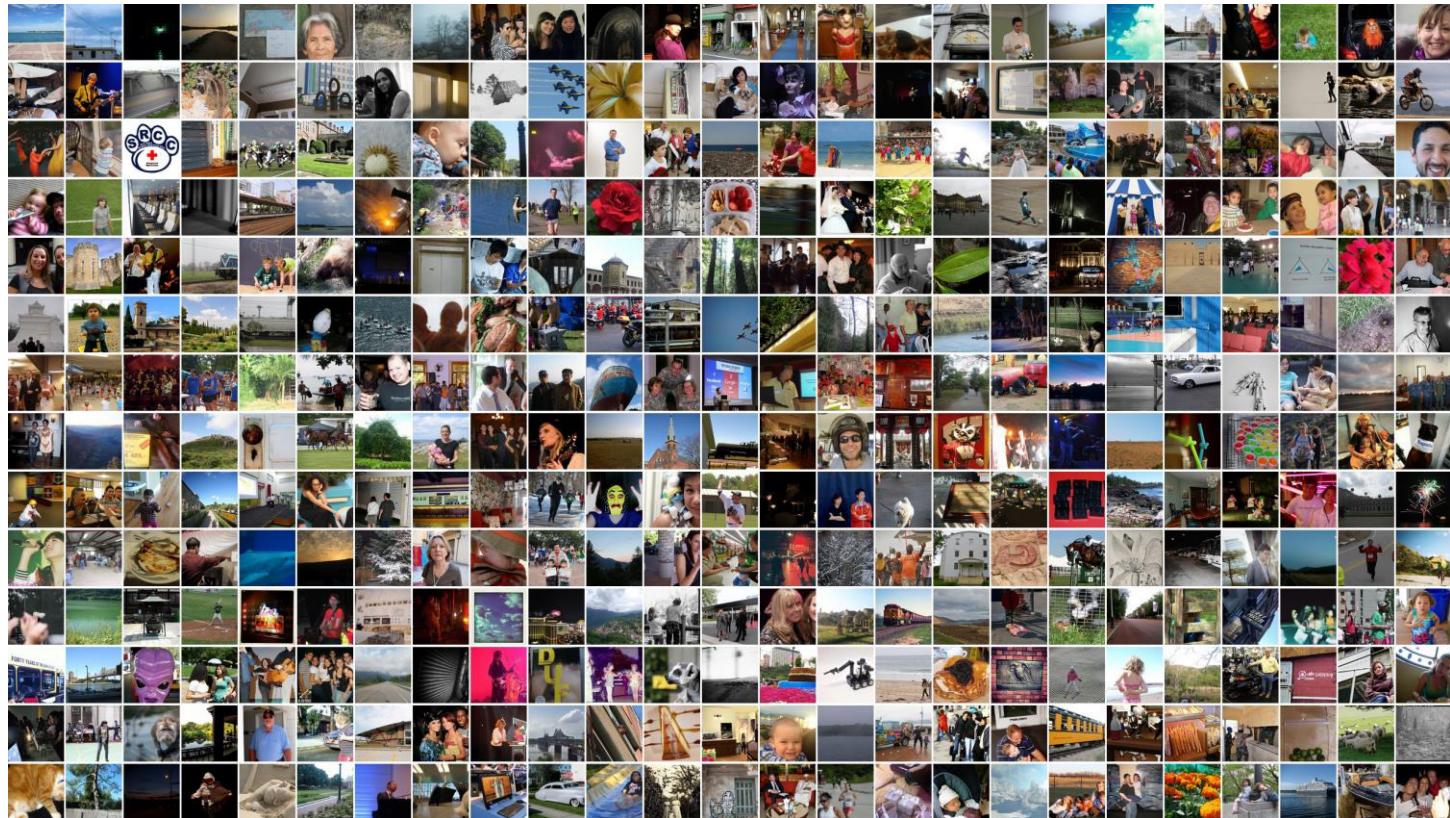


Microsoft

URC

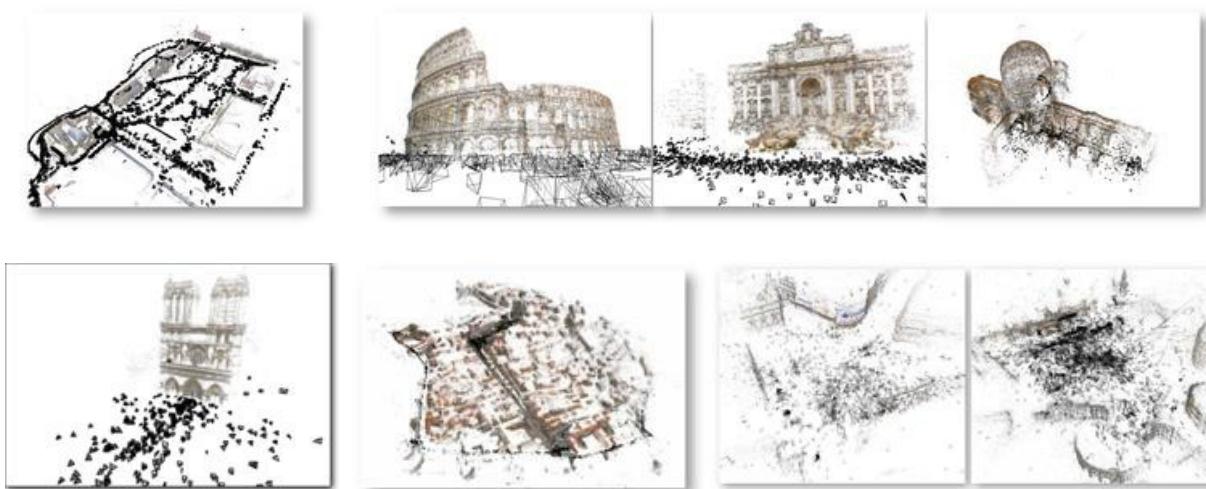
What are some sample datasets?

- Yahoo Flickr Creative Commons 100M



What are some sample datasets?

- Cornell BigSFM
 - Datasets with 1 – 16K images



Cornell University



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

Image Indexing and Retrieval



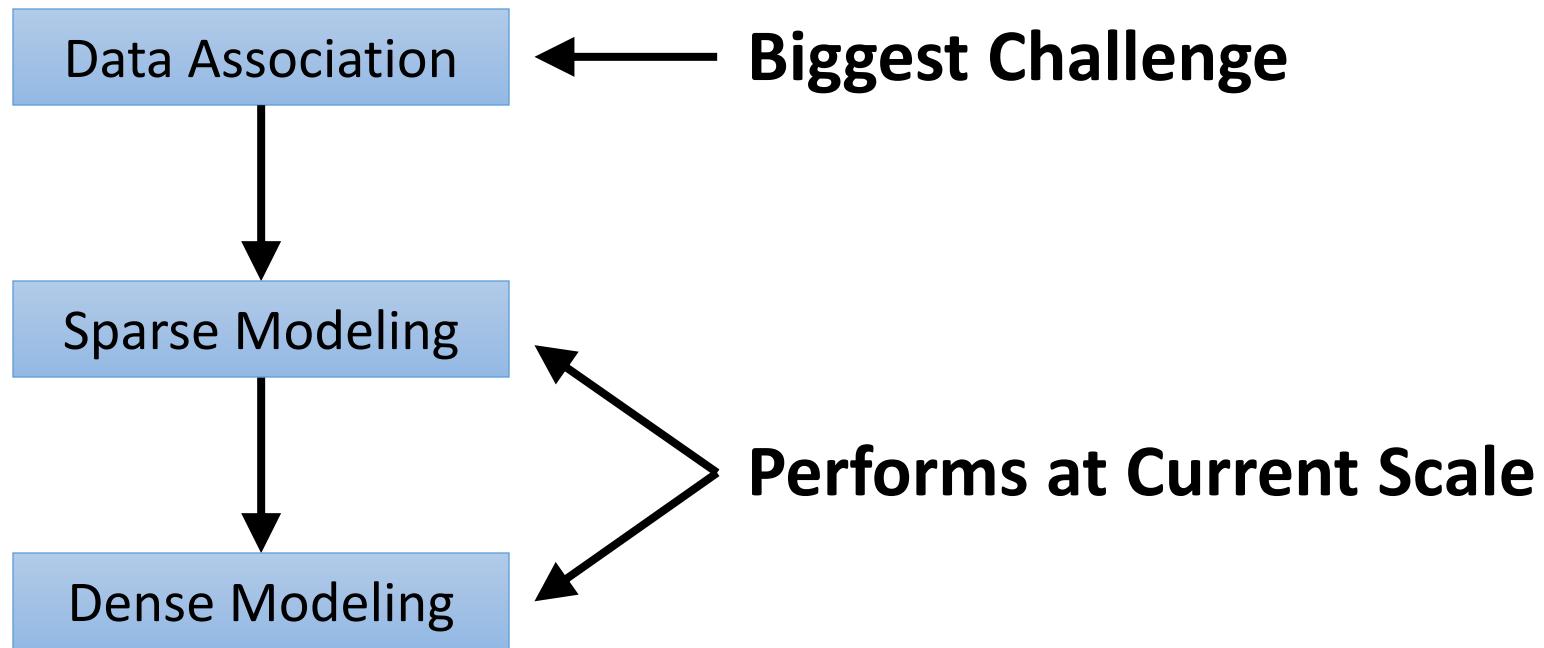
ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

3D Modeling Pipeline



What is image indexing?

Index

A

accordion, layouts
about 128
movie form, adding 131
nesting, in tab 128, 129
toolbar, adding 129-131
adapters, Ext
about 18
using 18, 20
Adobe AIR 285
Adobe Integrated Run time. *See* Adobe AIR
AJAX 12
Asynchronous JavaScript and XML.
See AJAX

B

built-in features, Ext
client-side sorting 86
column, reordering 86, 87
columns, hidden 86
columns, visible 86
button, toolbars
creating 63
handlers 67, 68
icon buttons 67
split button 64
buttons, form 53

lookup data stores, creating 83
two columns, combining 84
classes 254
ComboBox, form
about 47
database-driven 47-50
component config 59
config object
about 28, 29
new way 28, 29
old way 28
tips 26, 29
content, loading on menu item click 68, 69
custom class, creating 256-259
custom component, creating 264-266
custom events, creating 262-264

D

data, filtering
about 238
remote, filtering 238-244
data, finding
about 237
by field value 237
by record ID 238
by record index 237
data, formatting
about 278



What is image indexing?



ETH zürich

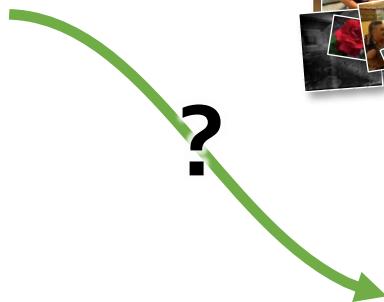


Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

What is image retrieval?



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Methods of Image Indexing

- Global descriptor

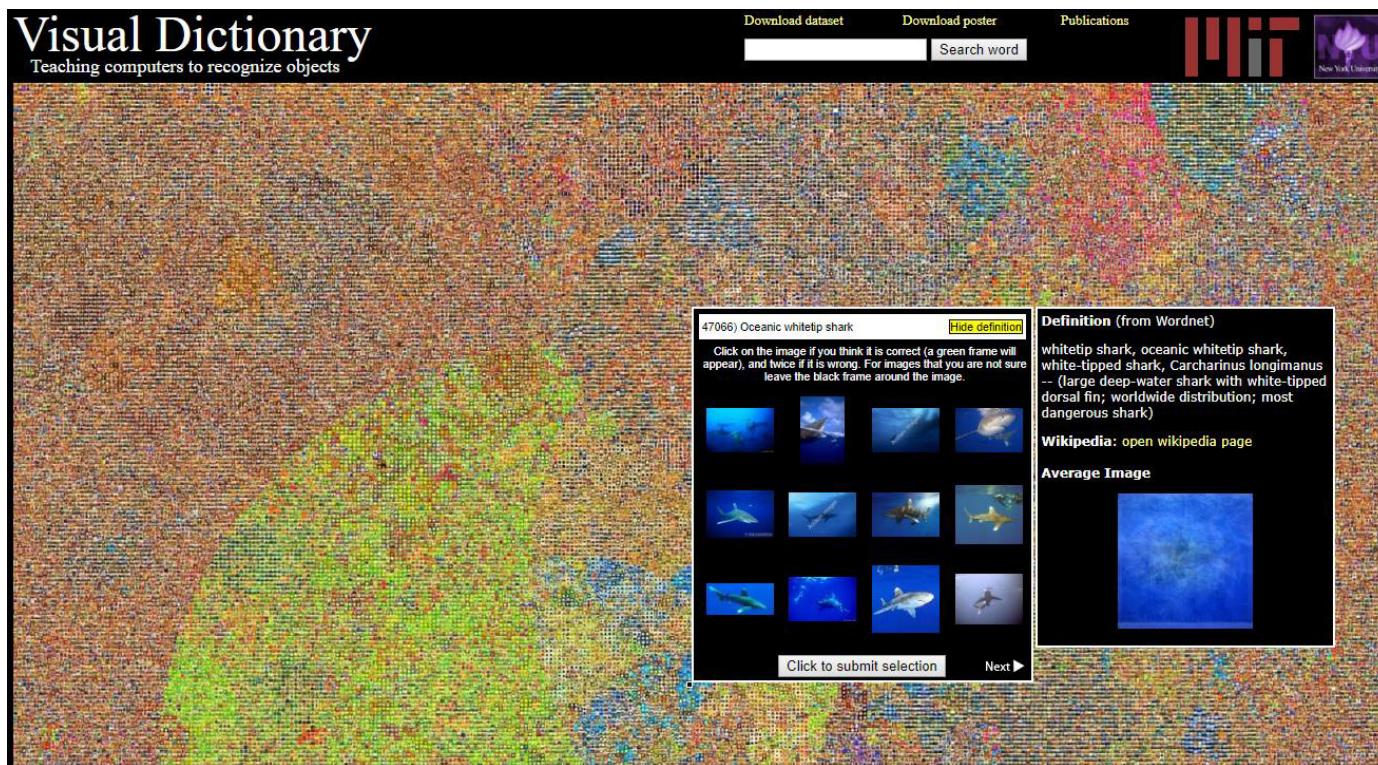


- Local descriptors



Global Descriptors

- Tiny image



Torralba et al., PAMI 2008



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Global Descriptors

- Tiny image



[0.12, 0.85, 0.37, ...]



[0.16, 0.82, 0.41, ...]



[0.09, 0.88, 0.36, ...]



[0.11, 0.79, 0.33, ...]



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

40

Global Descriptors

- Tiny image



[0.12, 0.85, 0.37, ...]



[0.43, 0.51, 0.34, ...]

[0.64, 0.30, 0.82, ...]

[0.16, 0.82, 0.41, ...]

[0.09, 0.88, 0.36, ...]

[0.94, 0.05, 0.57, ...]

[0.48, 0.24, 0.60, ...]

[0.11, 0.79, 0.33, ...]

⋮

Global Descriptors

- Tiny image



[0.12, 0.85, 0.37, ...]

?



[0.43, 0.51, 0.34, ...]

[0.64, 0.30, 0.82, ...]

[0.16, 0.82, 0.41, ...]

[0.09, 0.88, 0.36, ...]

[0.94, 0.05, 0.57, ...]

[0.48, 0.24, 0.60, ...]

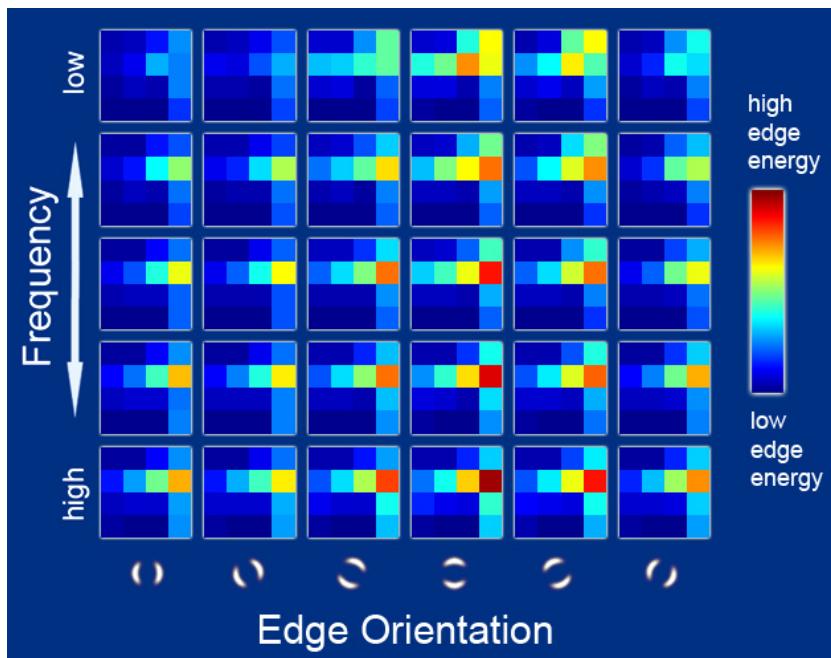
[0.11, 0.79, 0.33, ...]

⋮



Global Descriptors

- GIST



Oliva and Torralba, *IJCV* 2001



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Global Descriptors

- GIST



[0.12, 0.85, 0.37, 0.40, ...]

Oliva and Torralba, *IJCV 2001*



ETH zürich

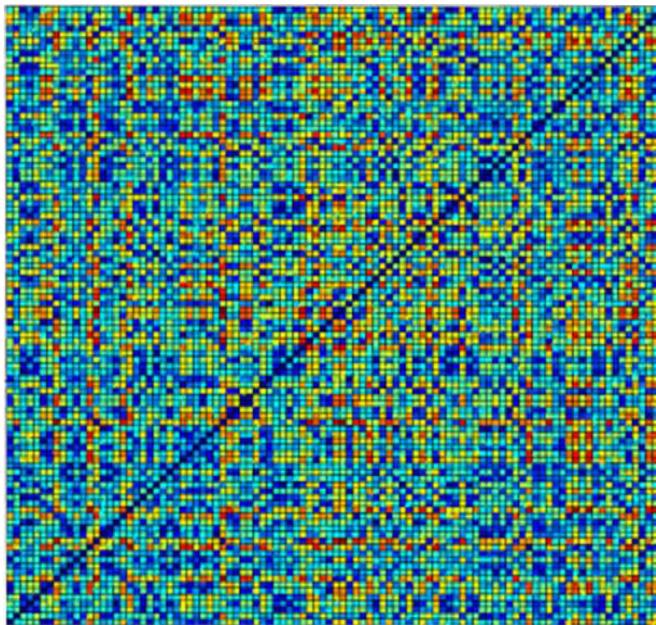


Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

Global Descriptors

- Search methods
 - Brute force



[0.43, 0.51, 0.34, ...]

[0.64, 0.30, 0.82, ...]

[0.16, 0.82, 0.41, ...]

[0.09, 0.88, 0.36, ...]

[0.94, 0.05, 0.57, ...]

[0.48, 0.24, 0.60, ...]

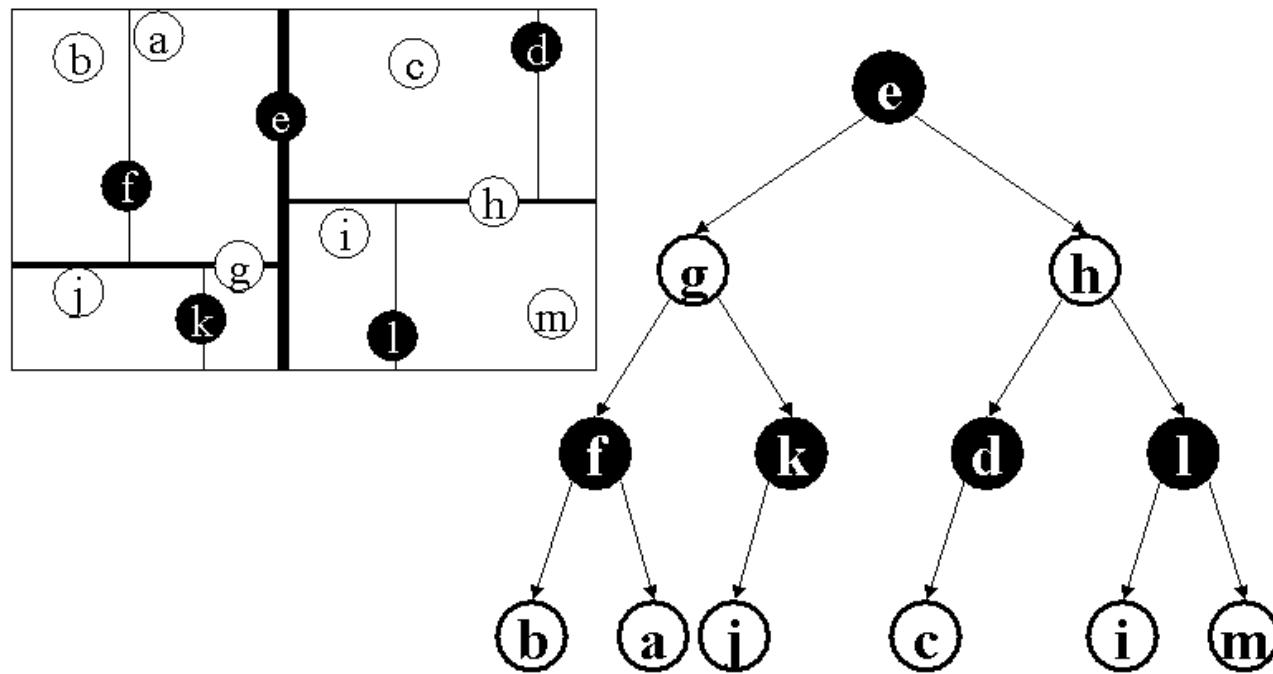
[0.11, 0.79, 0.33, ...]

⋮



Global Descriptors

- Search methods
 - kd-tree



Global Descriptors

- Search methods
 - Hashing



00000111001	0011100100	1011110110	0100000100	0100000010	1110001001
0001101111	1001001011	0001000100	0001111001	0110111010	1101101111
1001111001	1010001100	1001111101	0110000100	1000000000	0100101011
1100010001	0110110110	0000010011	1110111011	1110101101	0010011110
0111110011	1000011111	0111111000	0110001100	0001000111	0001111011
1000011101	1011101010	1000101001	0110011101	0100010111	1110110010
1100011111	1101100110	1110101101	1001001000	1100010010	0011001010
1001000100	0010011010	0001111110	1011111100	1000001001	0111000011
0011100101	1111001101	0001110111	0101110100	0110010110	1101100111



ETH zürich



Microsoft URCV

Local Descriptors



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Local Descriptors

- 2D Features
 - Real-valued descriptors
 - SIFT
 - SURF
 - Binary descriptors
 - BRIEF
 - BRISK
 - FREAK



→ [0.03, 0.15, 0.03, 0.92, ...]



→ [0.13, 0.55, 0.47, 0.02, ...]



→ [0.70, 0.05, 0.32, 0.01, ...]



→ [0, 1, 1, 0, 1, 0, 0, 0, 1, ...]



→ [1, 0, 1, 0, 0, 1, 1, 0, 1, ...]



→ [1, 1, 1, 0, 1, 1, 0, 1, 0, ...]



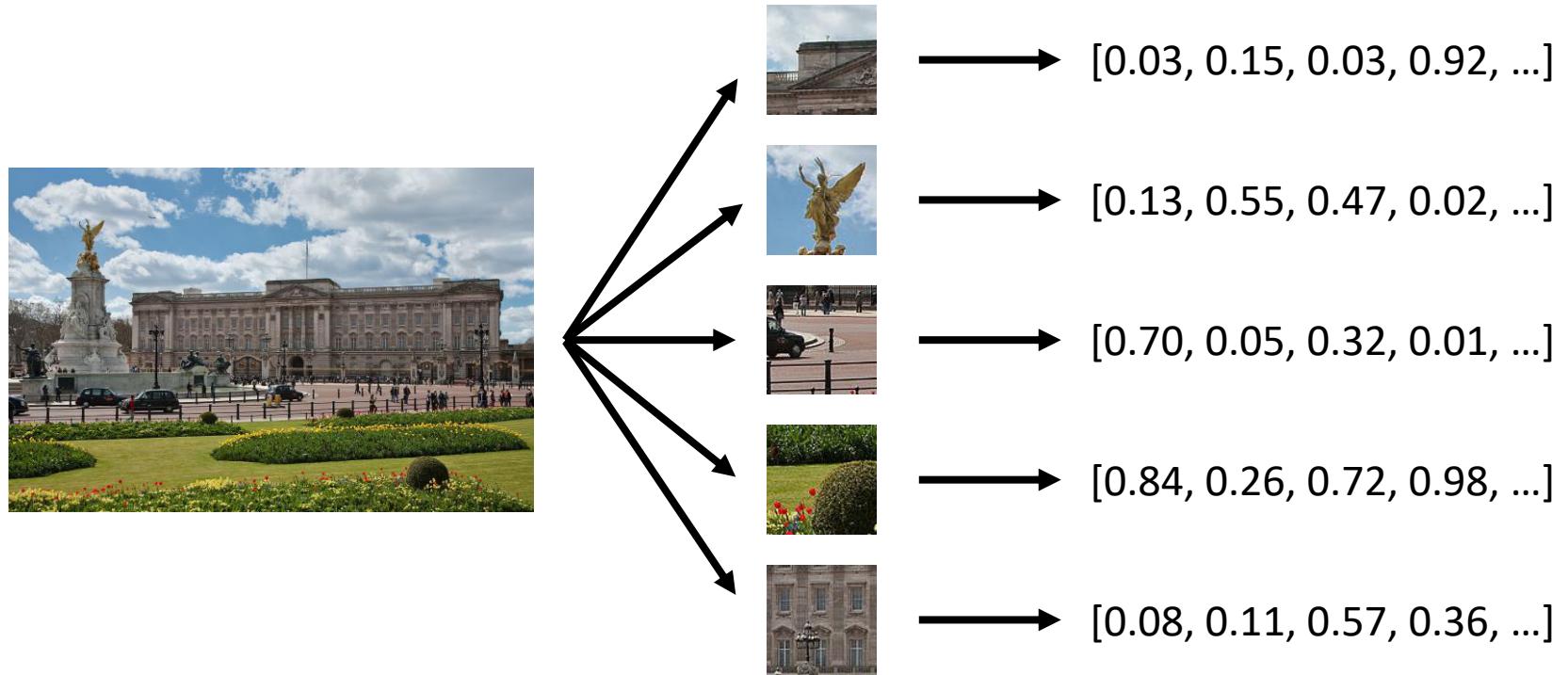
ETH zürich



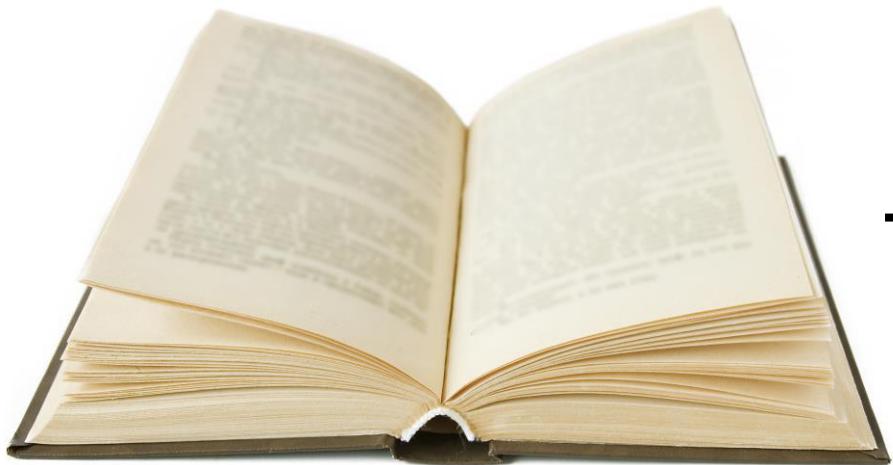
Microsoft

URCV

Local Descriptors



Visual Vocabulary



The quick brown fox jumped...



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Visual Vocabulary



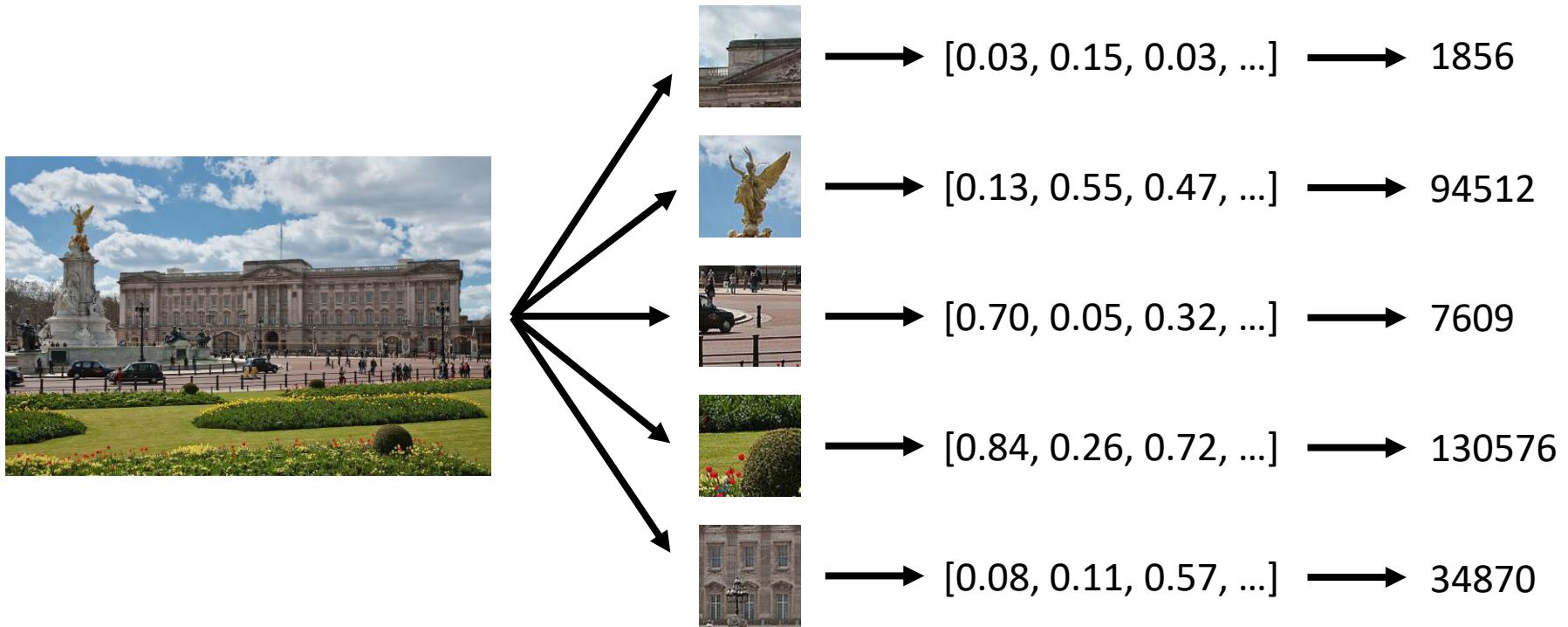
ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Visual Vocabulary



ETH zürich

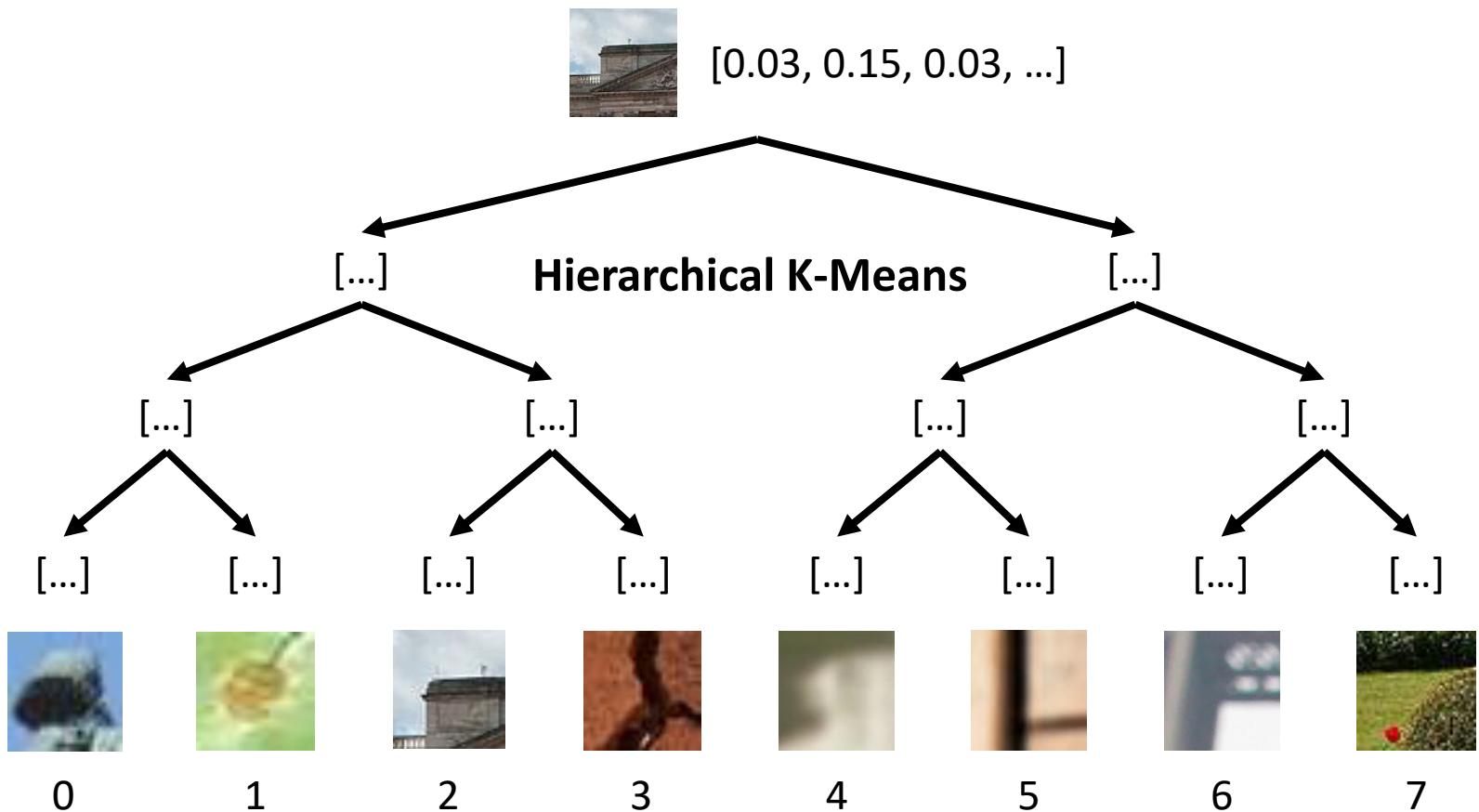


Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Vocabulary Tree



Bag of Words



→ [183, 976, 4385, 97121, 11802]



→ [976, 1018, 4385, 11802, 187049]



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Bag of Words



* Dot Product



ETH zürich

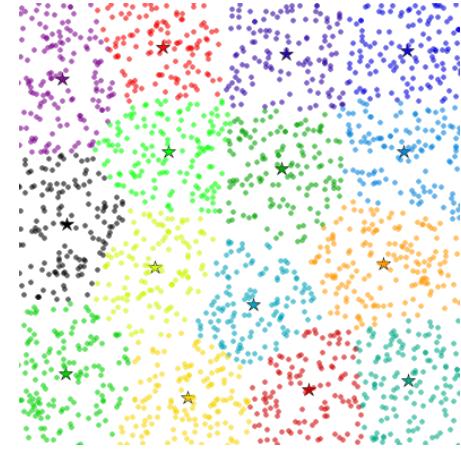


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Binary Vocabulary

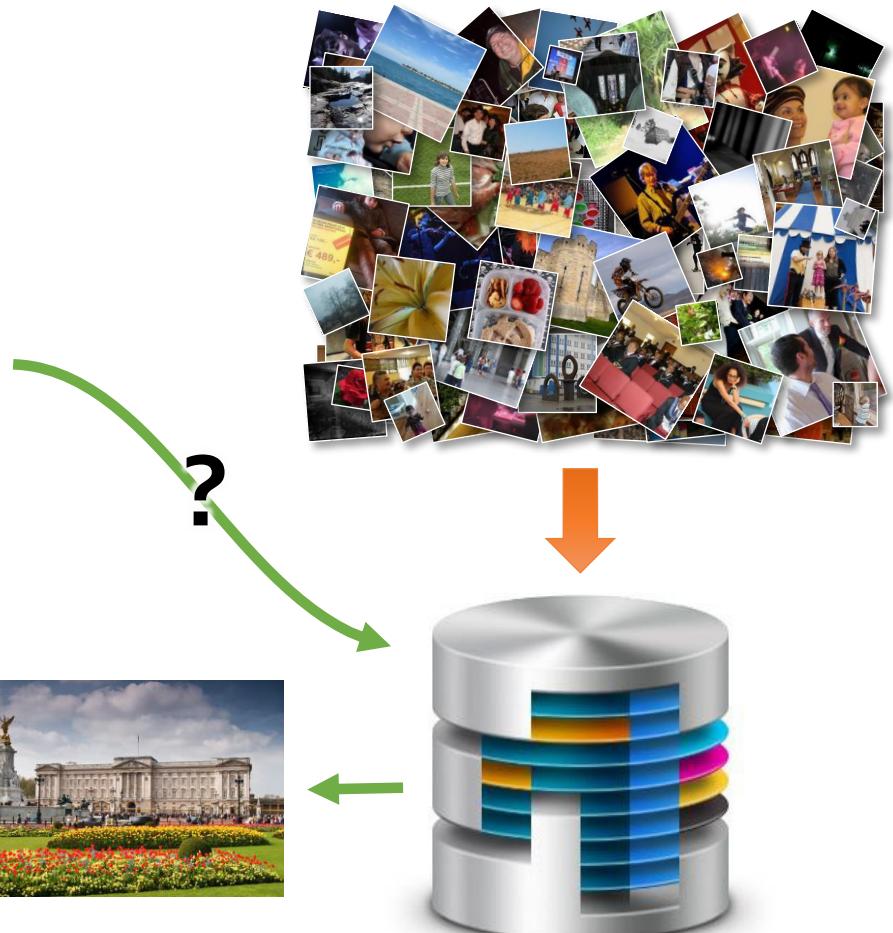
- Hierarchical K-Means not as effective
 - Trzcinski, Lepetit, Fua, *Pattern Recognition Letters* 2012
- Vocabulary construction
 - K-Medoids clustering
- Vocabulary retrieval
 - LSH (Locality Sensitive Hashing)



0000111001	0011100100	1011110110	0100000100	0100000010	1110001001
0001101111	1001001011	0001000100	0001111001	0110111010	1101101111
1001111001	1010001100	1001111101	0110000100	1000000000	0100101011
1100010001	0110110110	0000010011	1110111011	1110101101	0010011110
0111110011	1000011111	0111111000	0110001100	0001000111	0001111011
1000011101	1011101010	1000101001	0110011101	0100010111	1110110010
1100001111	1101100110	1110101101	1001001000	1100010010	0011001010
1001000100	00100011010	0001111110	1011111100	1000001001	0111000011
0011100101	1111001101	0001110111	0101110100	0110010110	1101100111



Image Indexing and Retrieval



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

Connected-Component Discovery



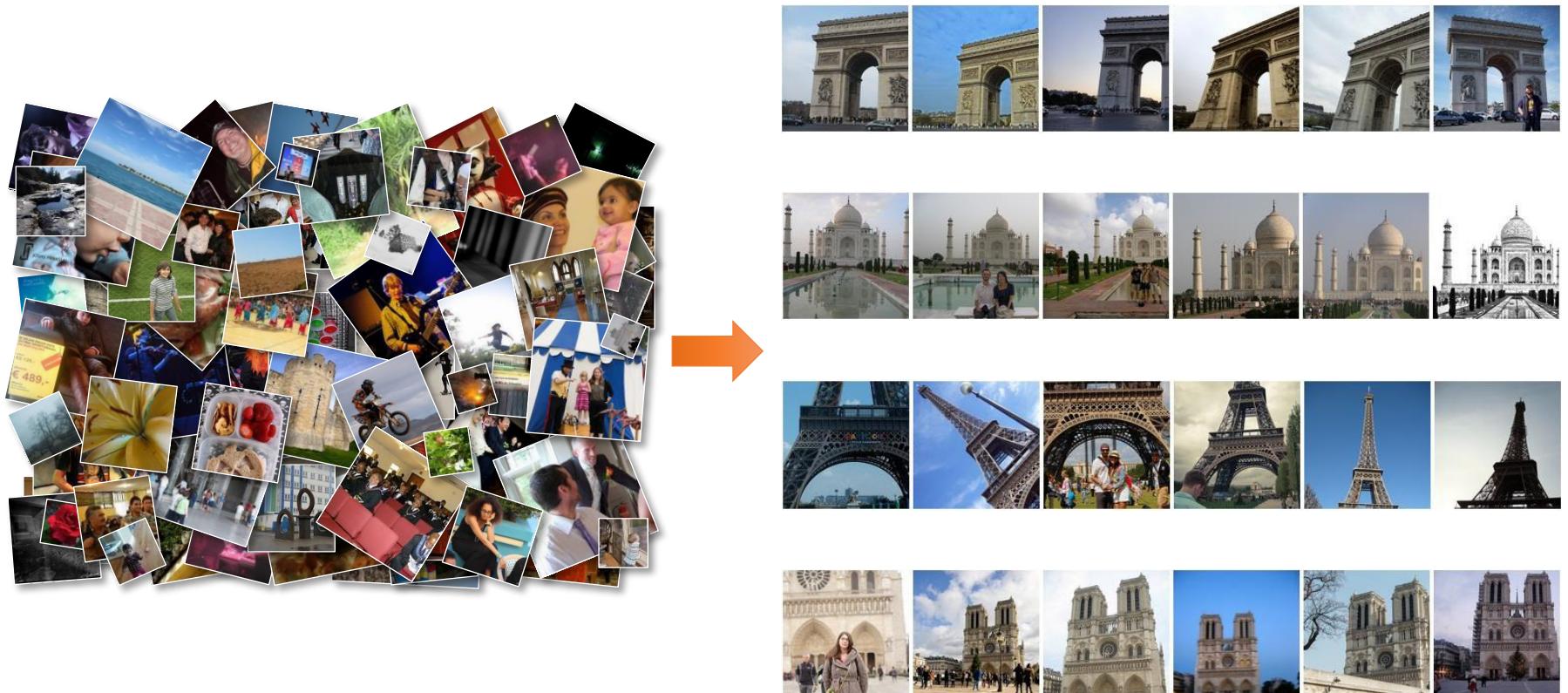
ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Connected Component Discovery



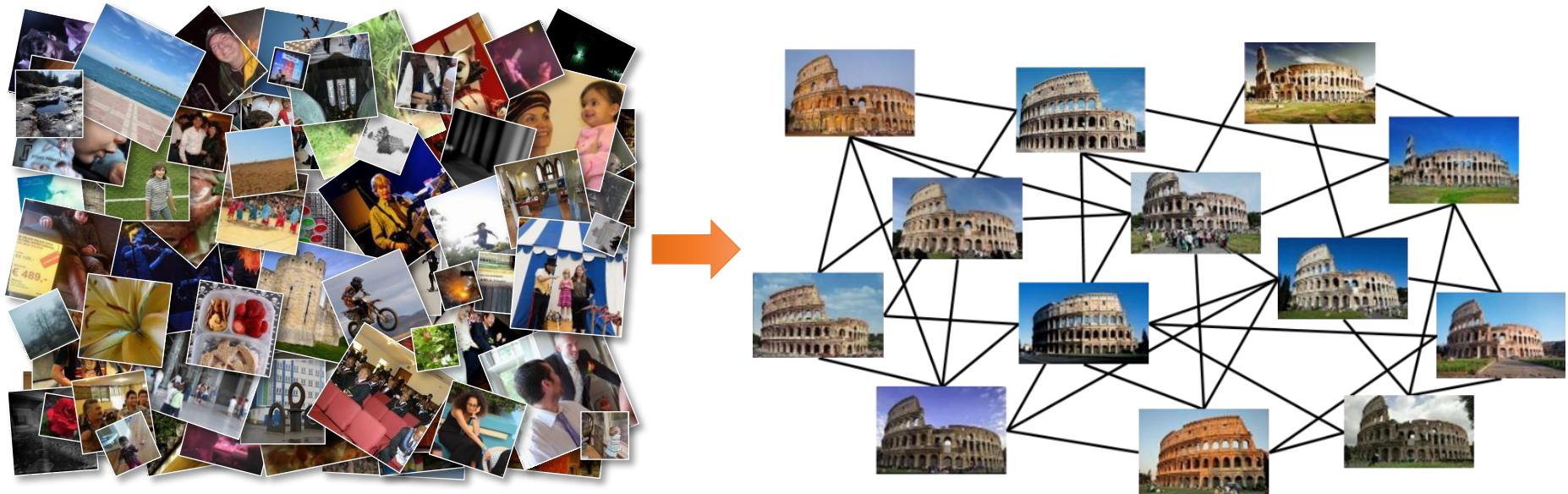
ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Connected Component Discovery



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Connected Component Discovery

- Discovery strategies
 - Brute force
 - Image retrieval
 - Clustering
 - Streaming



ETH zürich

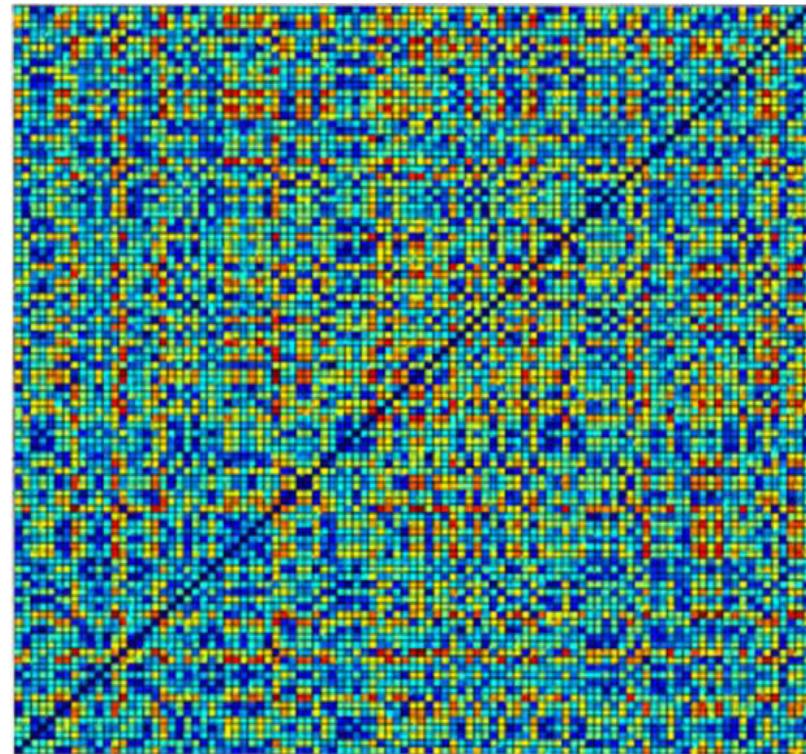


Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

Component Discovery: Brute Force

- Naive



ETH zürich

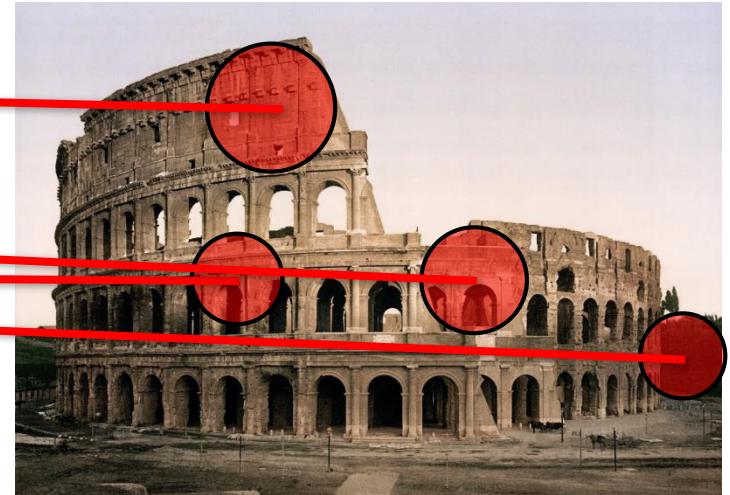


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Component Discovery: Brute Force

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



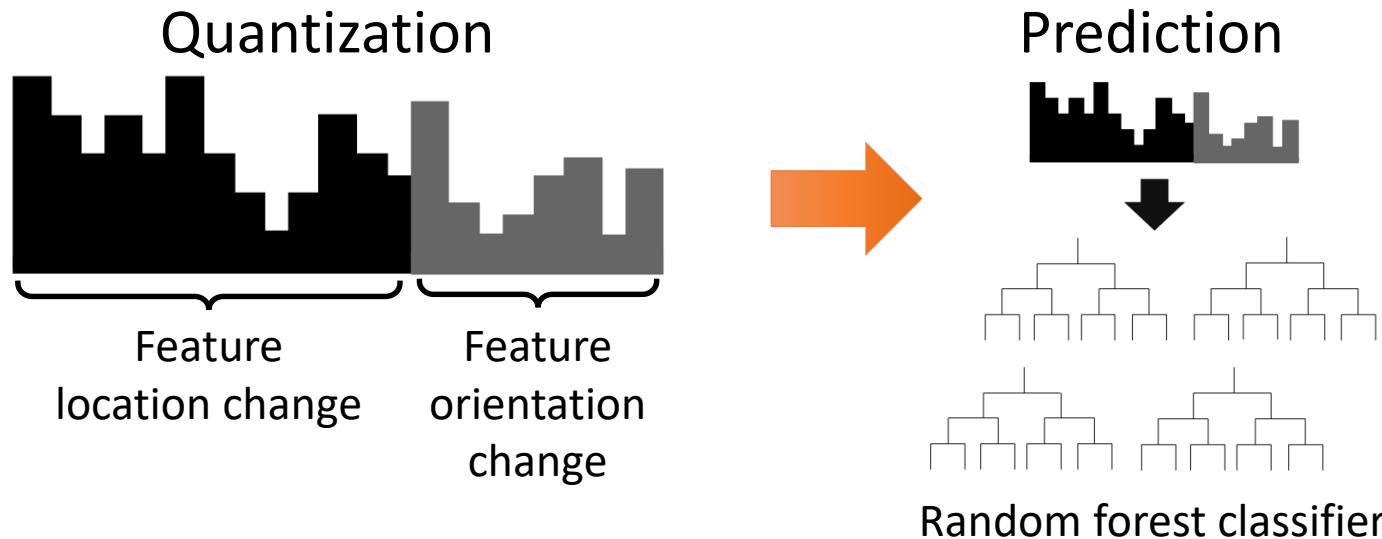
Component Discovery: Brute Force

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



Component Discovery: Brute Force

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



Component Discovery: Image Retrieval

- K-nearest neighbor retrieval



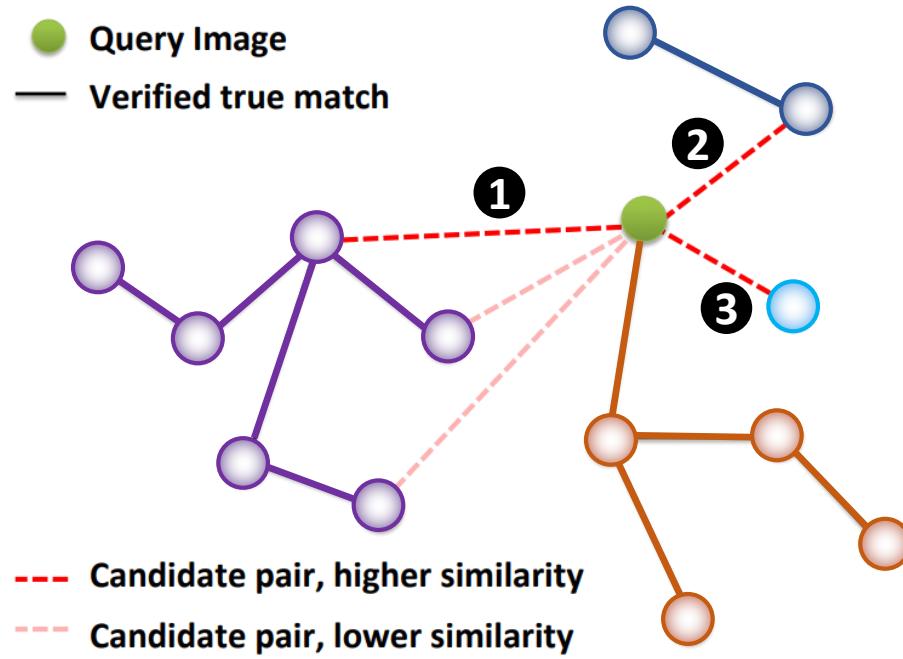
Component Discovery: Image Retrieval

- MatchMiner
 - Lou, Snavely, Gehrke, *ECCV 2012*
 - Prioritize retrieval to maximize length of transitive links



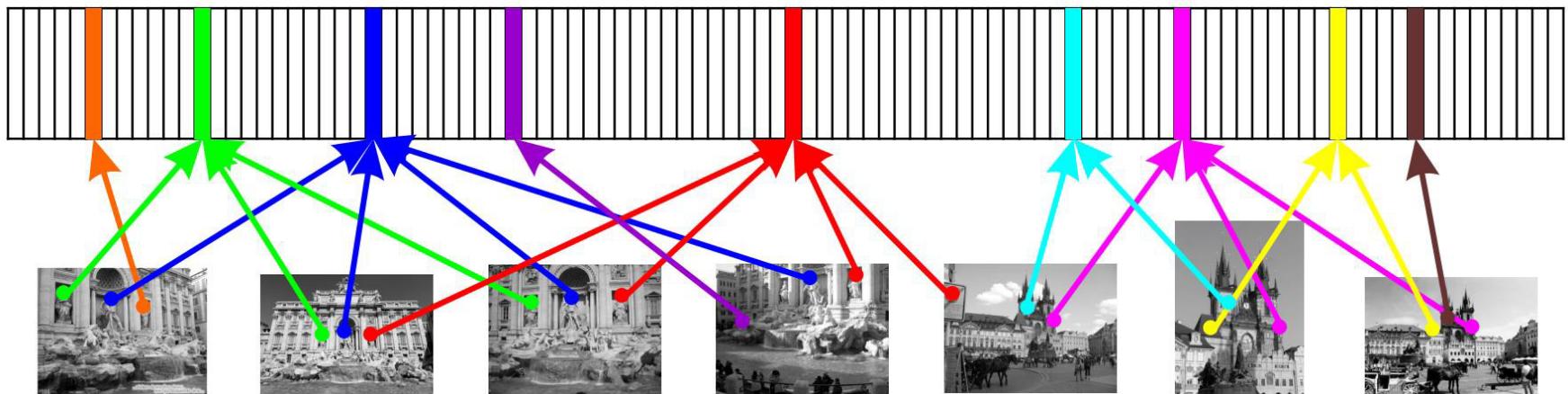
Component Discovery: Image Retrieval

- MatchMiner
 - Lou, Snavely, Gehrke, *ECCV 2012*
 - Prioritize retrieval to maximize length of transitive links



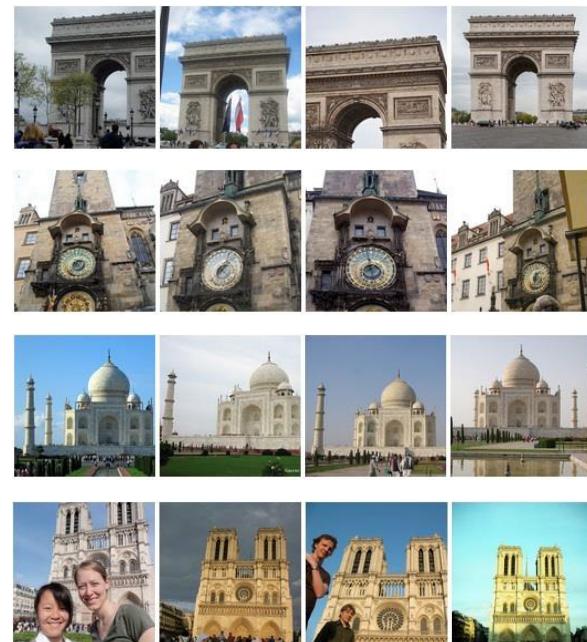
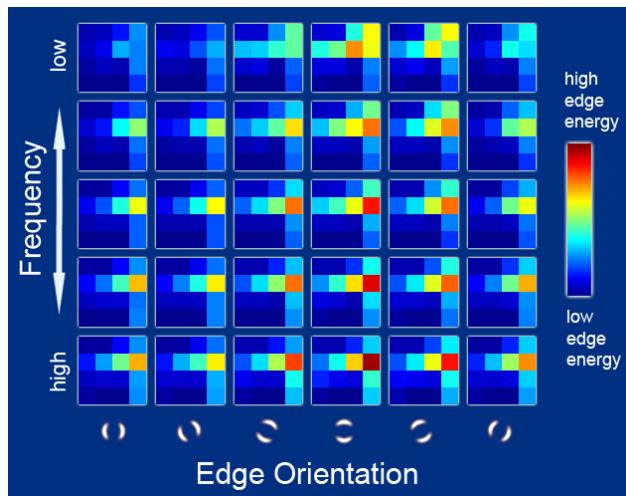
Component Discovery: Image Retrieval

- VocMatch
 - Havlena and Schindler, *ECCV 2014*
 - Treat visual words as direct feature matches



Component Discovery: Image Clustering

- Building Rome on a Cloudless Day
 - Frahm et al, *ECCV 2010*
 - K-medoids clustering of GIST descriptors



ETH zürich



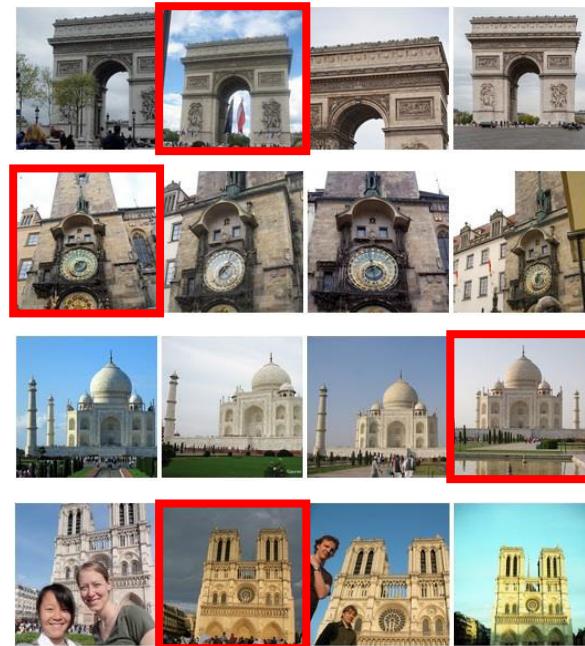
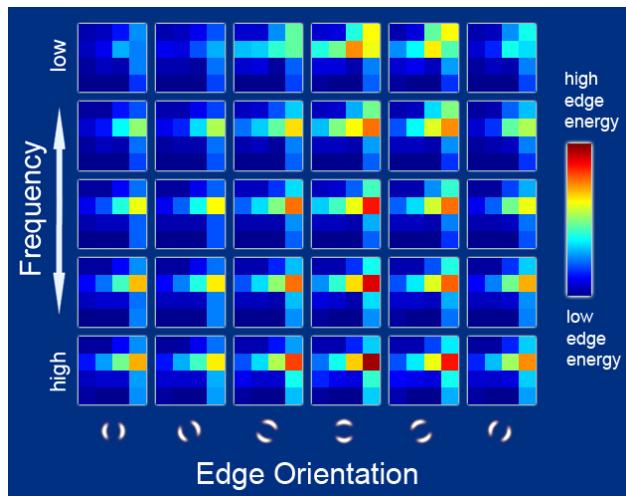
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Component Discovery: Image Clustering

- Building Rome on a Cloudless Day
 - Frahm et al, *ECCV 2010*
 - K-medoids clustering of GIST descriptors
 - Iconic image selection



ETH zürich

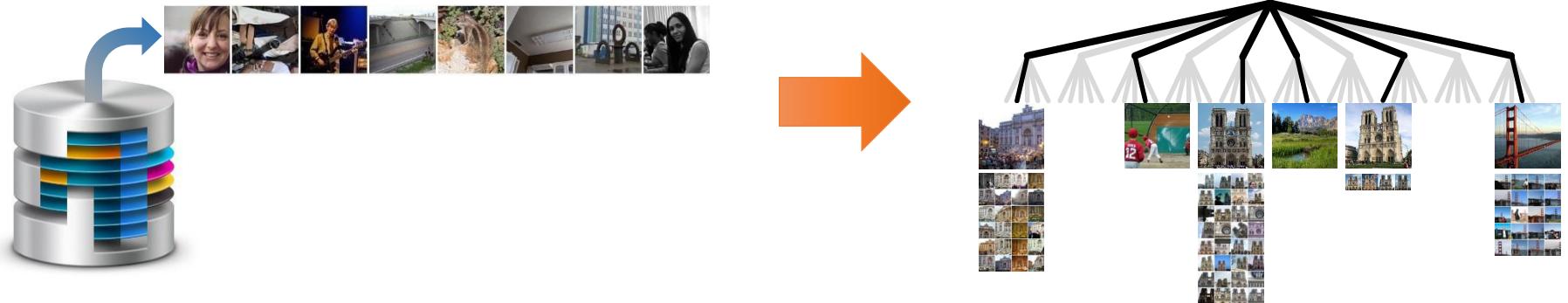


Microsoft

URCV

Component Discovery: Streaming

- Building the World in Six Days
 - Heinly, Schönberger, Dunn, Frahm, *CVPR 2015*
 - Combine image retrieval and iconic image selection



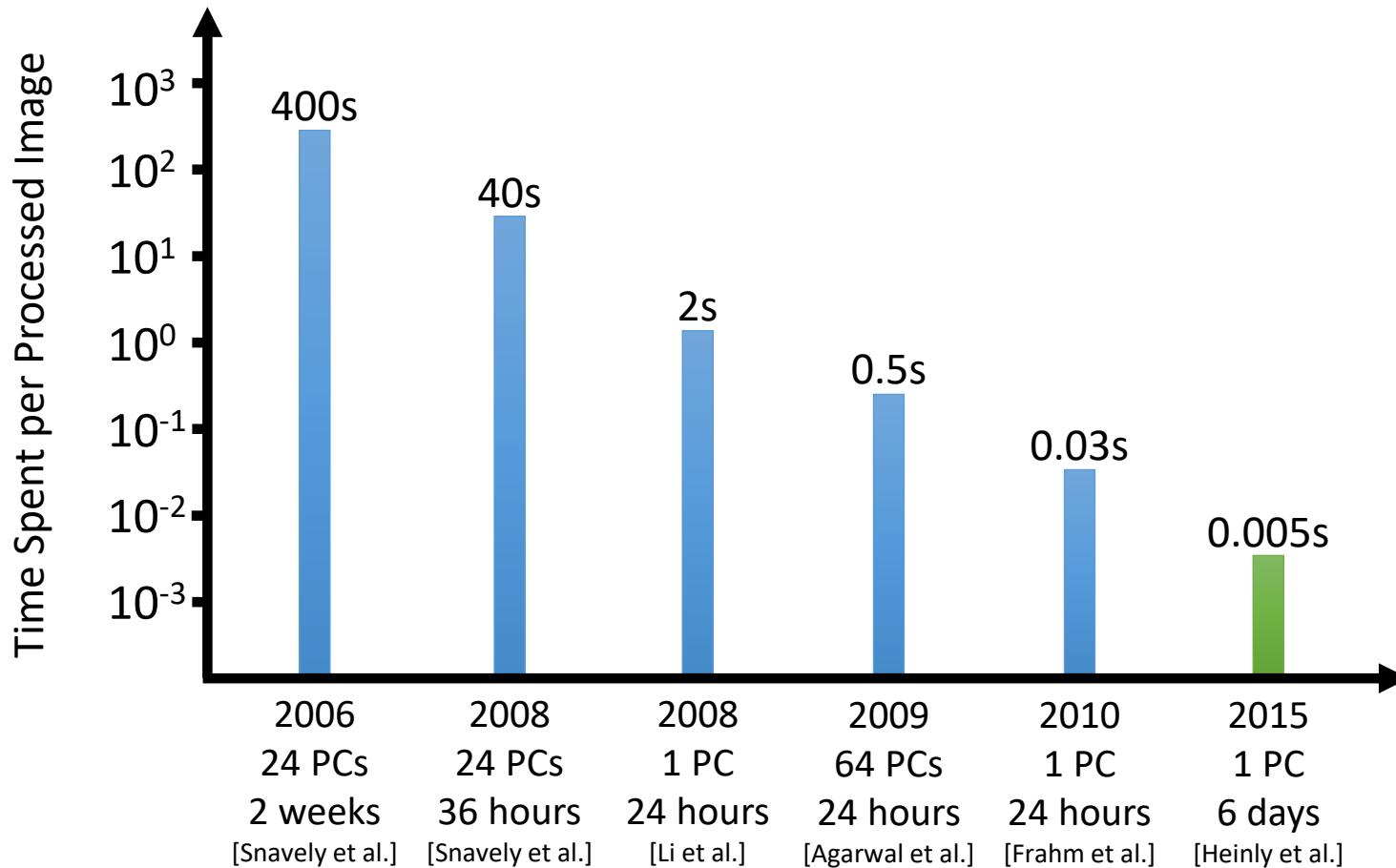
ETH zürich



Microsoft URCV

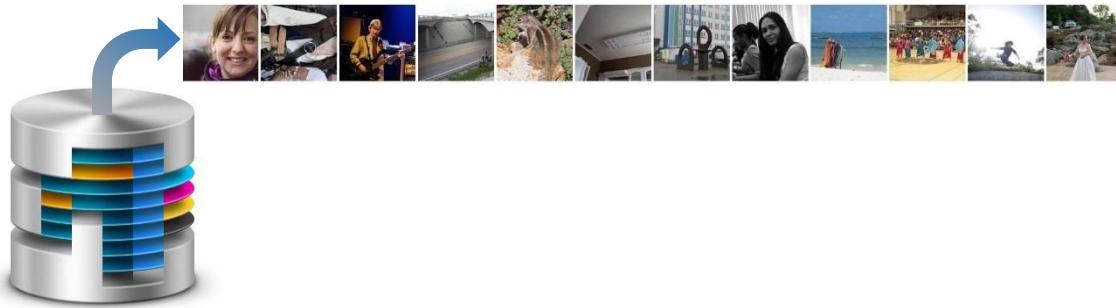
Large-scale 3D Modeling from Crowdsourced Data

Large-Scale Performance



Streaming Paradigm

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



ETH zürich



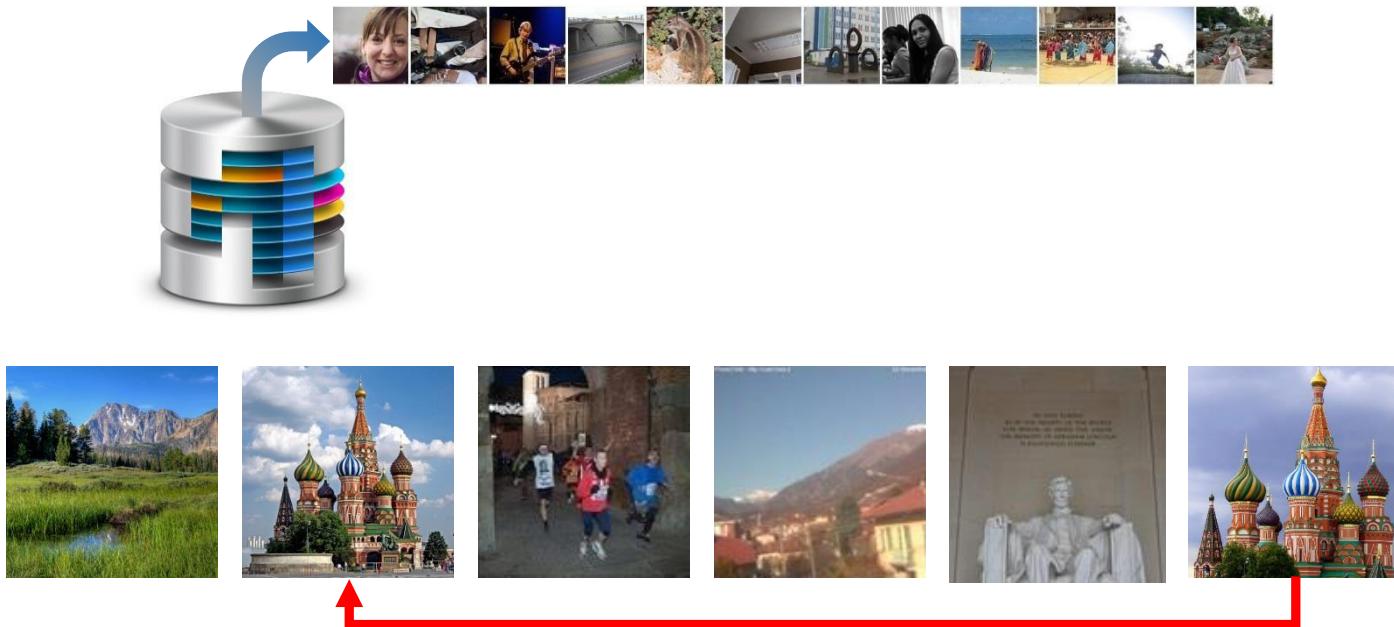
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

Challenges of Streaming

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



ETH zürich



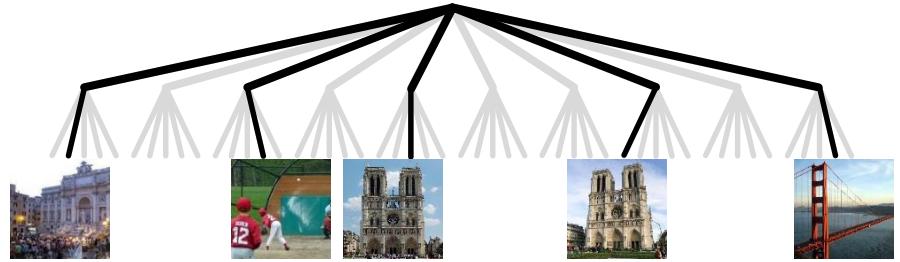
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



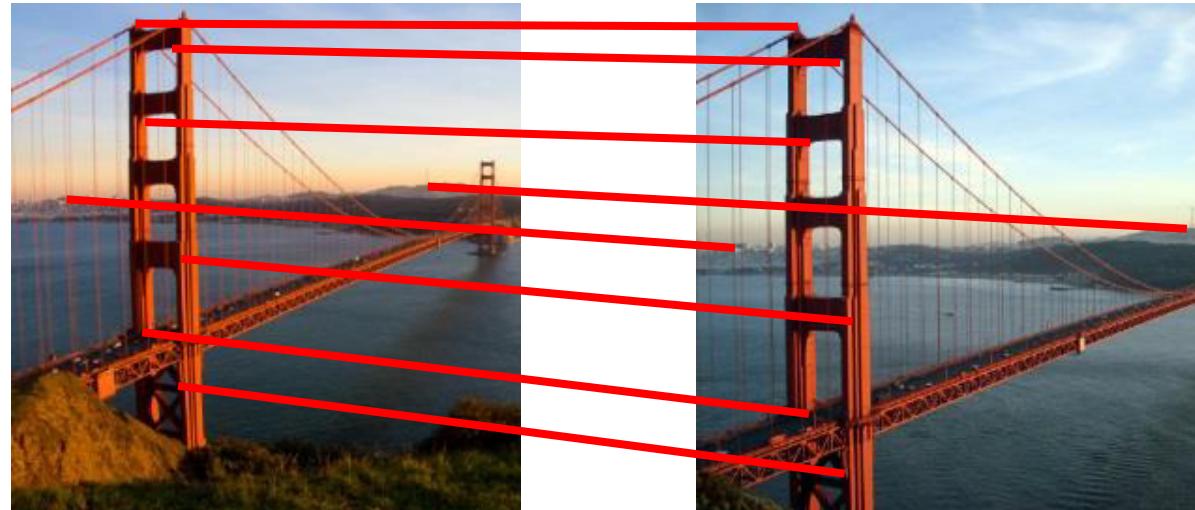
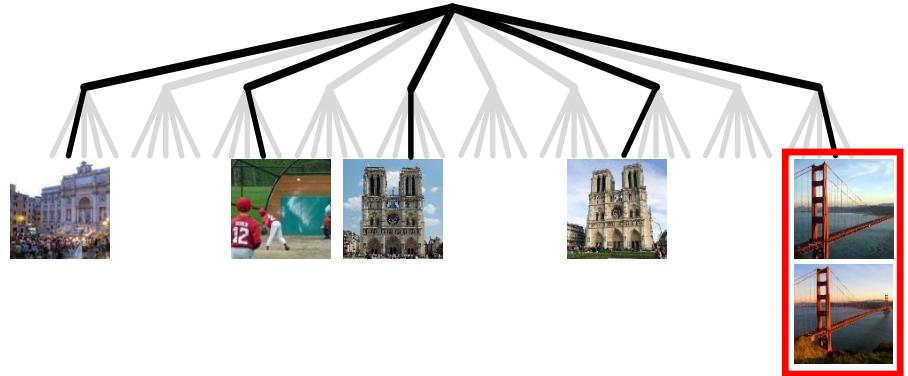
100M Images



Streaming Data Association



100M Images



ETH zürich

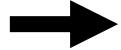


Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

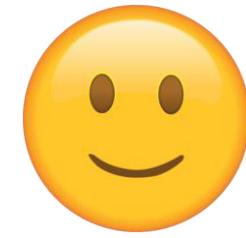
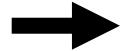
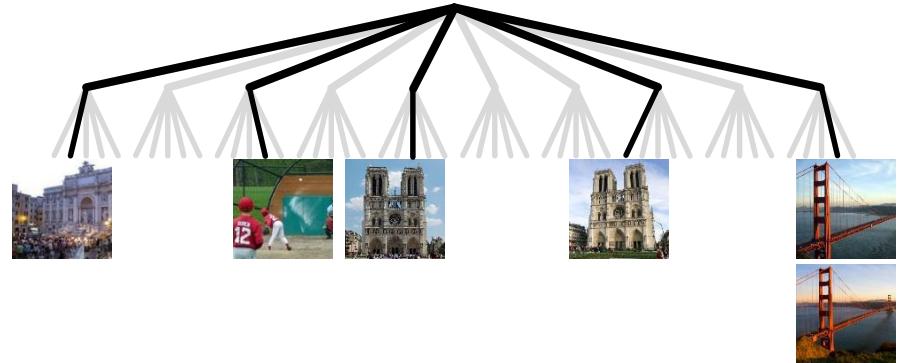
Image Registration



Streaming Data Association



100M Images



ETH zürich



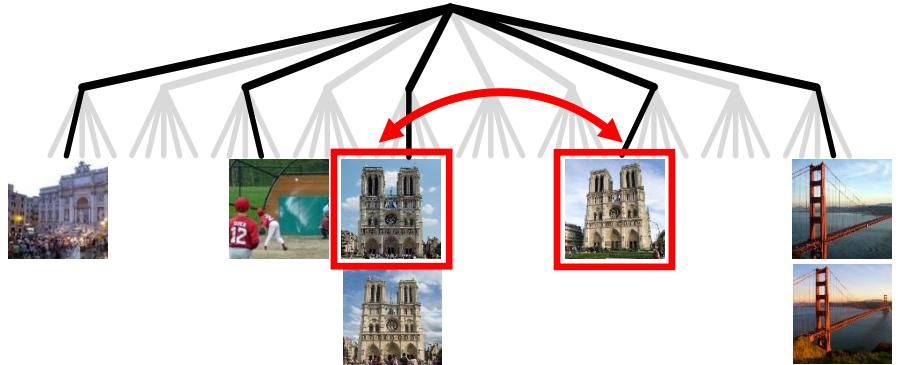
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



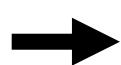
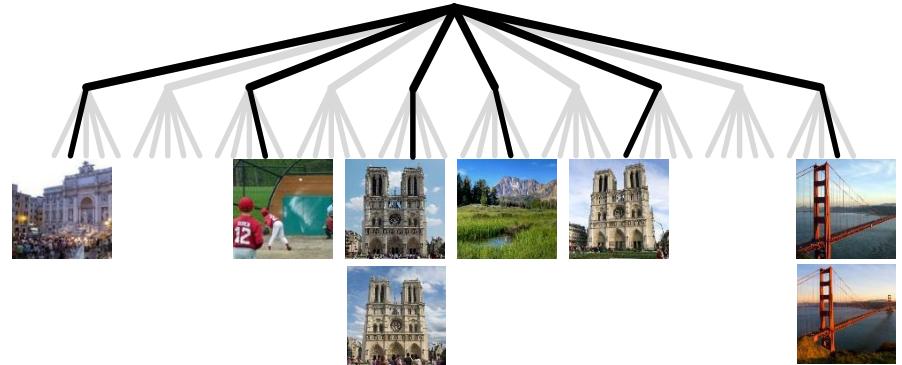
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



Microsoft

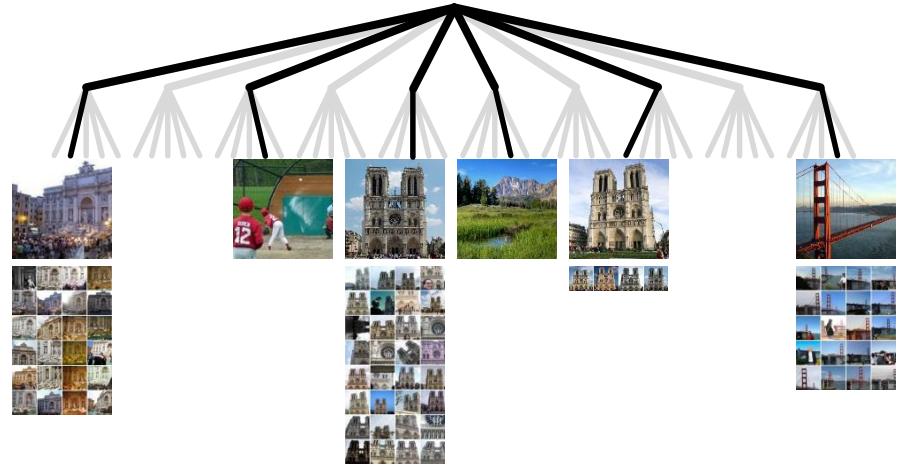
URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



Microsoft URCV

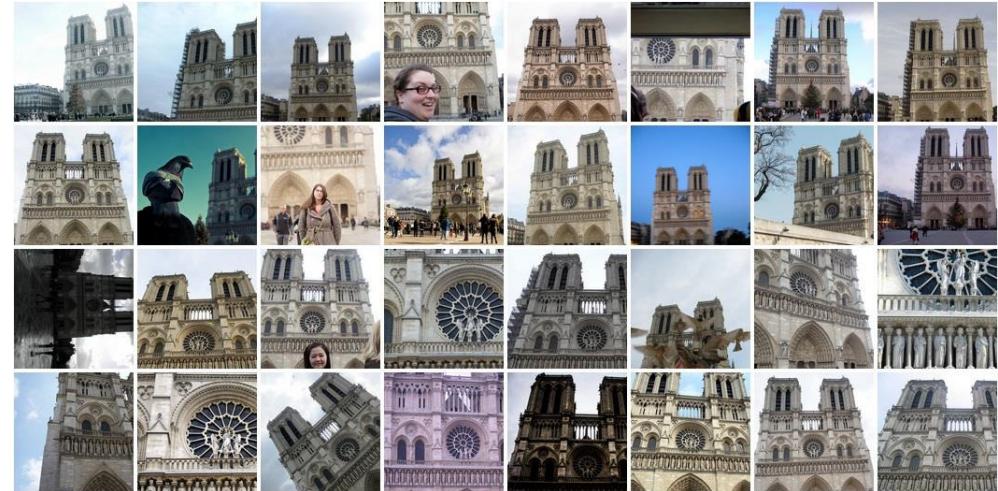
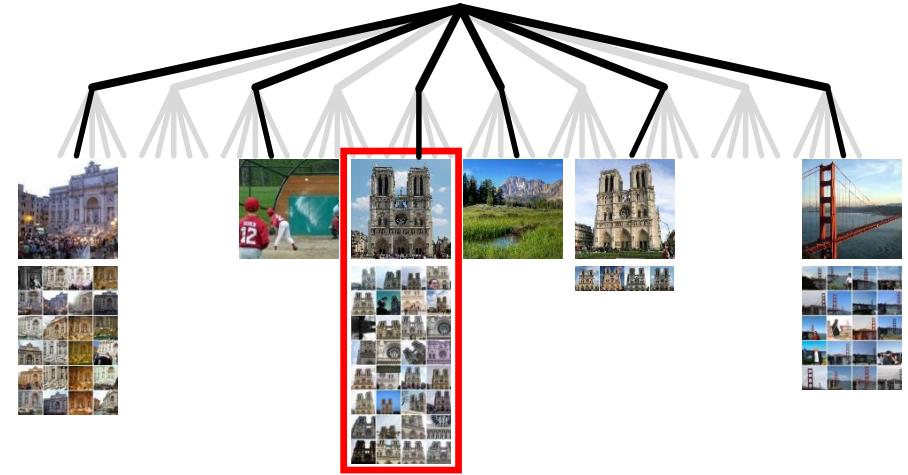
Large-scale 3D Modeling from Crowdsourced Data

Cluster Formation



100M Images

Iconic Image



ETH zürich

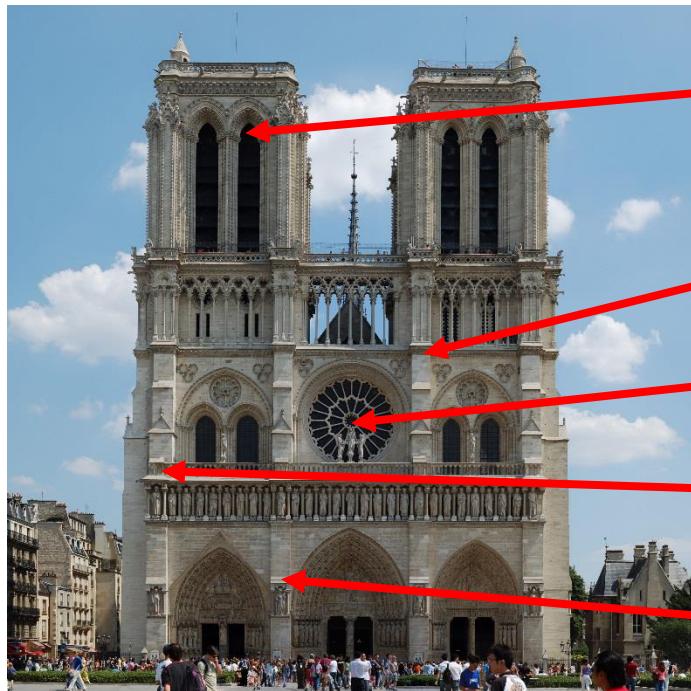


Microsoft URCV

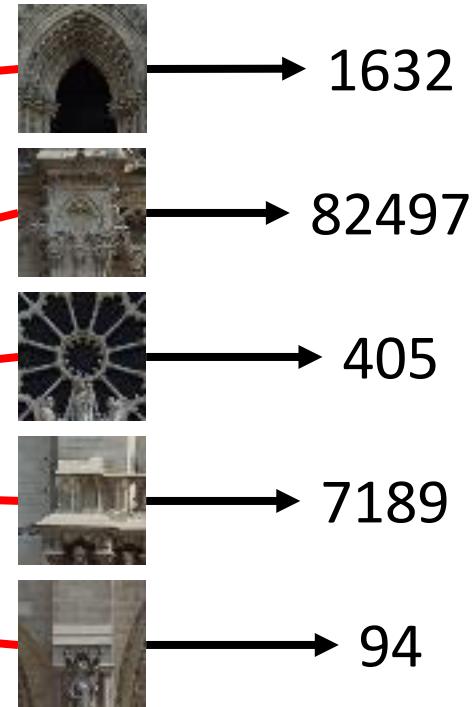
Large-scale 3D Modeling from Crowdsourced Data

Cluster Representation

Iconic Image



Bag of Visual Words



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

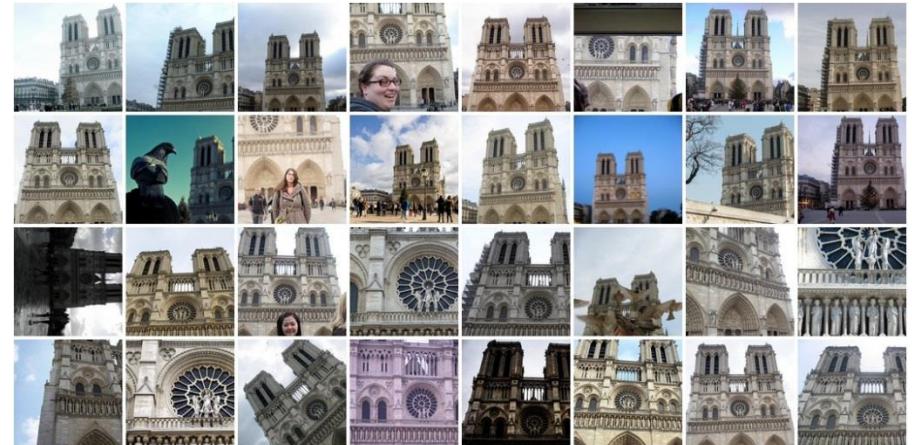
Cluster Representation

Iconic Image



Bag of
Visual Words

1632
82497
405
7189
94



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

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

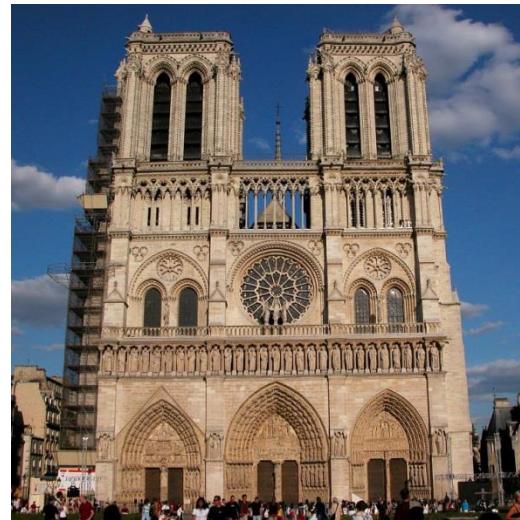
Iconic Image



Bag of
Visual Words

1632
82497
405
7189
94

Cluster Image



Registered
Visual Words

1632
63917
383
7189
2219



ETH zürich



Microsoft

URCV

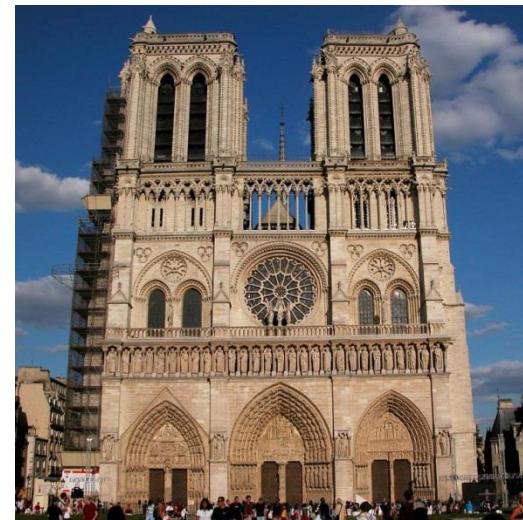
Cluster Representation



Bag of
Visual Words

1632
82497
405
7189
94
63917
383
2219

Cluster Image



Registered
Visual Words

1632
63917
383
7189
2219



ETH zürich

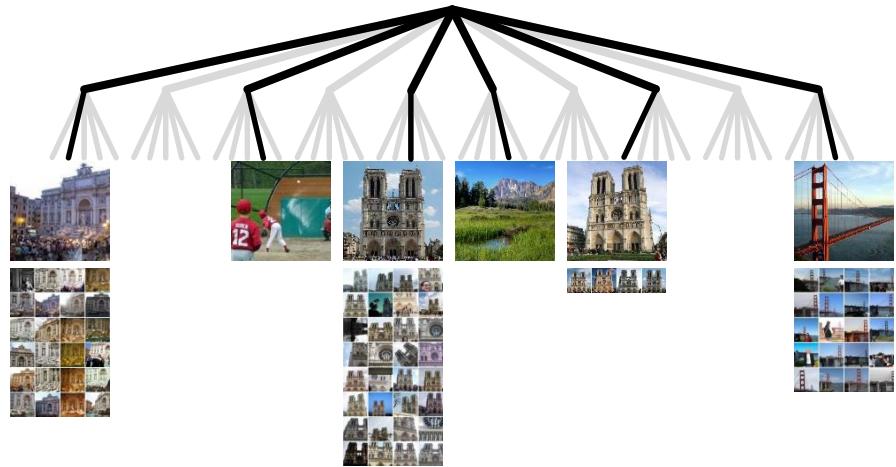


Microsoft URCV

Streaming Data Association



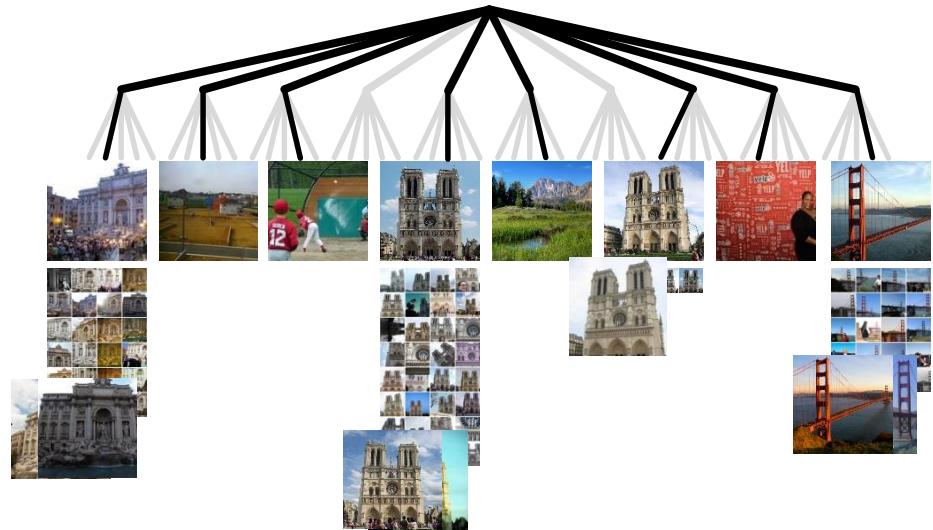
100M Images



Streaming Data Association



100M Images



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



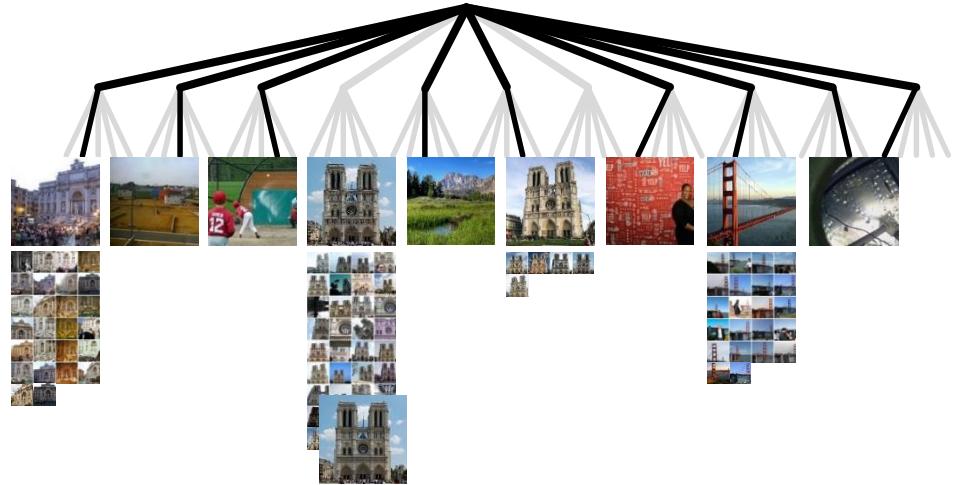
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



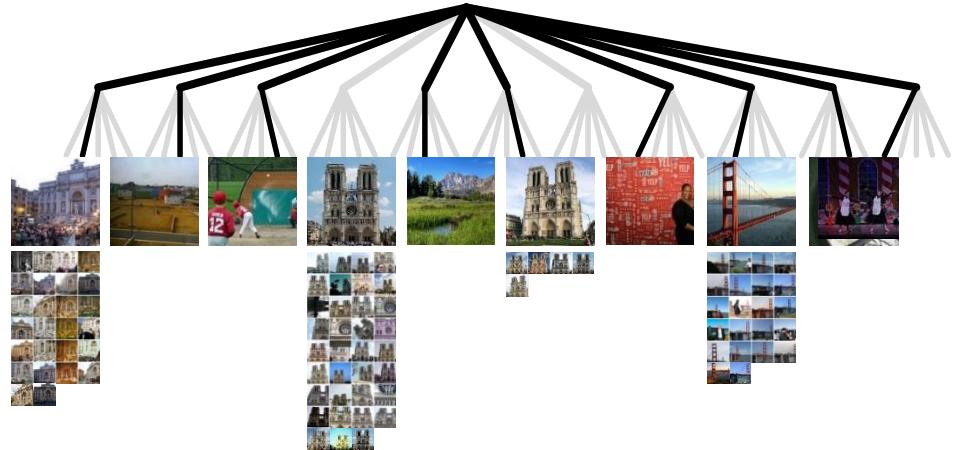
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



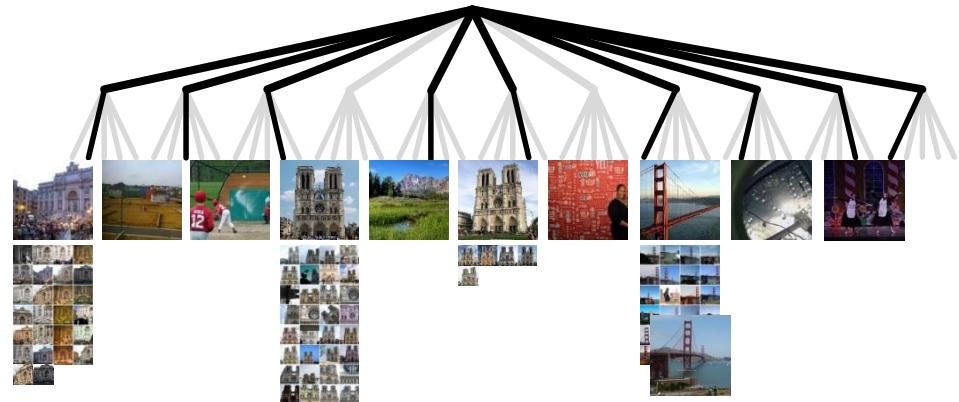
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



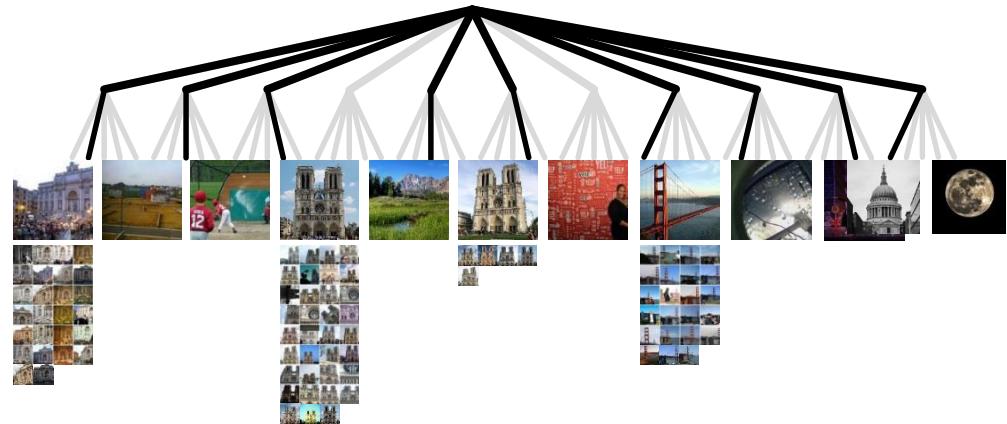
100M Images



Streaming Data Association



100M Images



ETH zürich



Microsoft URCV

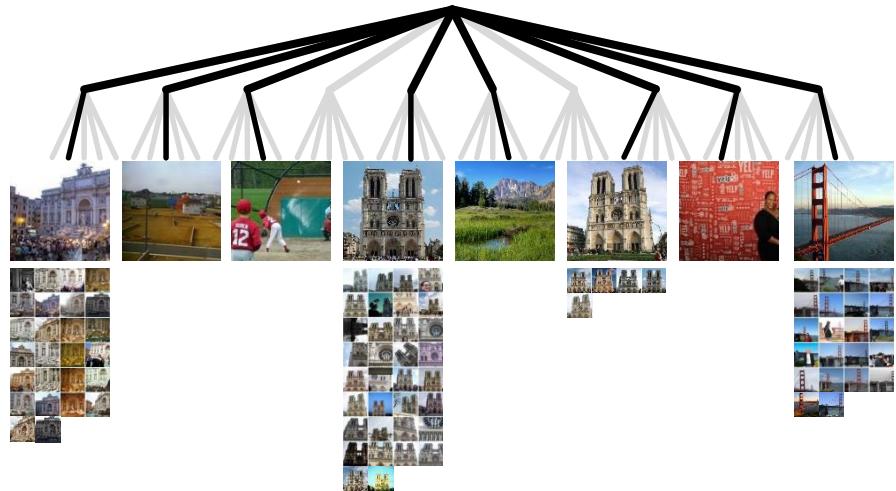
Large-scale 3D Modeling from Crowdsourced Data

***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
Kernel 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



ETH zürich



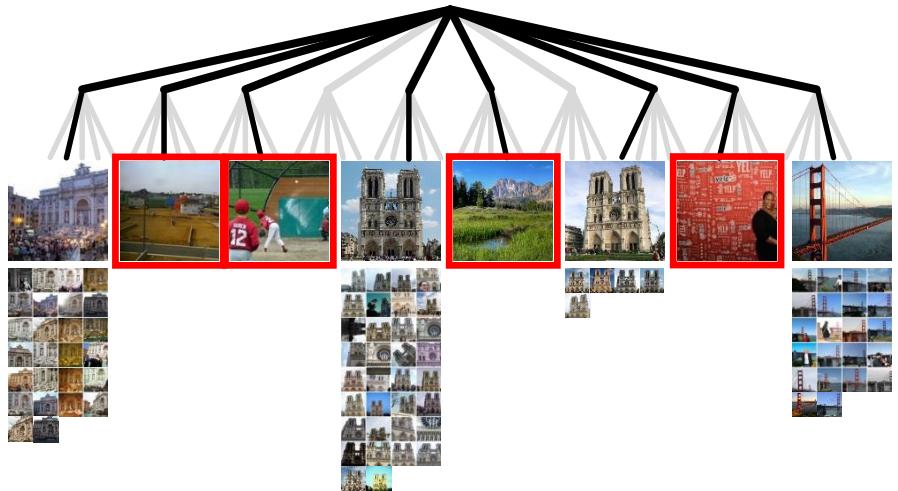
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Streaming Data Association



100M Images



ETH zürich



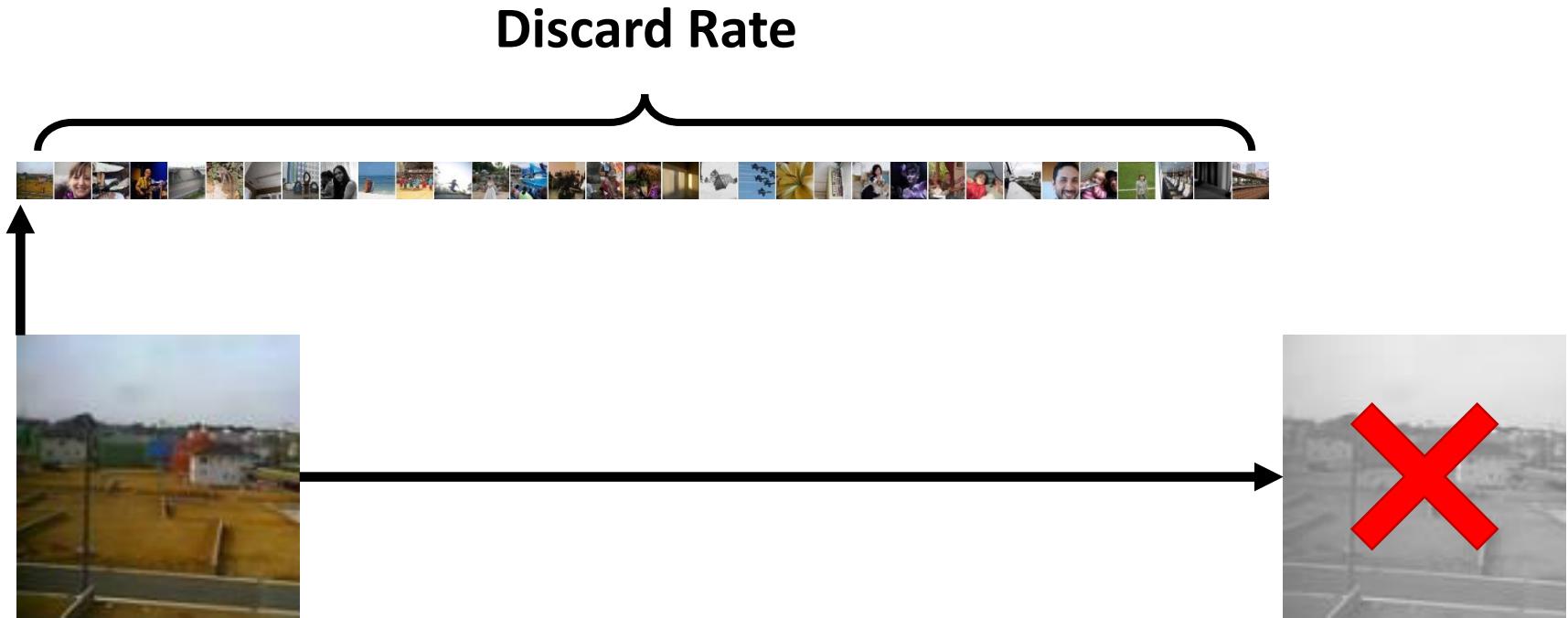
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

100

Cluster Discarding



ETH zürich



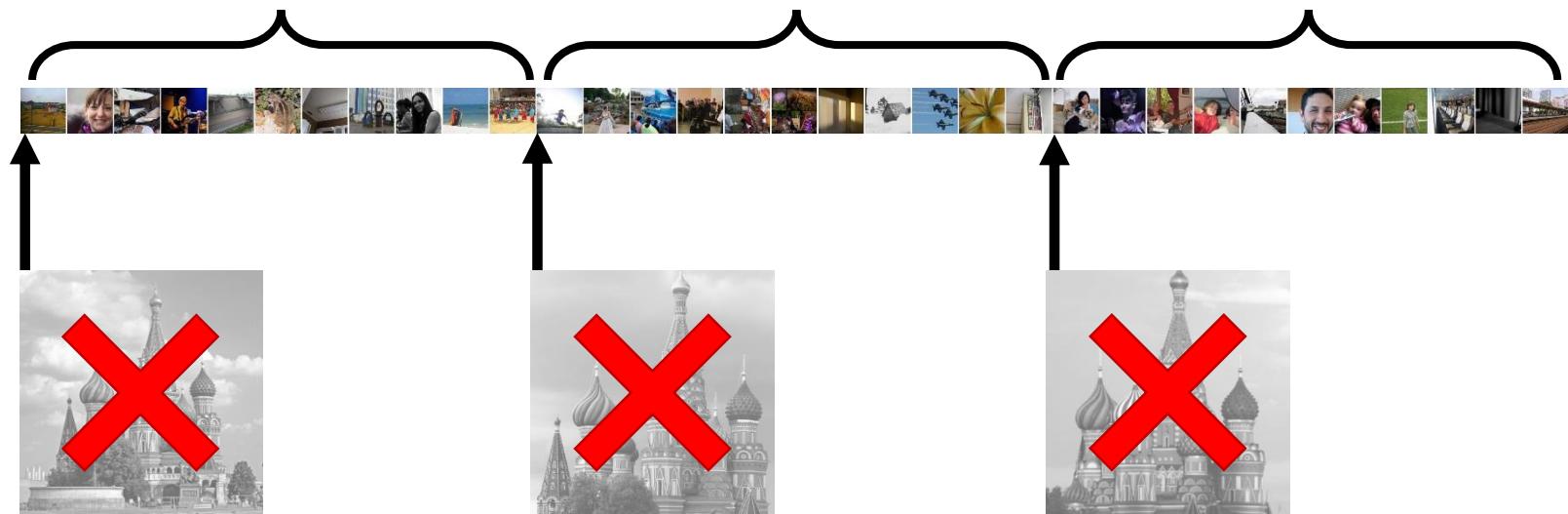
Microsoft

URCV

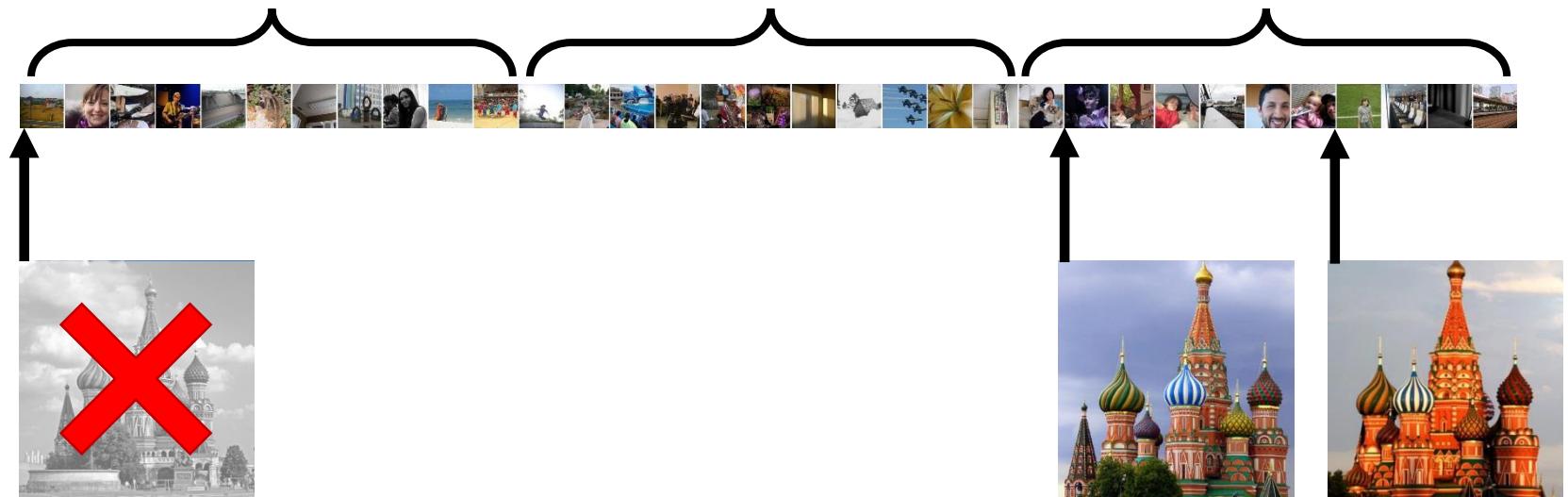
Large-scale 3D Modeling from Crowdsourced Data

101

Cluster Discarding



Cluster Discarding



ETH zürich

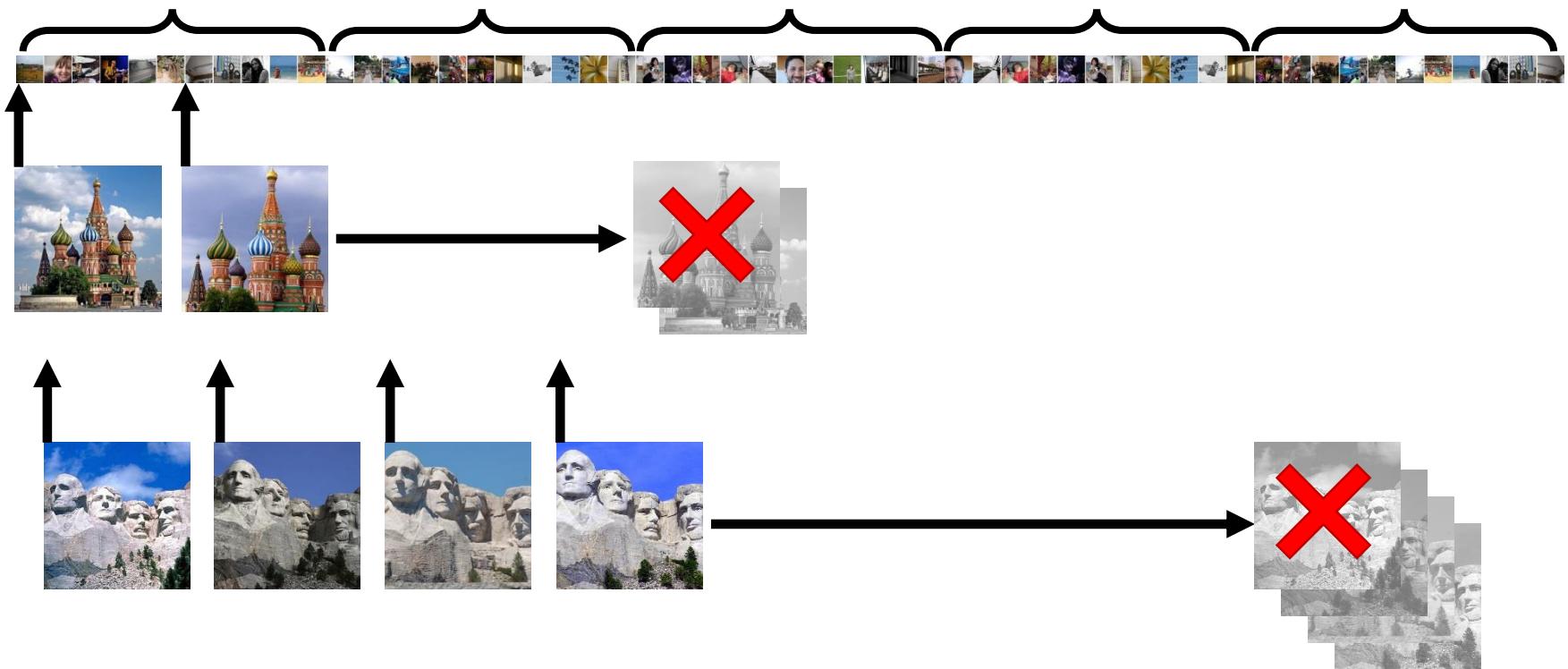


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

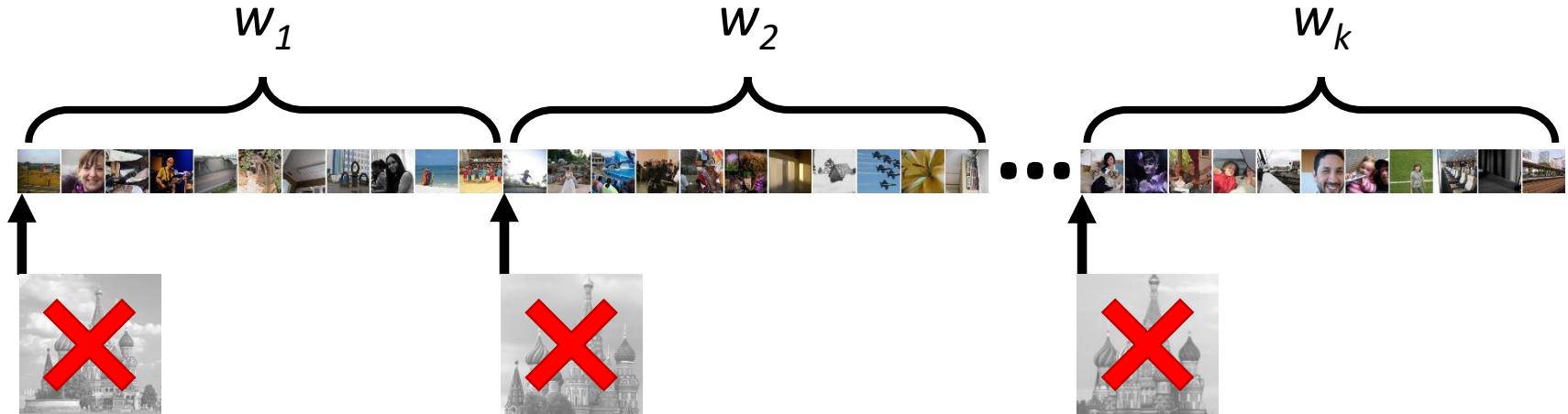
103

Cluster Discarding



Recoverable Cluster Size

What is the minimal recoverable cluster size?



c_r = Recovered cluster size

c = Cluster size

$$c_r = c - k$$

One missed image per discard window

Recoverable as long as $c > k$



ETH zürich

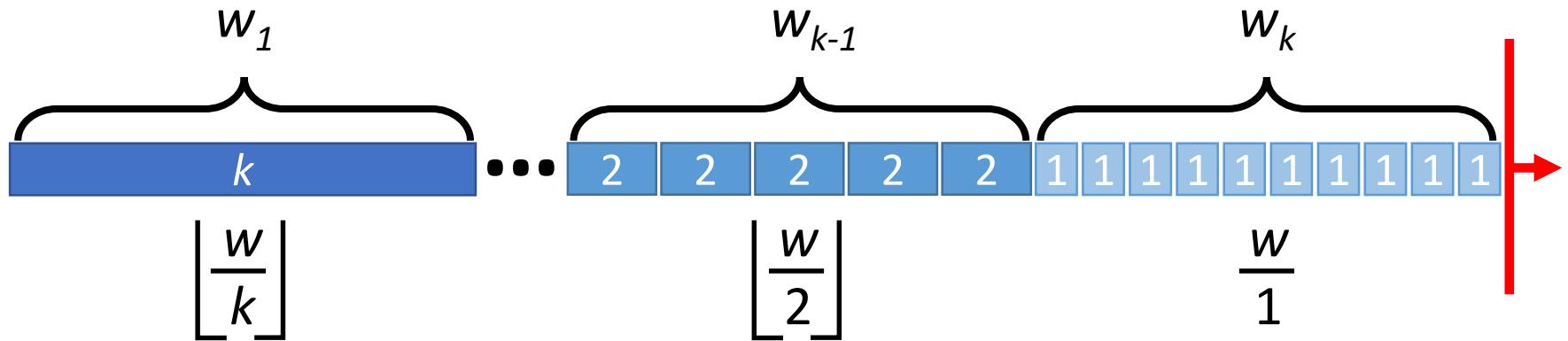


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

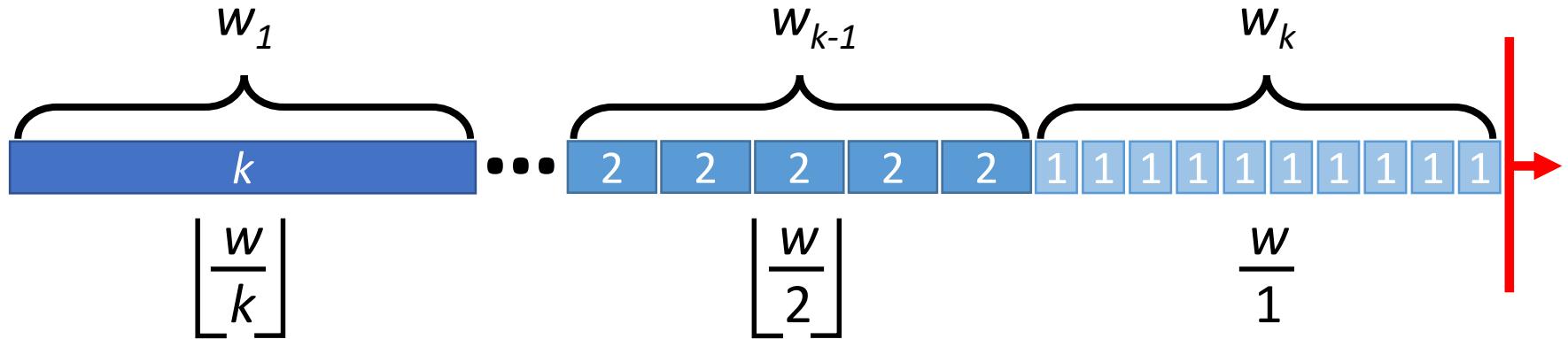
Memory Consumption

What is the upper bound of clusters in memory?



Memory Consumption

What is the upper bound of clusters in memory?



B = Upper bound
of clusters

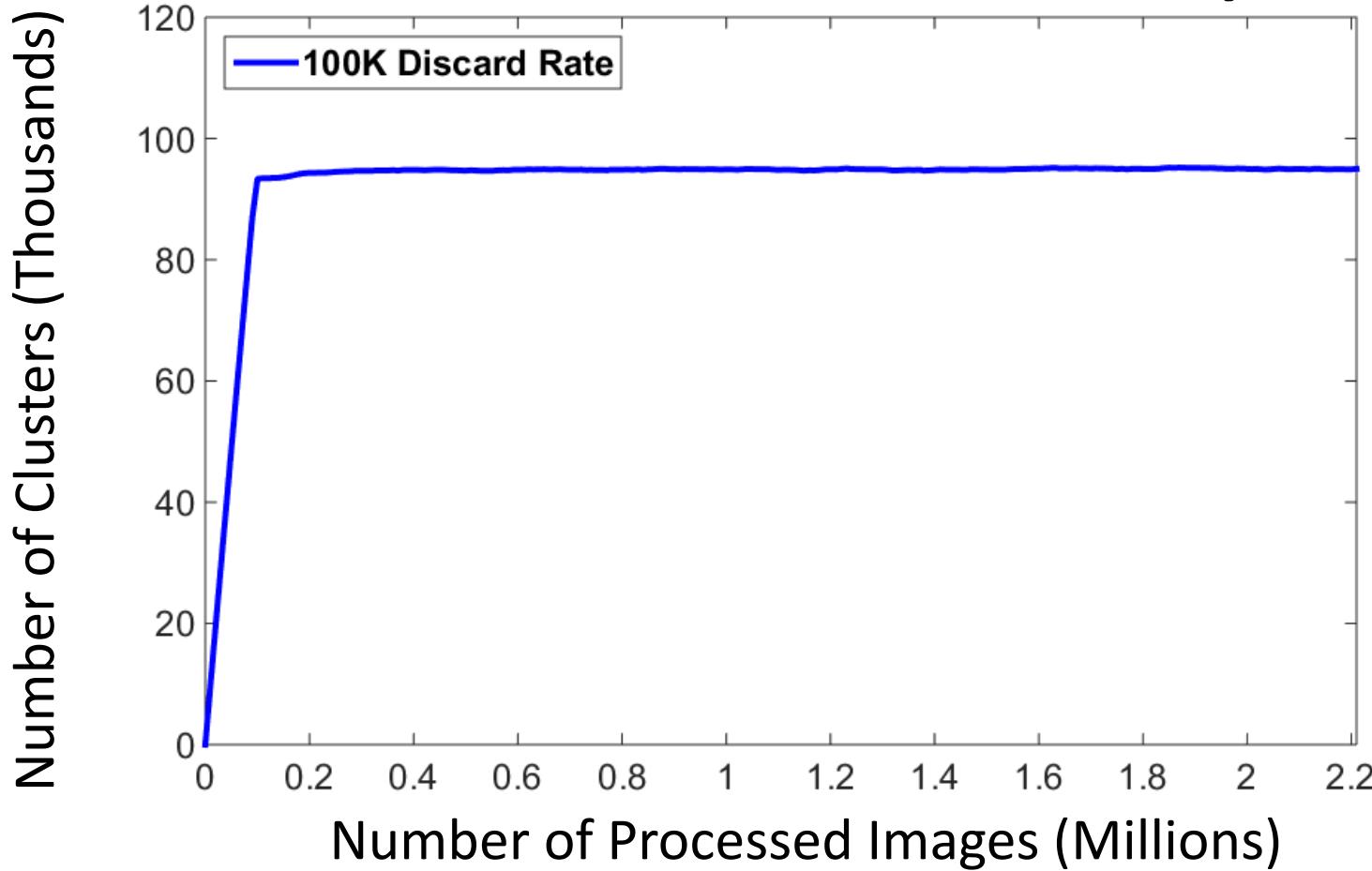
$$B \leq \sum_{i=1}^k \underbrace{\frac{w}{i}}_{\text{Number of clusters per discard window}} \leq w \log(k)$$

Number of discard windows



Memory Consumption

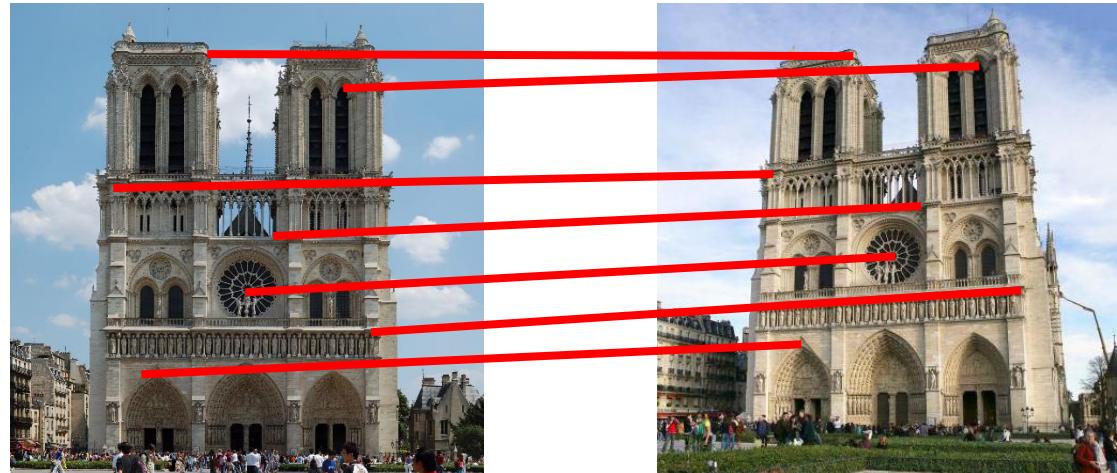
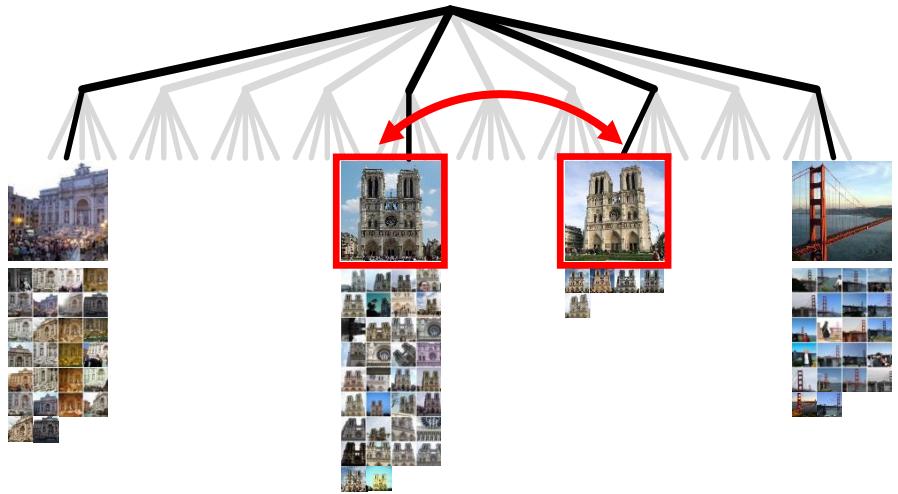
Number of Clusters in Memory



Streaming Data Association



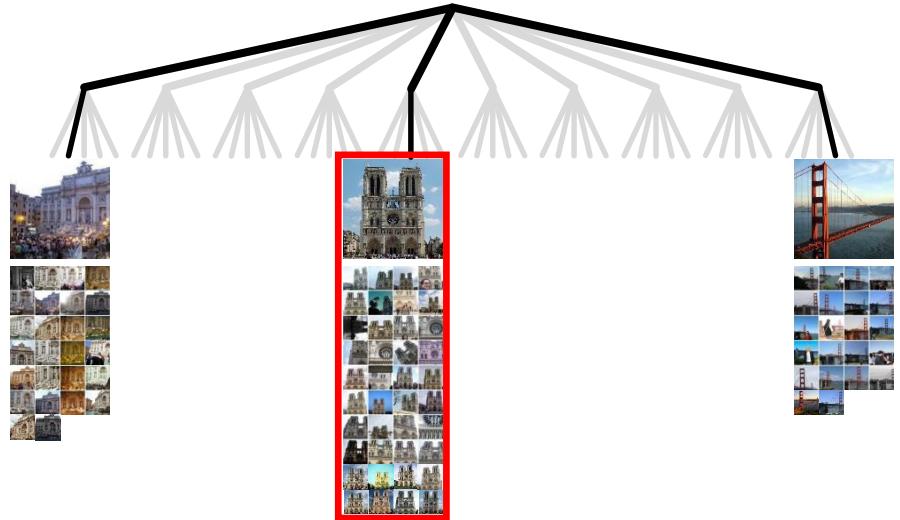
100M Images



Streaming Data Association



100M Images



ETH zürich



Microsoft URCV

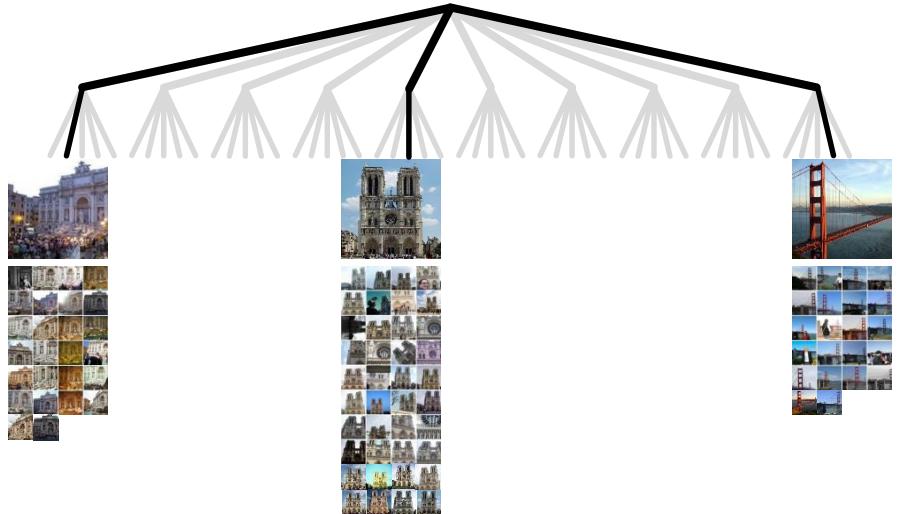
Large-scale 3D Modeling from Crowdsourced Data

110

Streaming Data Association



100M Images



ETH zürich

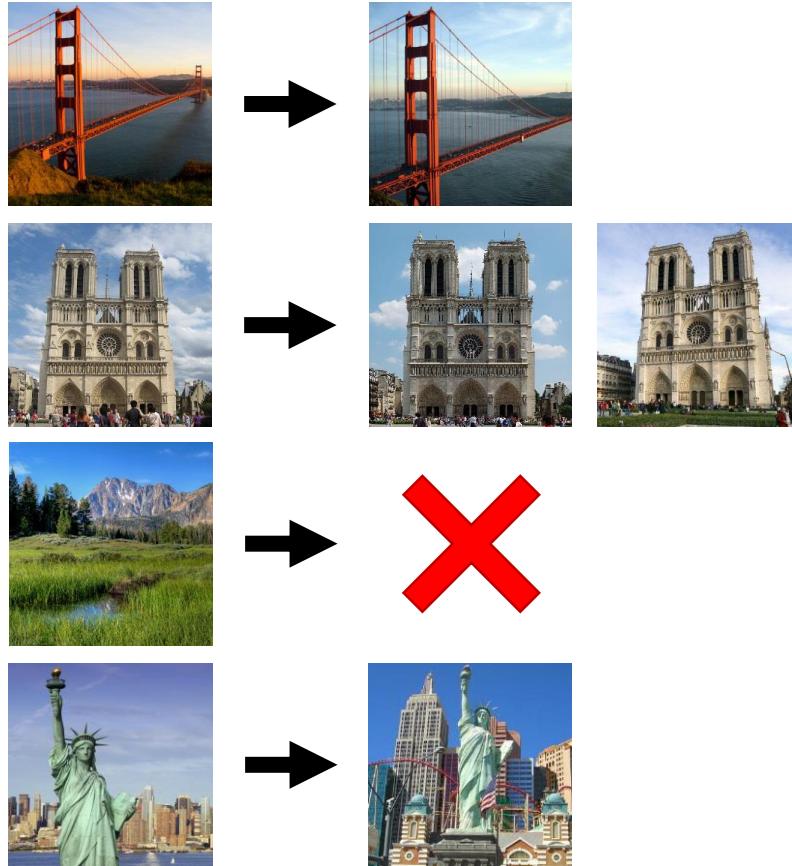


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

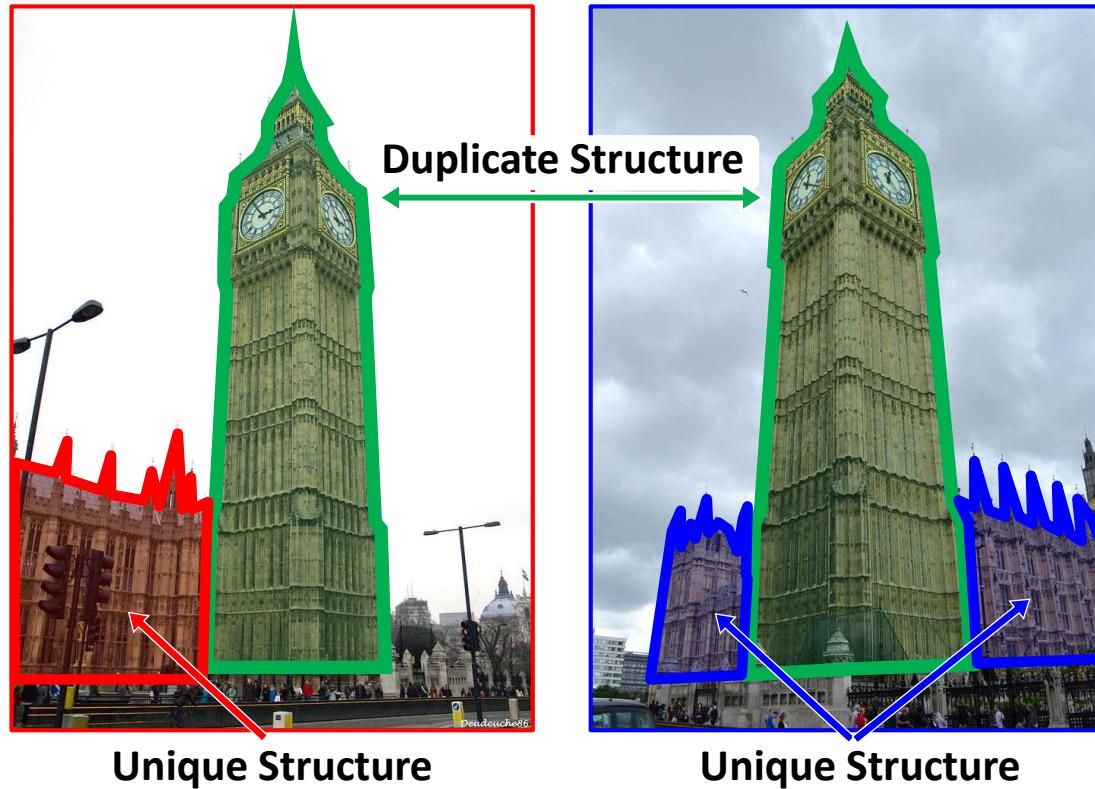
111

Image Registration



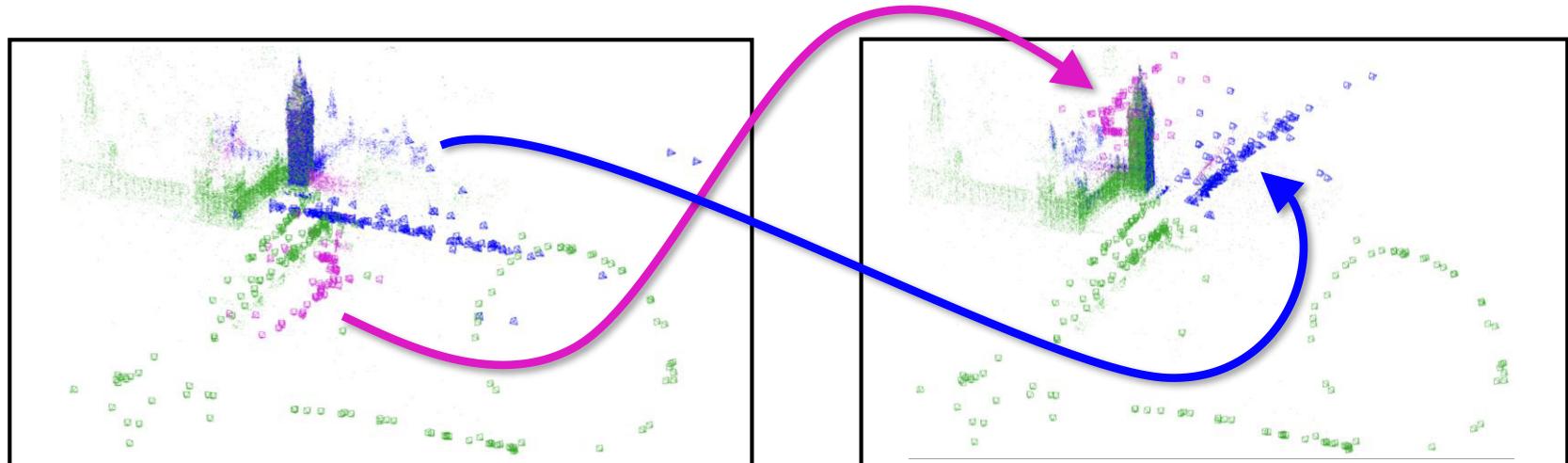
Duplicate Structure Disambiguation

- Heinly, Dunn, Frahm, *ECCV 2014*



Duplicate Structure Disambiguation

- Heinly, Dunn, Frahm, *ECCV 2014*
- Automatic model splitting and rearranging



github.com/jheinly/sfm_duplicate_structure_correction



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

114

Connected Components

- Discovery strategies
 - Brute force
 - Image retrieval
 - Clustering
 - Streaming



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

115

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

116

Reconstruction of Connected Components



ETH zürich



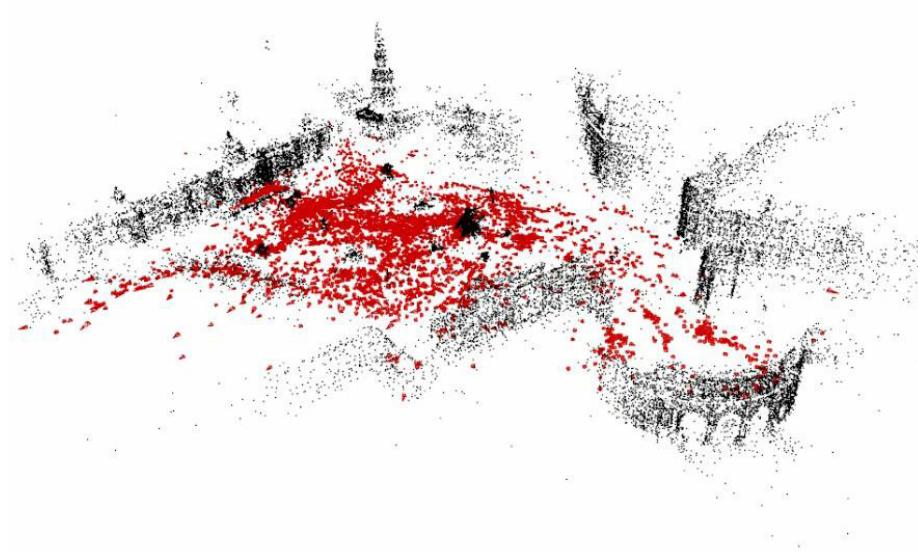
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

117

Reconstruction of Components

- Large-scale structure from motion



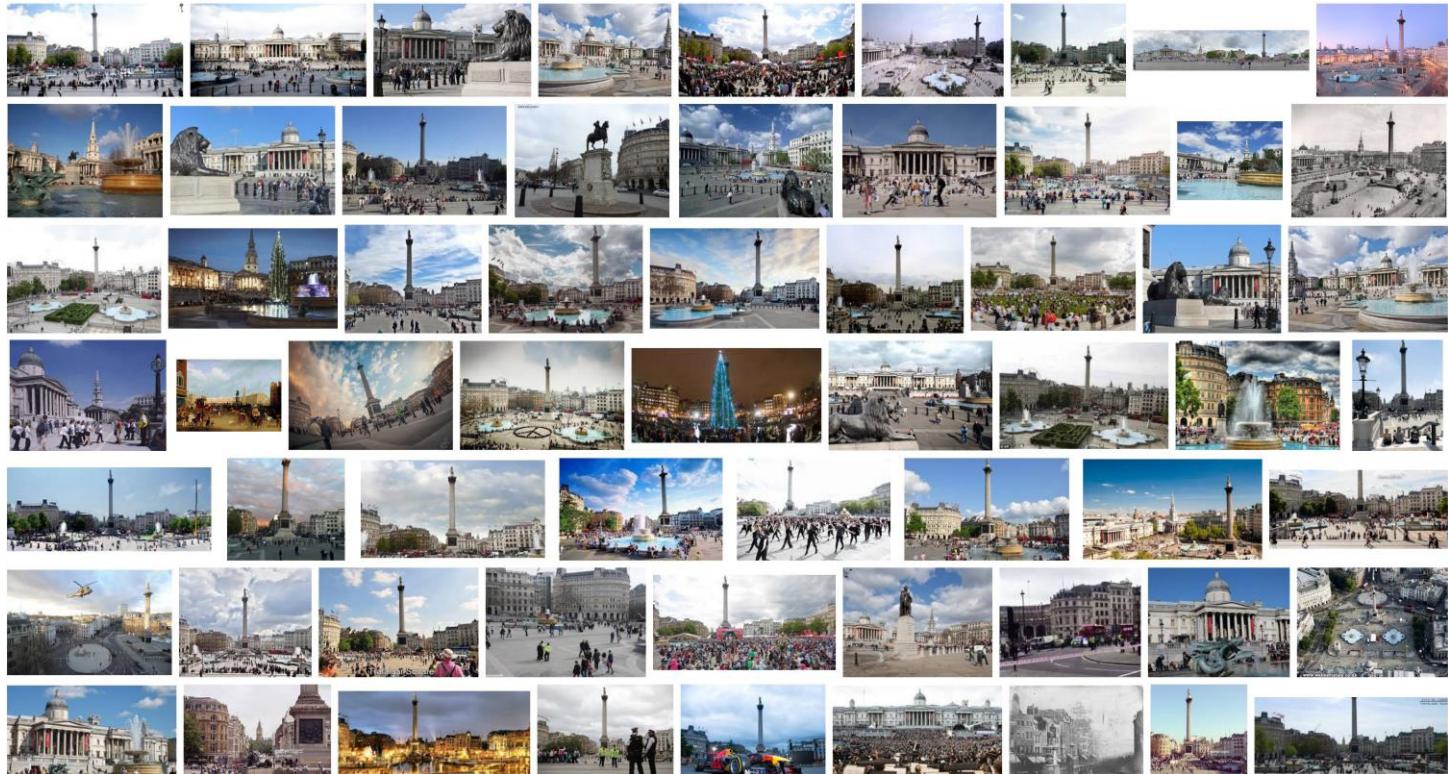
ETH zürich



Microsoft URCV

Reconstruction Strategies

- Brute force



ETH zürich

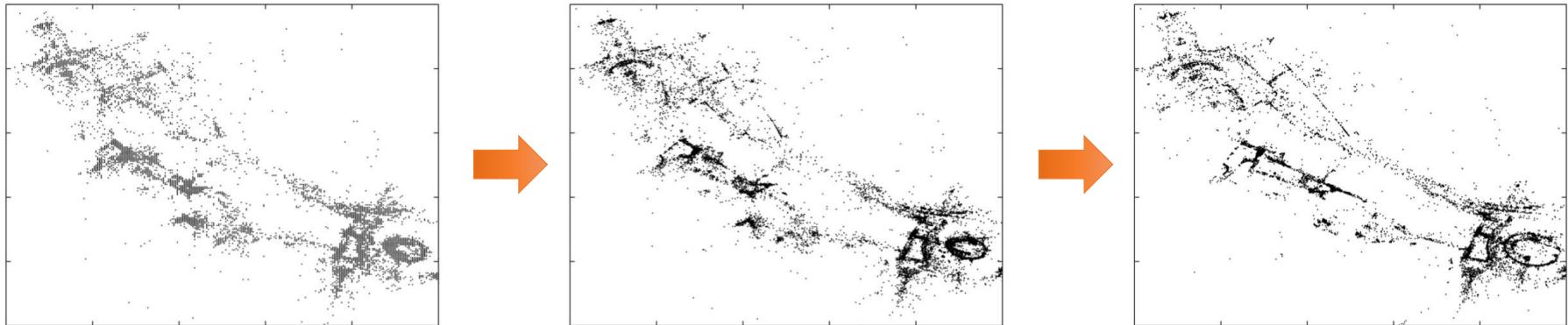


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

Reconstruction Strategies

- Global solvers
 - Discrete-Continuous Optimization for Large-Scale SfM
 - Crandall, Owens, Snavely, Huttenlocher, *CVPR 2011*



ETH zürich



Microsoft

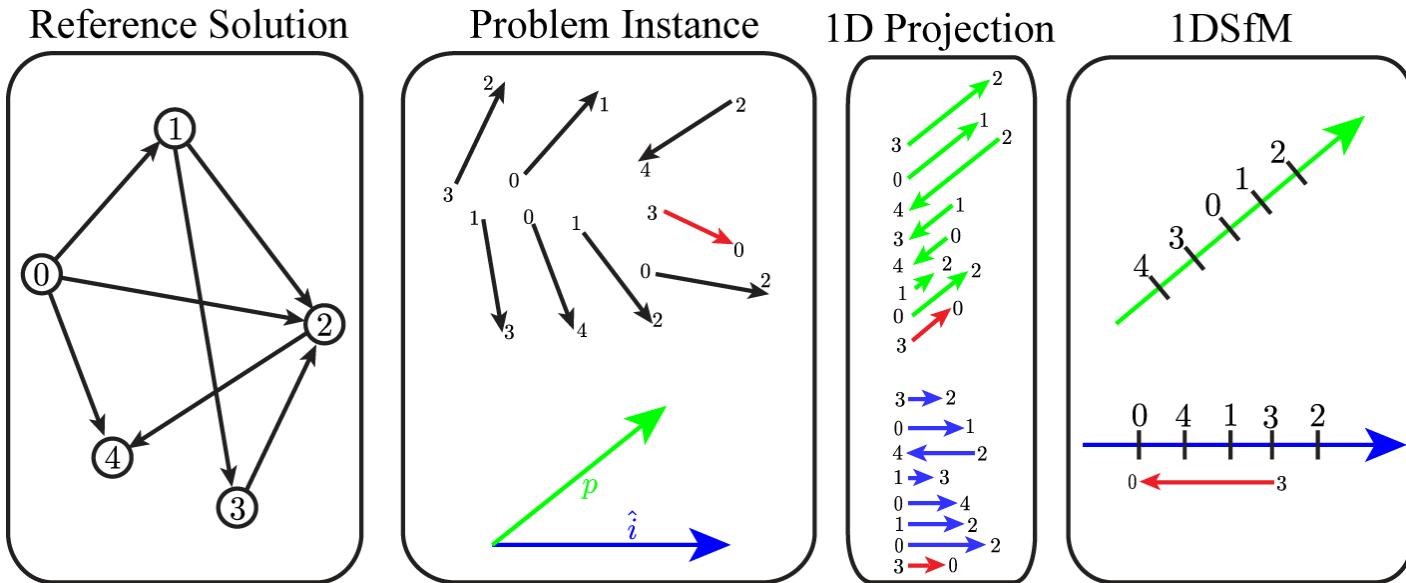
URCV

Large-scale 3D Modeling from Crowdsourced Data

120

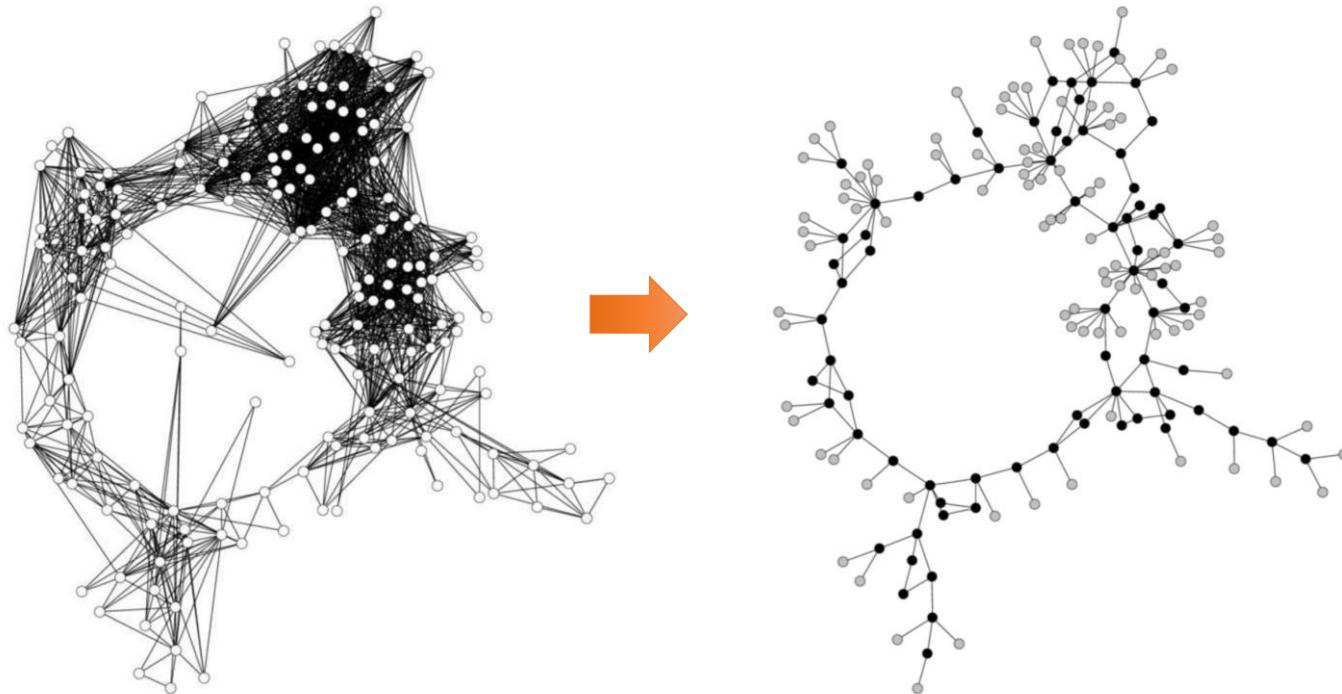
Reconstruction Strategies

- Global solvers
 - 1DSfM – Global translation solver
 - Wilson, Snavely, *ECCV 2014*



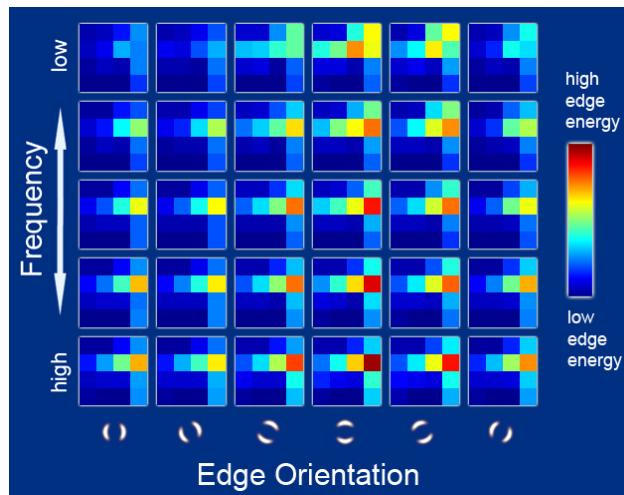
Reconstruction Strategies

- Skeletal graphs
 - Snavely, Seitz, Szeliski, *CVPR 2008*



Reconstruction Strategies

- Iconic images
 - GIST-based clustering
 - Frahm et al, *ECCV 2010*



ETH zürich



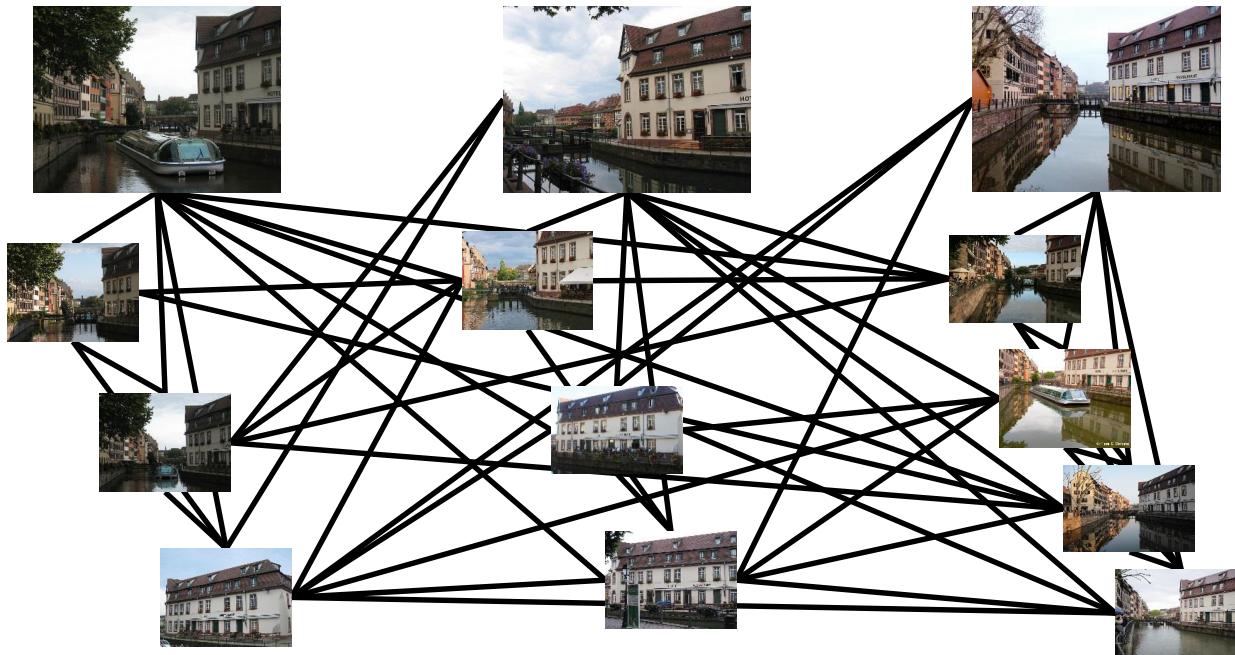
Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

123

Reconstruction Strategies

- Iconic images
 - Streaming-based clusters
 - Heinly et al, *CVPR 2015*



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

124

Reconstruction Strategies

- Iconic images
 - Streaming-based clusters
 - Heinly et al, *CVPR 2015*



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

125

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

126

Design of a Real Pipeline



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

127

Overview

- Reconstructing the World in Six Days, *CVPR 2015*
- Streaming connected component discovery
- 1 PC
- Multi-core, multi-GPU implementation
- Open-source

github.com/jheinly/streaming_connected_component_discovery



ETH zürich

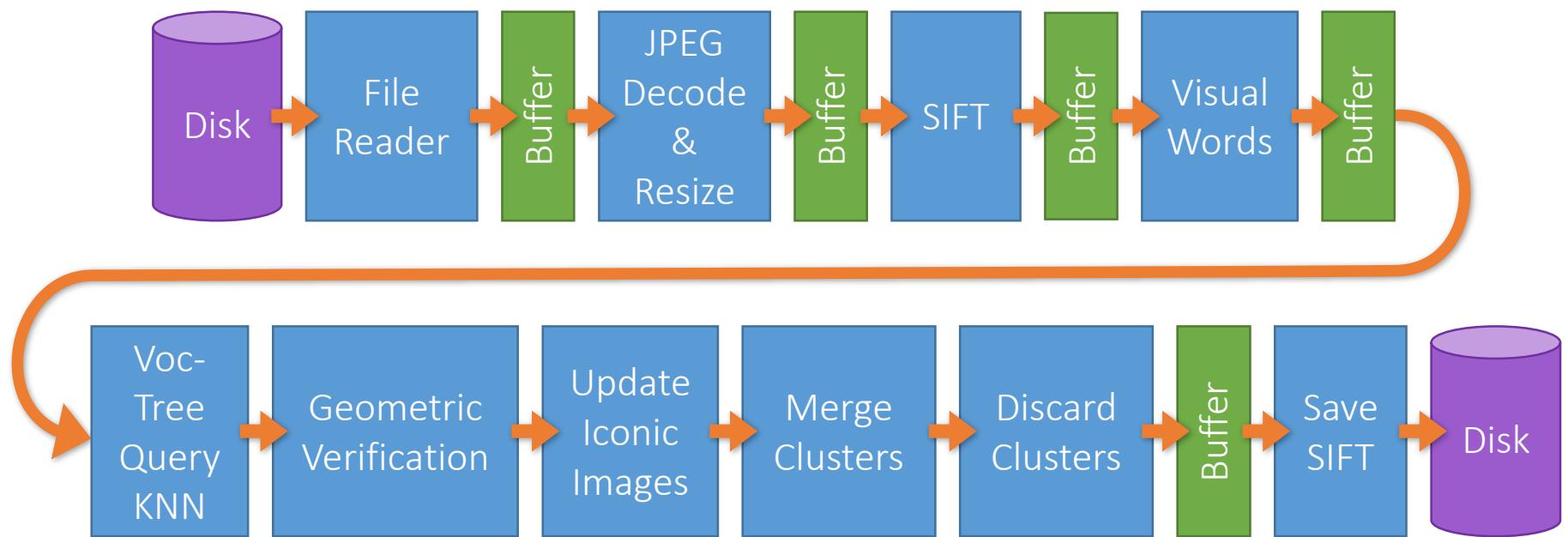


Microsoft **URCV**

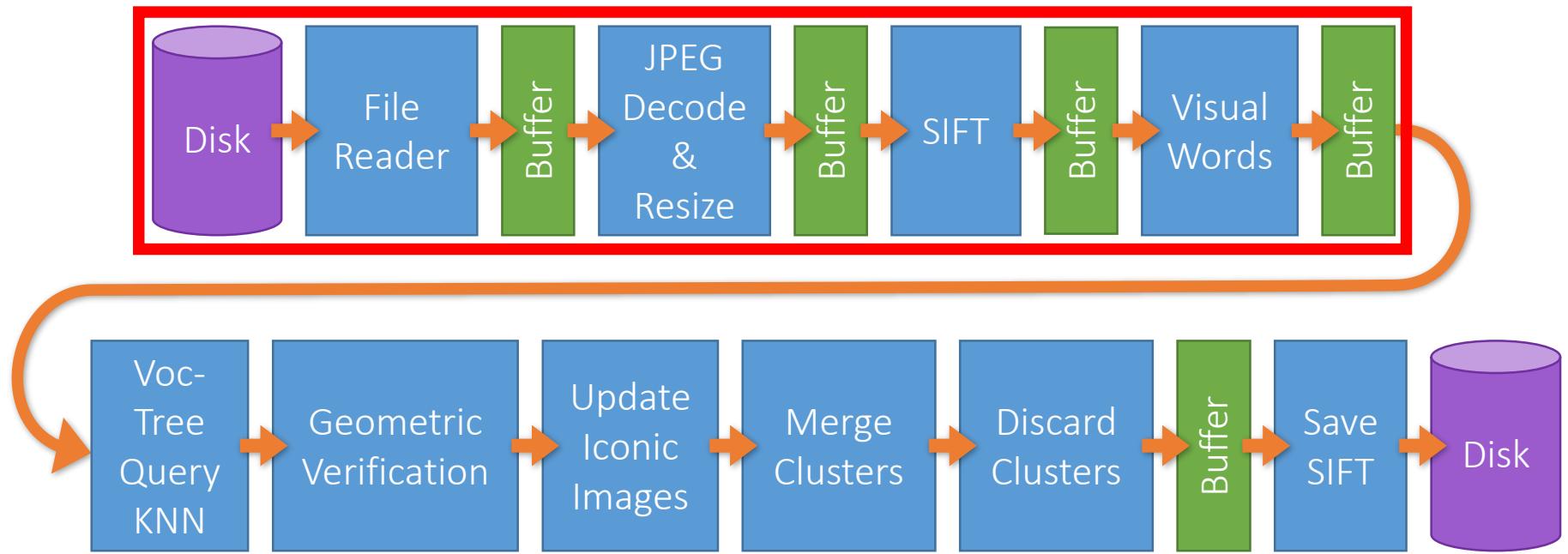
Large-scale 3D Modeling from Crowdsourced Data

128

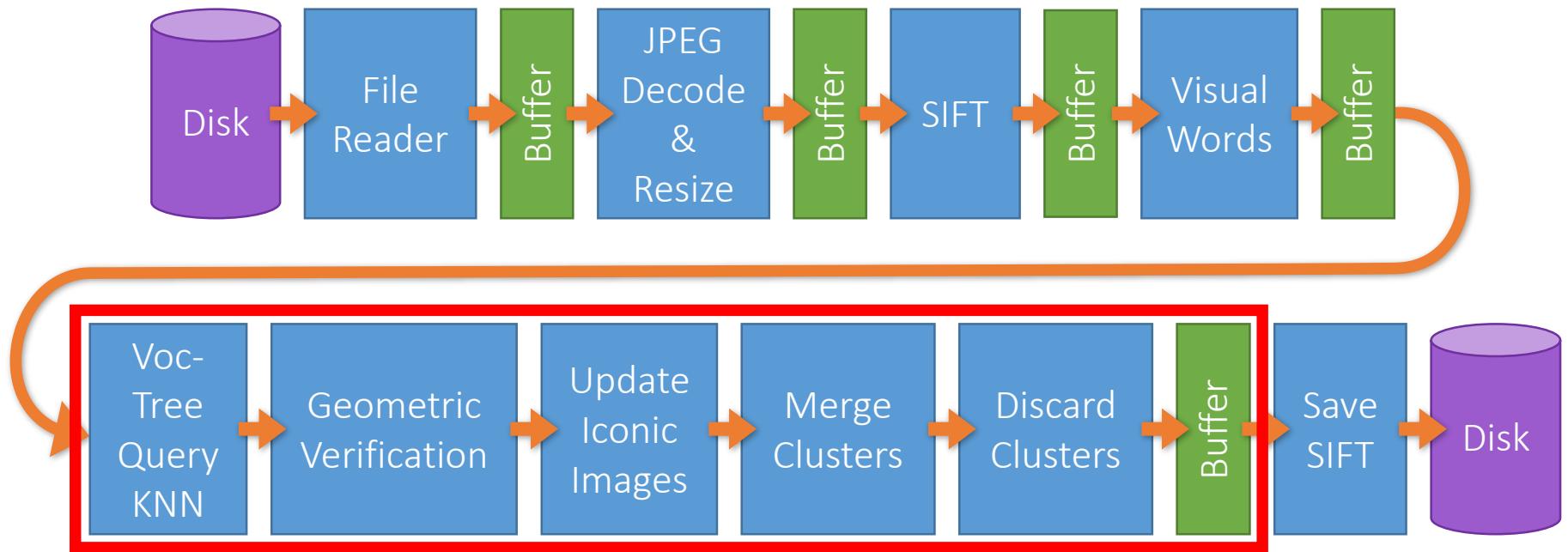
Overview



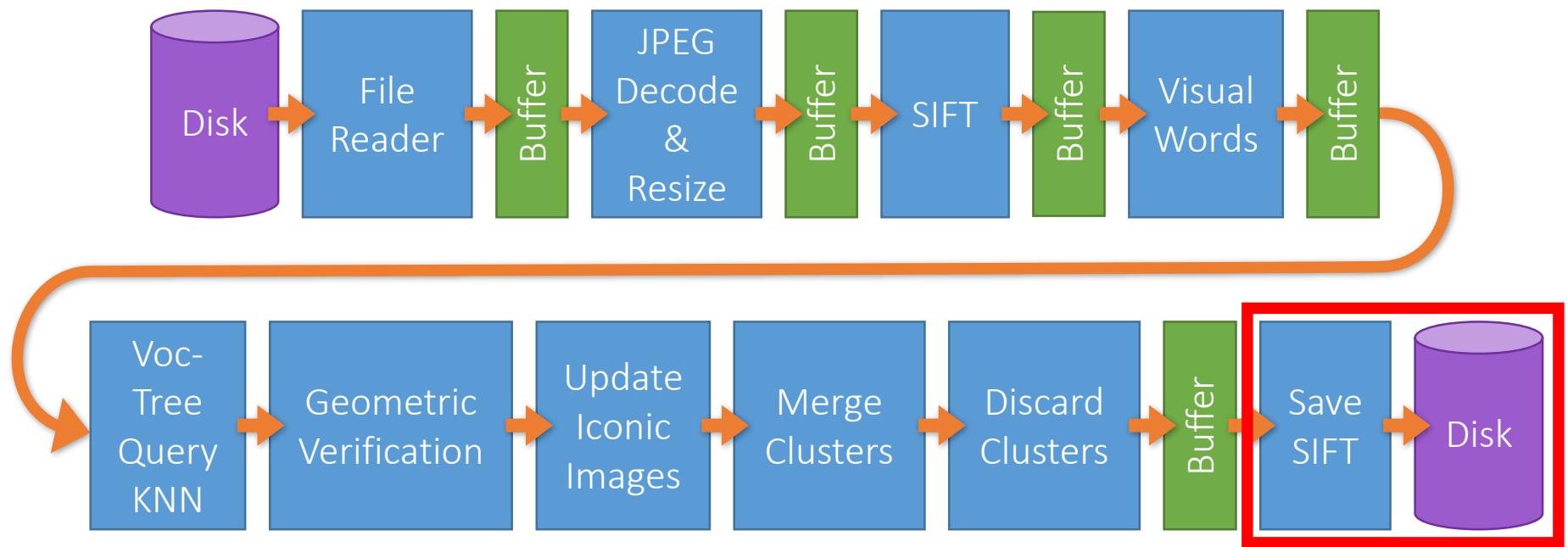
Prepare Images



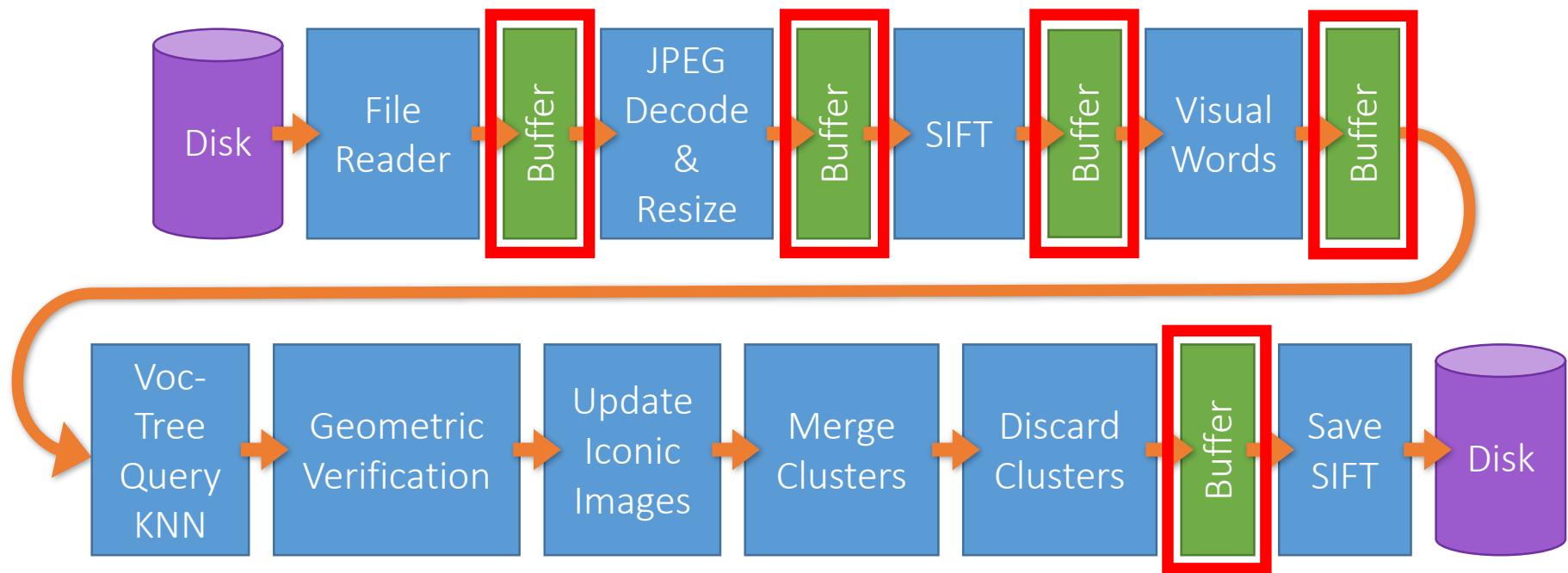
Update Clusters and Components



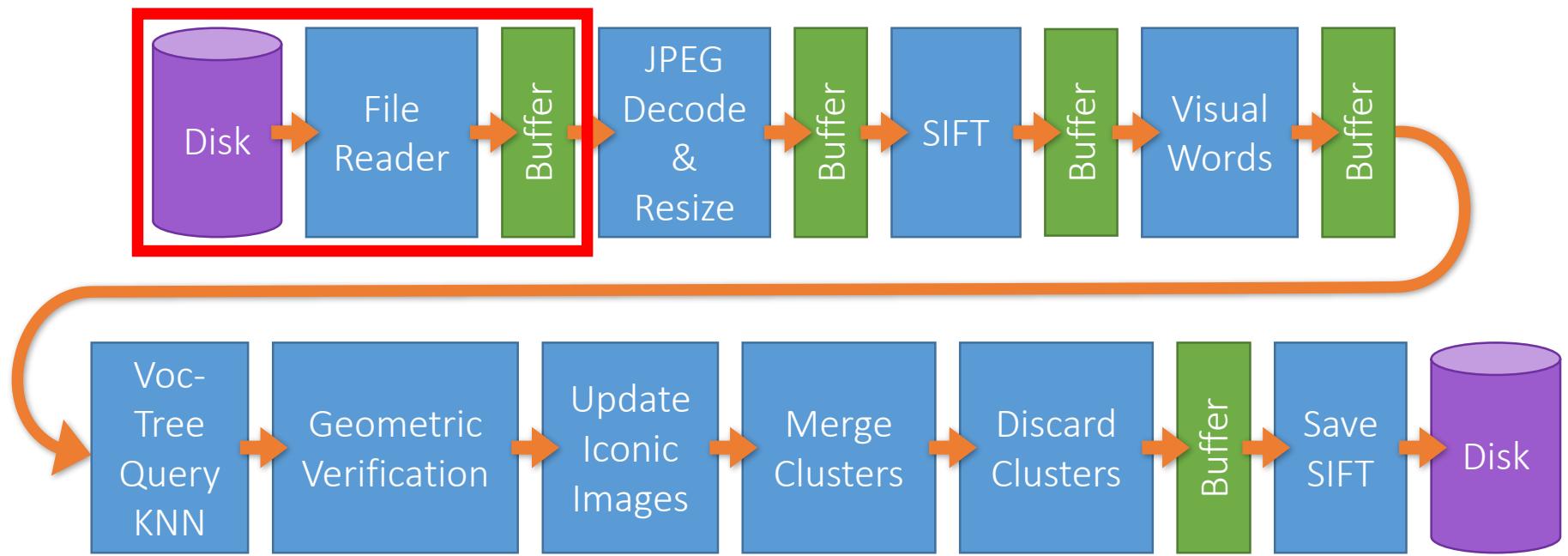
Save Results



Batch Processing and Buffering

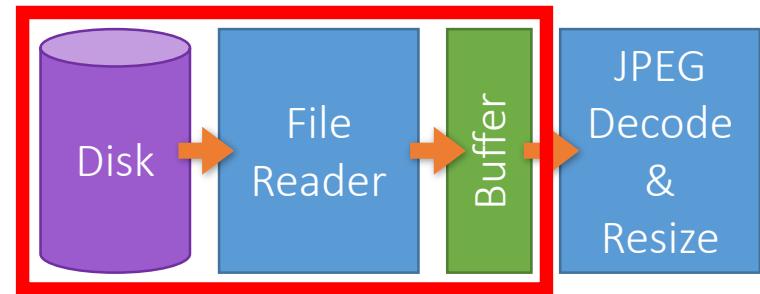


File Reader

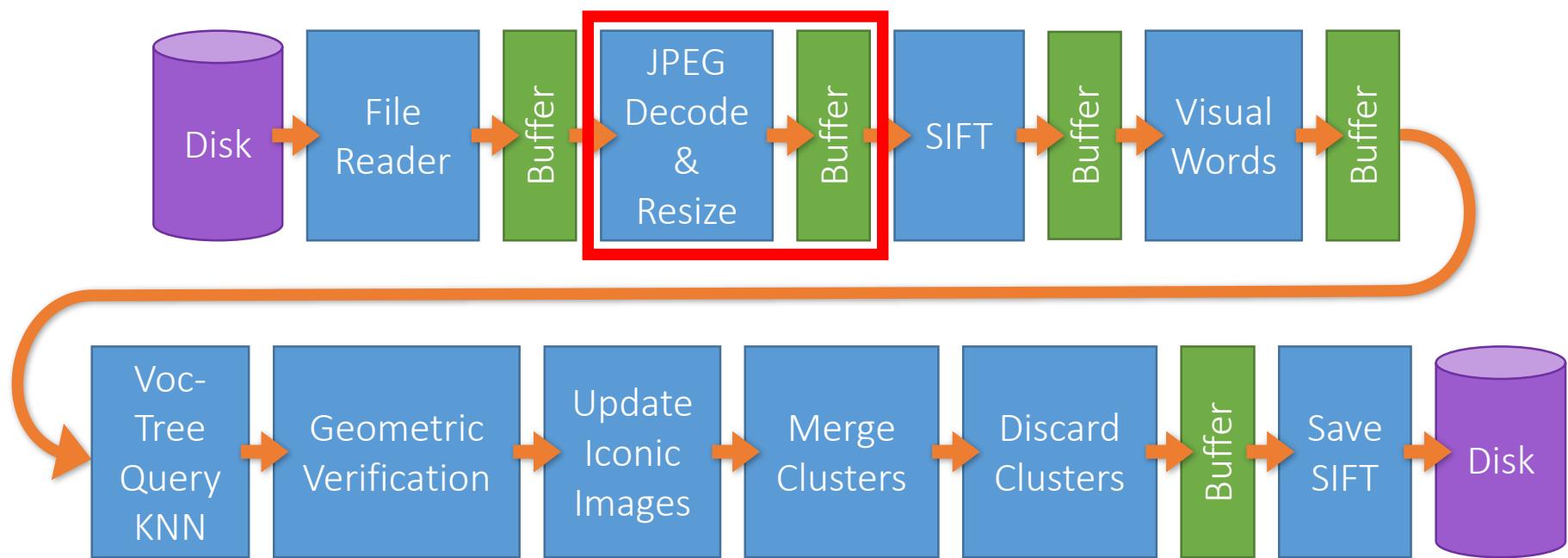


File Reader

- Decouple JPEG decode from file I/O
- Multiple hard drives
- One thread per drive
- Enforce a balanced load
- 1024x768 images
- 4 hard drives
- 120 Hz



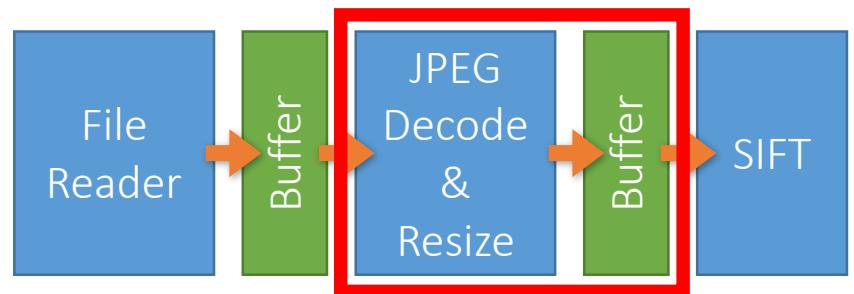
JPEG Decode



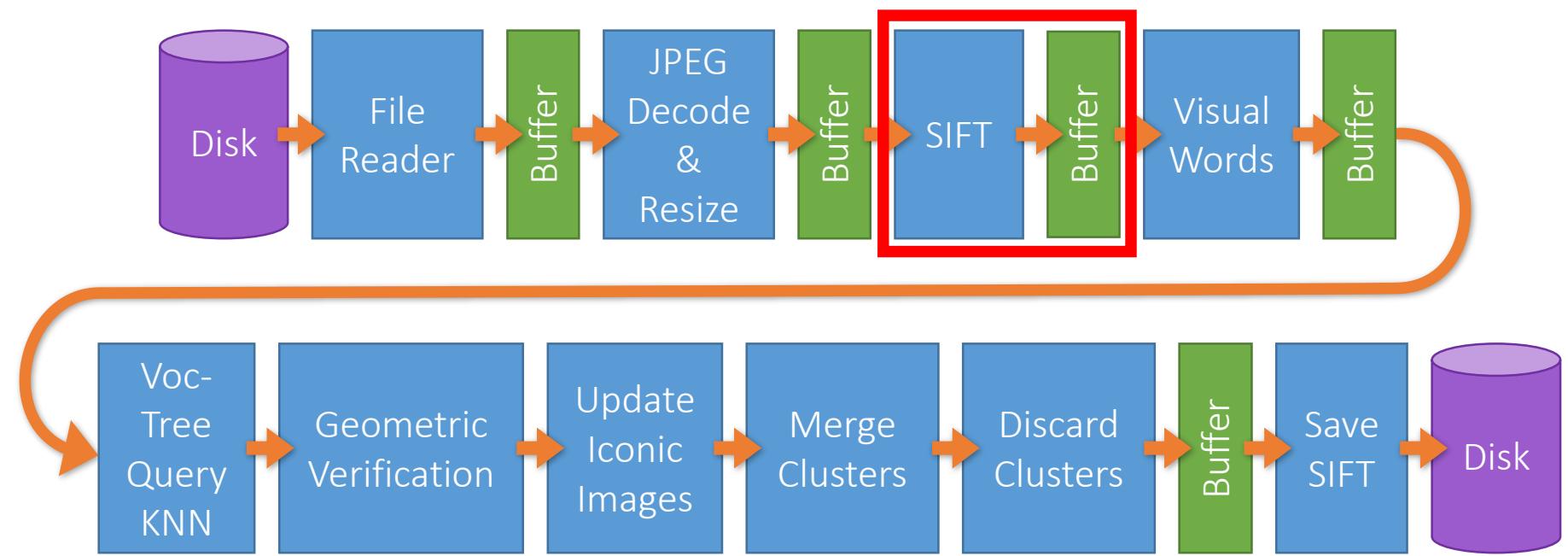
JPEG Decode

- libjpeg-turbo
- Resize by power of 2 during decode
- OpenCV resize to final resolution

- 4 threads
- 177 Hz



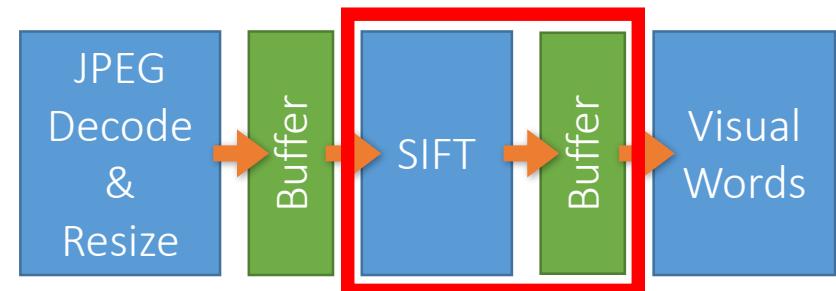
SIFT



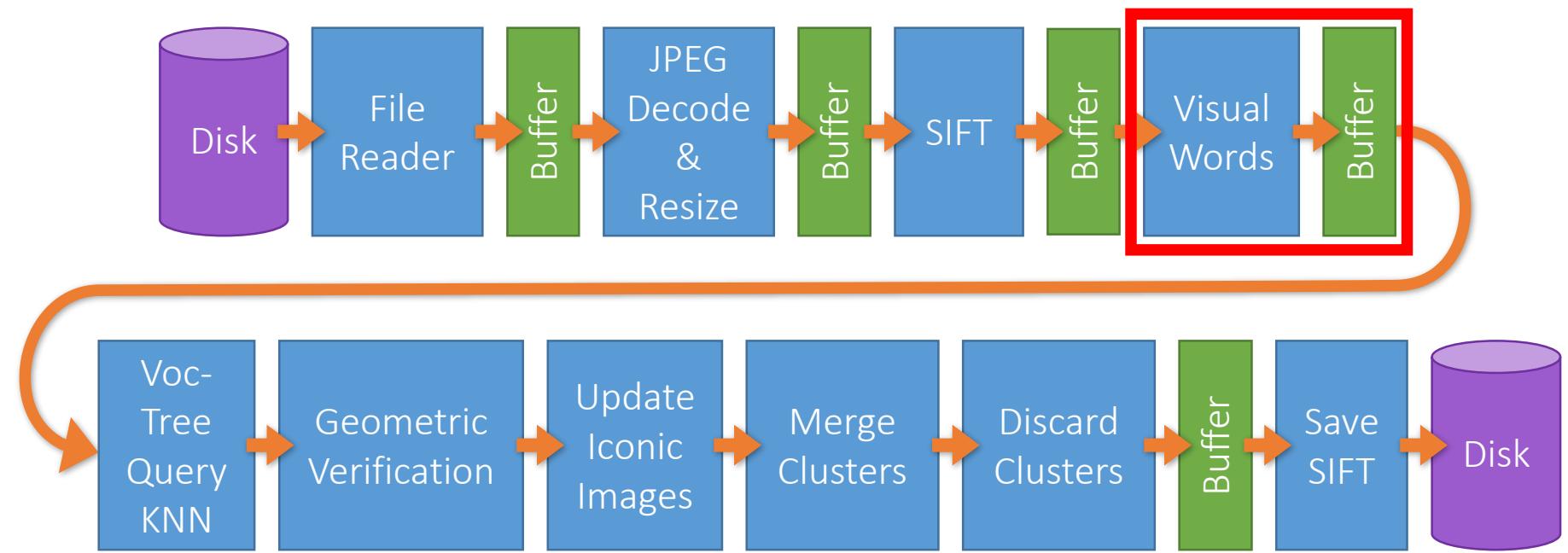
SIFT

- SiftGPU by Changchang Wu
- CUDA-enabled, multi-process support

- 8 threads, 8 GPUs
- GTX 295
- 138 Hz



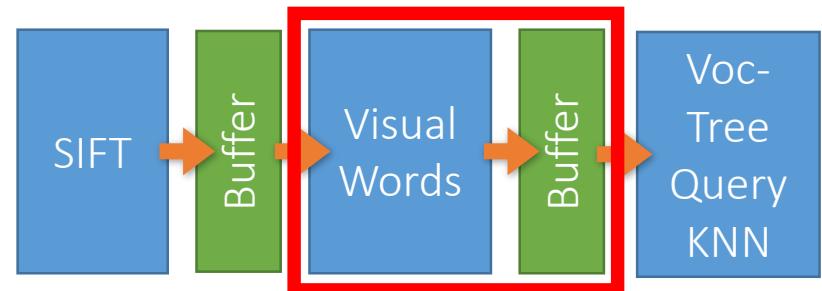
Visual Words



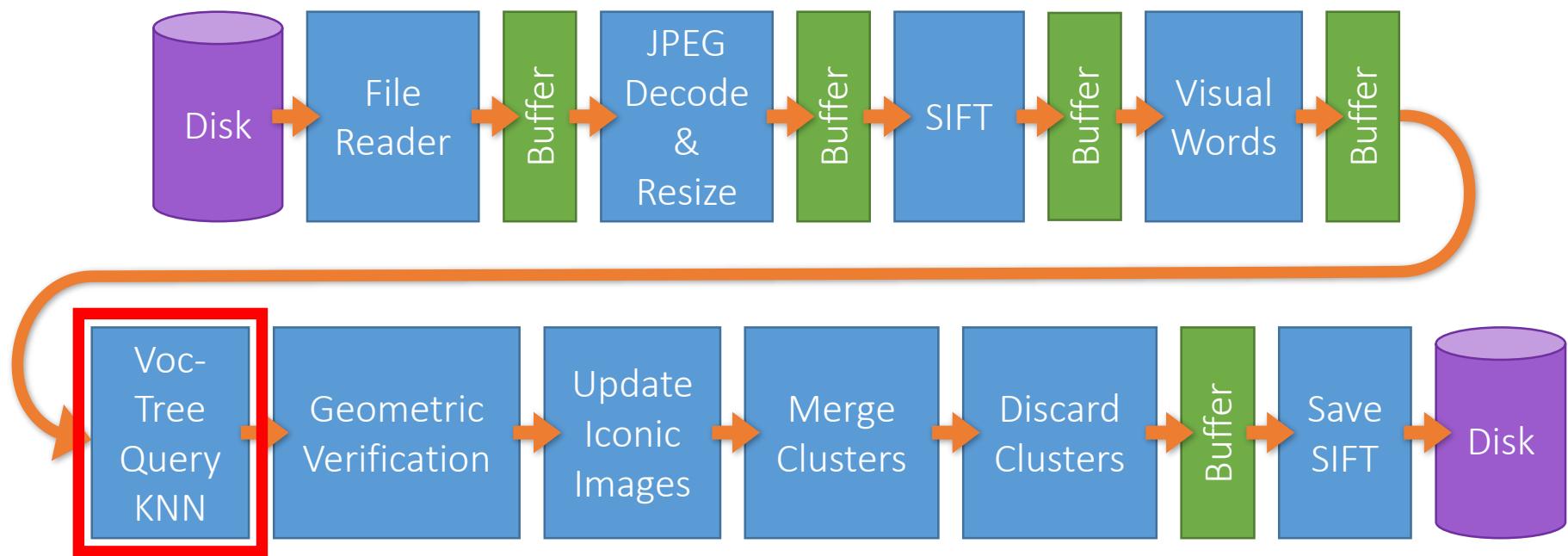
Visual Words

- Optimized VocabTree2 by Noah Snavely
 - SSE, multithreading, and faster data structures
- 1 million visual word vocabulary

- 4 threads
- 434 Hz

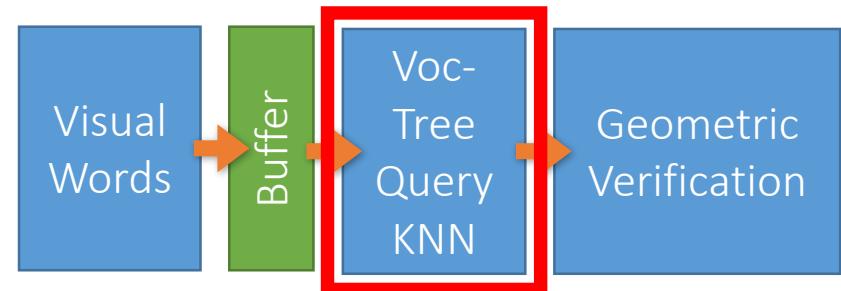


Vocabulary Tree Query KNN

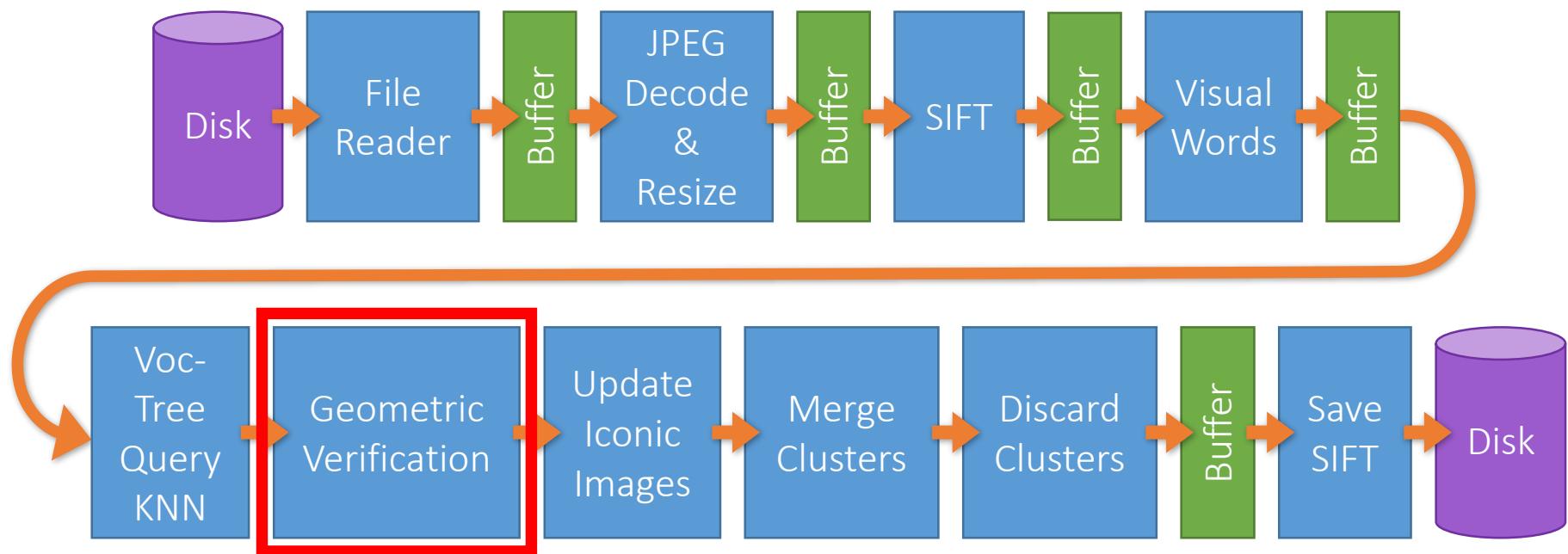


Vocabulary Tree Query KNN

- Optimized VocabTree2 by Noah Snavely
 - SSE, multithreading, and faster data structures
- 1 million visual word vocabulary
- 25 nearest neighbors
- 16 threads
- 4,475 Hz



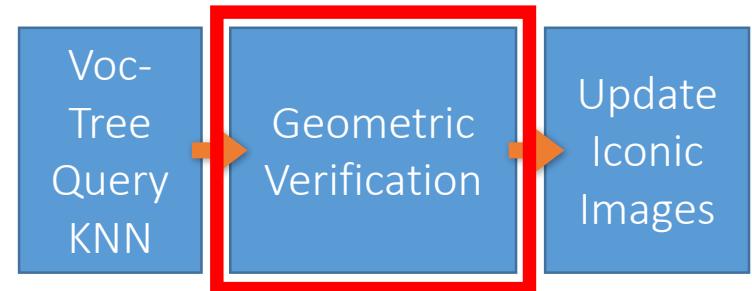
Geometric Verification



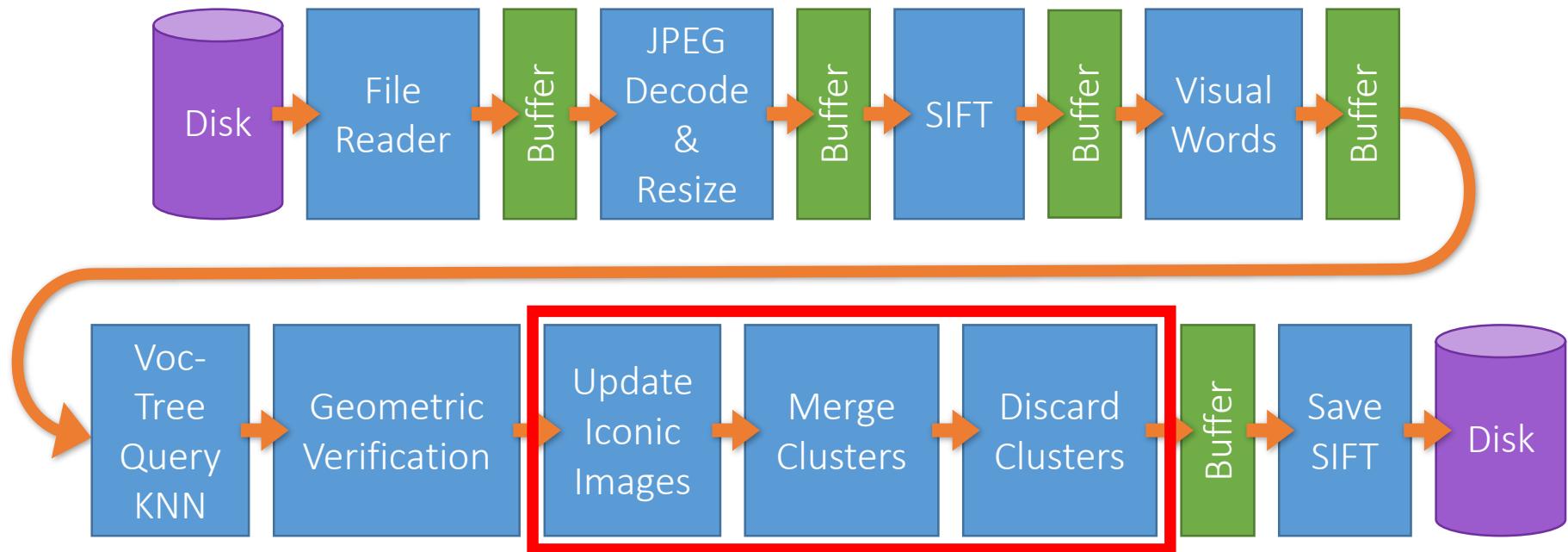
Geometric Verification

- ARRSAC, Raguram, Frahm, Pollefeys, *ECCV 2008*
- GPU-enabled SIFT matching
- Essential matrix estimation
 - Focal length from EXIF
- 2 verification attempts per image
- Save verification results in SQLite database

- 16 threads, 8 GPUs
- 261 Hz

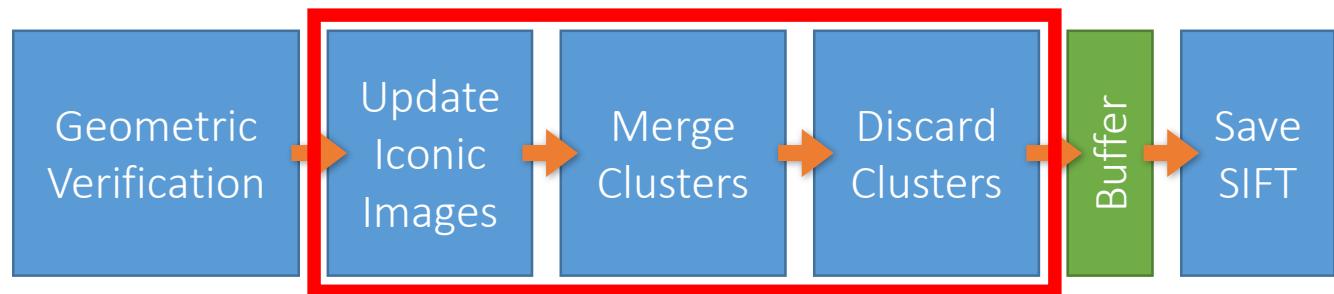


Update Clusters and Components

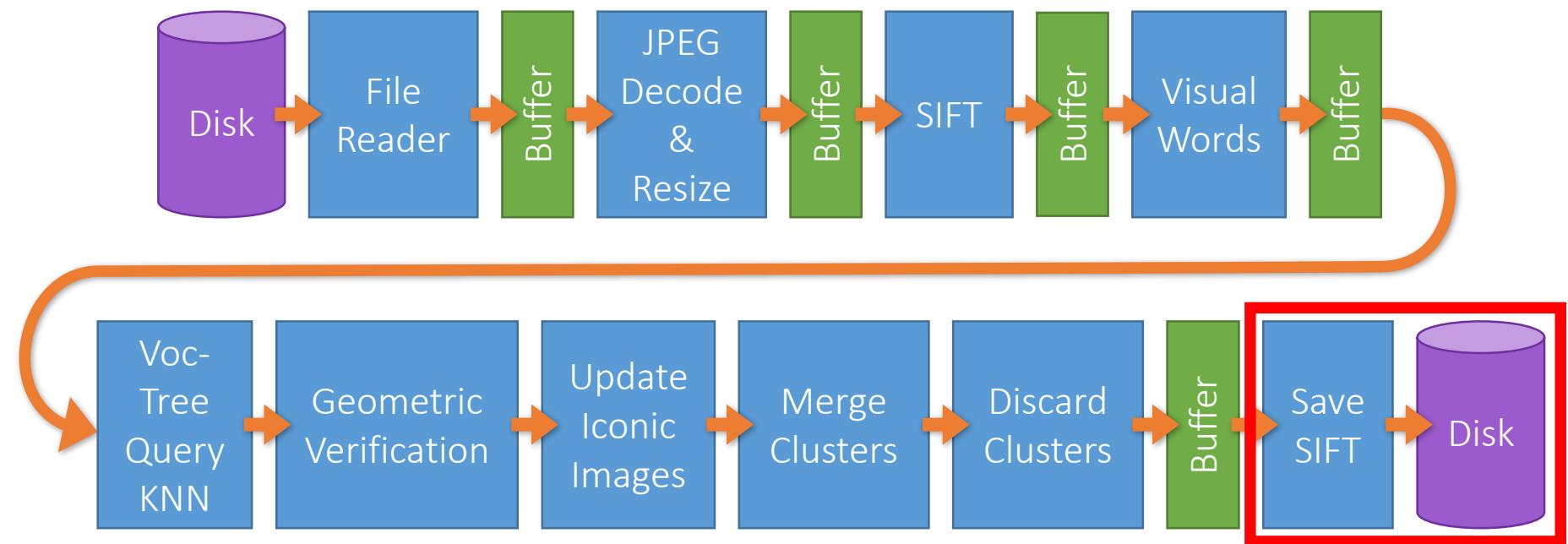


Update Clusters and Components

- Update vocabulary tree inverted index
 - Optimized VocabTree2 by Noah Snavely
- 16 threads
- 14,485 Hz

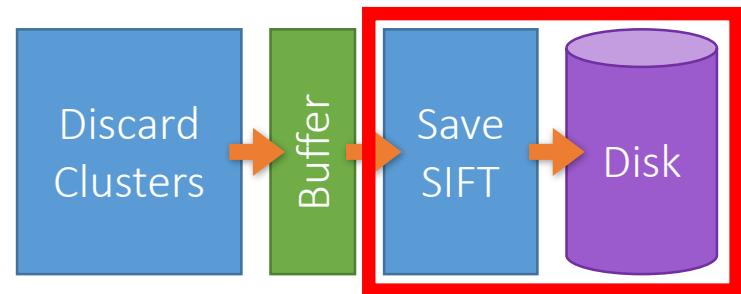


Save SIFT

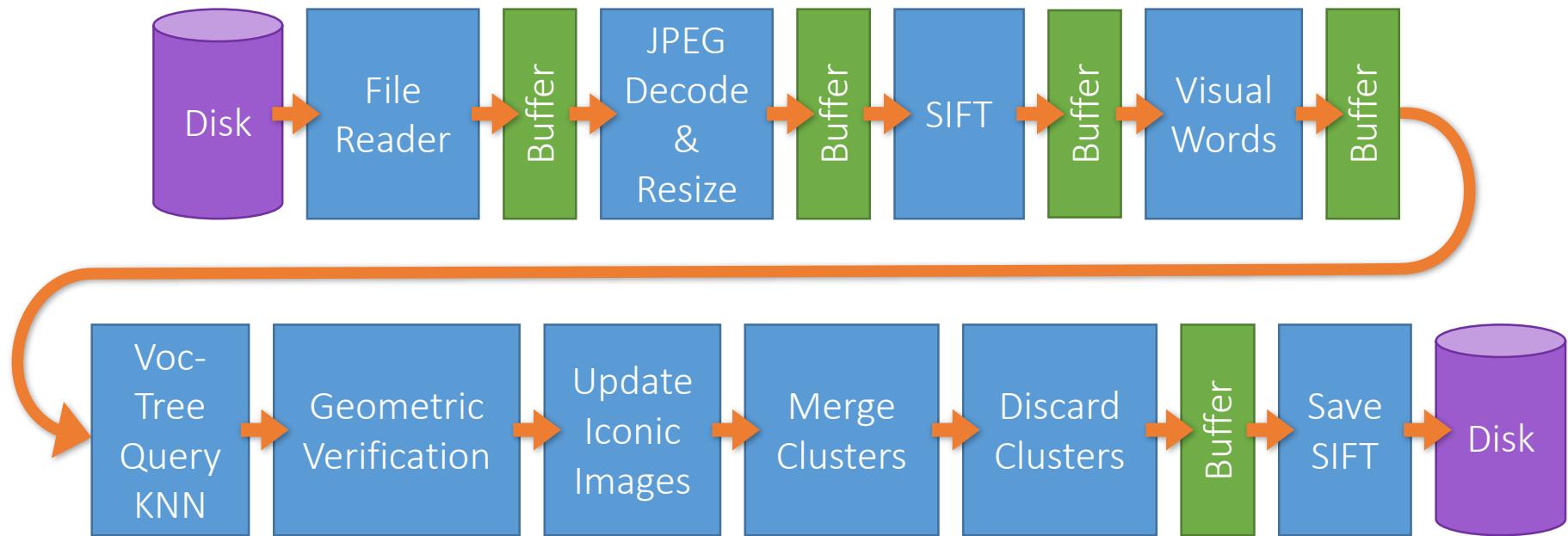


Save SIFT

- Save SIFT features to SSD
 - 2D keypoints used in SfM
- 3 threads
- 186 Hz

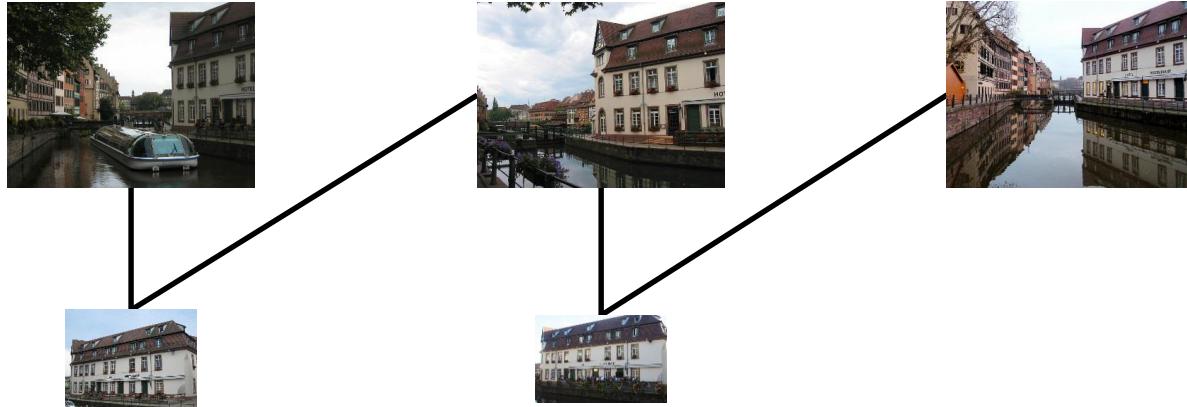


Overview



Reconstruction

- Reconstruction of iconic and connecting images
- Register remaining images from clusters
- COLMAP by Johannes Schönberger



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

151

Notre Dame Cathedral, Paris, France



126K Cameras



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

152

Berlin Cathedral, Berlin, Germany



26K Cameras



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

153

Results

- Complexity

	Our Method	Previous Works
Computation	$O(N)$ 2 registration attempts per image	Ranges from $O(N)$ to $O(N^2)$ Multiple registration attempts per image
Memory	$O(\log(N))$ Close to $O(1)$ in practice	$O(N)$



Results

Berlin, Germany (2.7M images)

	Frahm et al, 2010	Ours
Registered	4.6%	26%
Reconstructed	1.1%	8.7%
Data Association Time*	13.3 Hours	7.9 Hours

*Identical Hardware Configuration



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

155

Results

Berlin, Germany (2.7M images)

Data Association Strategy	Match Attempts	Registered
Frahm et al, 2010 GIST	1	<div style="width: 4.6%;">4.6%</div>
Streaming GIST	2	<div style="width: 8.9%;">8.9%</div>
Streaming Bag-of-Words	1	<div style="width: 25%;">25%</div>
Streaming Bag-of-Words	2	<div style="width: 26%;">26%</div>



Results – Effect of Parameters

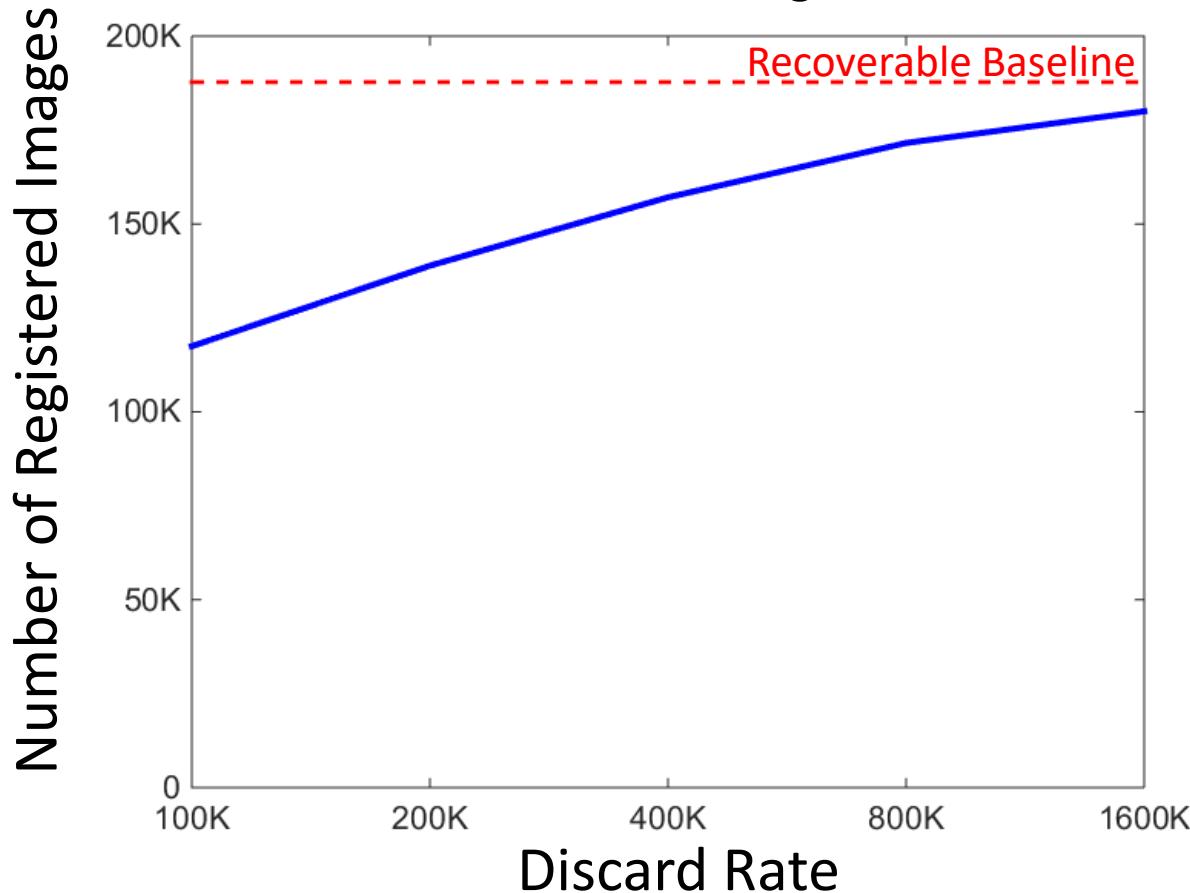
- 2.2M geo-tagged subset of Yahoo 100M dataset
- Baseline
 - Ground-truth connectivity



Results

Effect of Discard Rate

Match to $k = 2$ Neighbors



Yahoo® Flickr® 100M Dataset

- 14 TB
- 640x480 resolution



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

159

Results

- 100 million images
- 1.5 million images registered
- 6 days
 - 4.4 days streaming
 - 0.9 days SfM
- 1 PC



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

160

Results



Sacre Coeur, Paris, France



ETH zürich

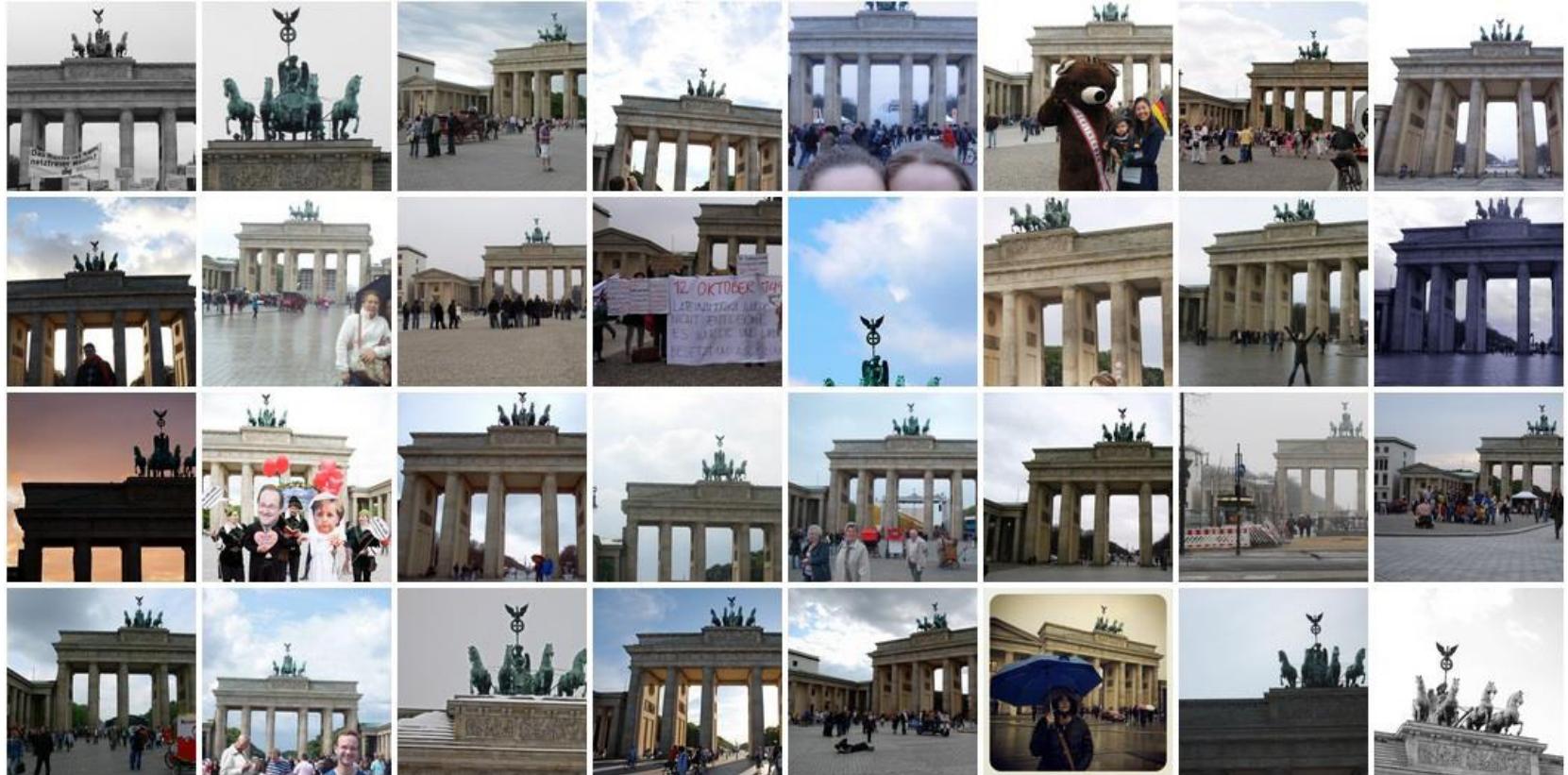


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

161

Results



Brandenburg Gate, Berlin, Germany



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

162

Results



Buckingham Palace, London, England



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

163

Results



Golden Gate Bridge, San Francisco, California



ETH zürich



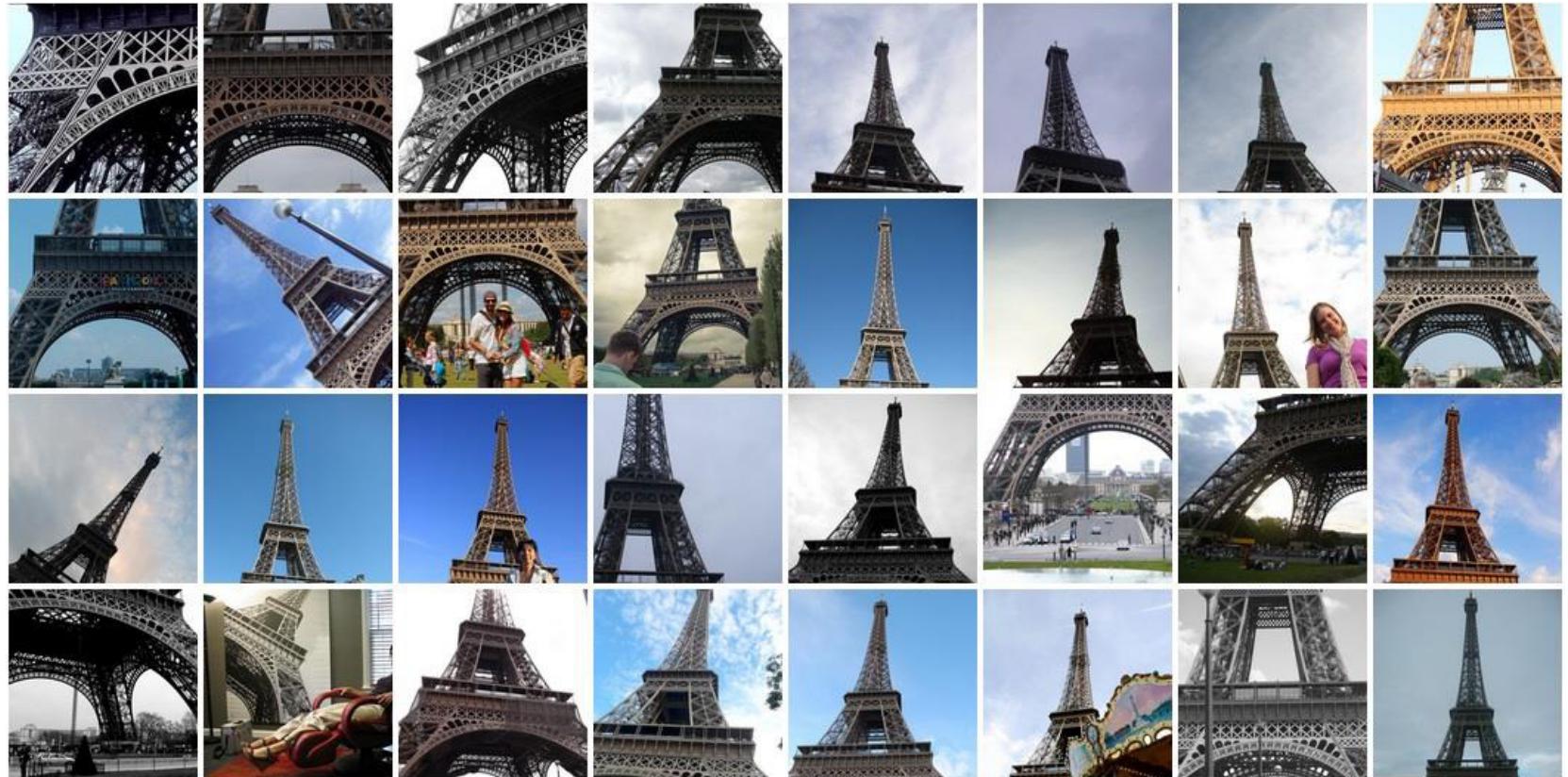
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

164

Results



Eiffel Tower, Paris, France



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

165

Results



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

166

Results



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

167

Results



ETH zürich

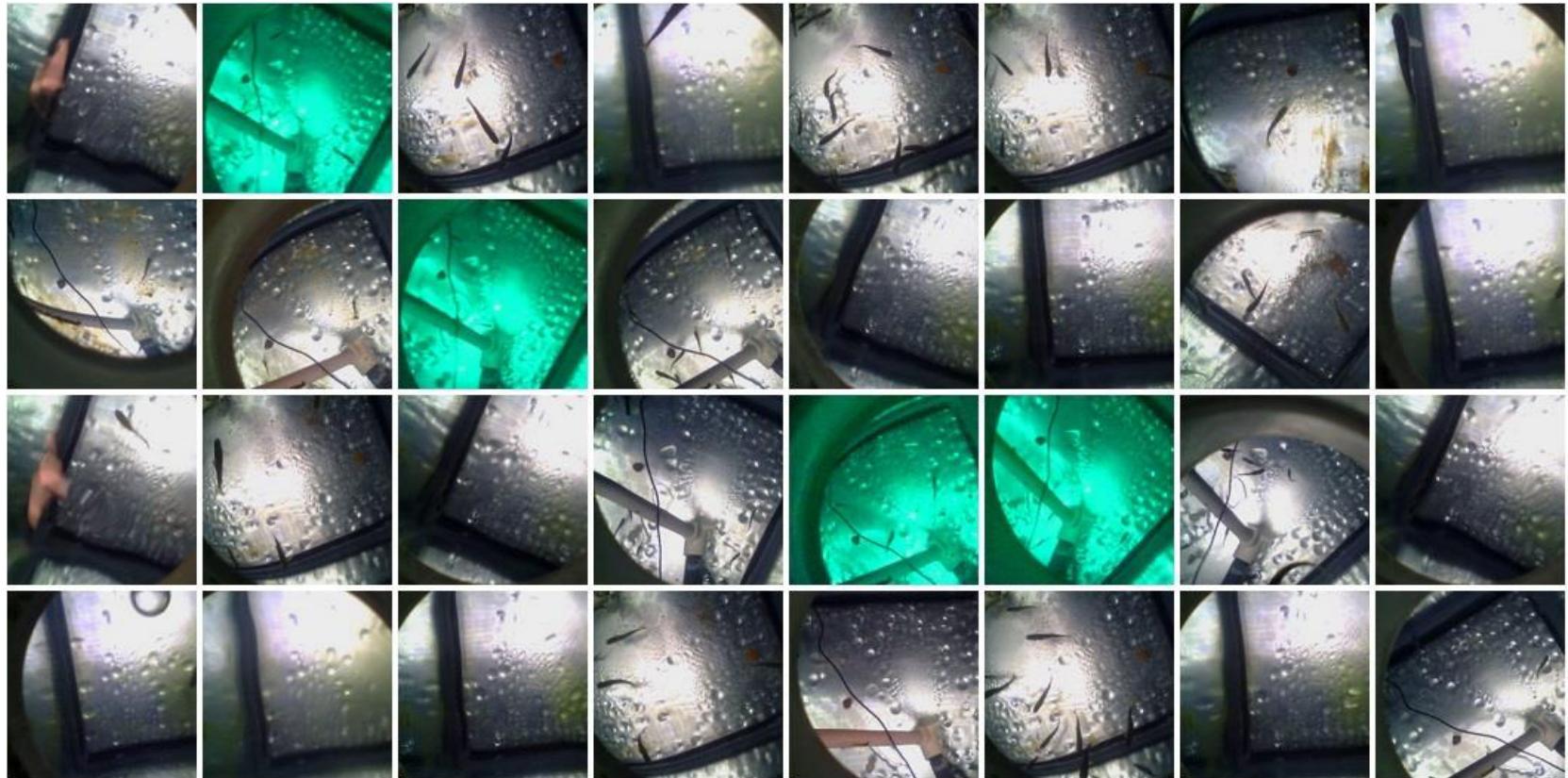


Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

168

Results



ETH zürich



Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

169

Results



ETH zürich



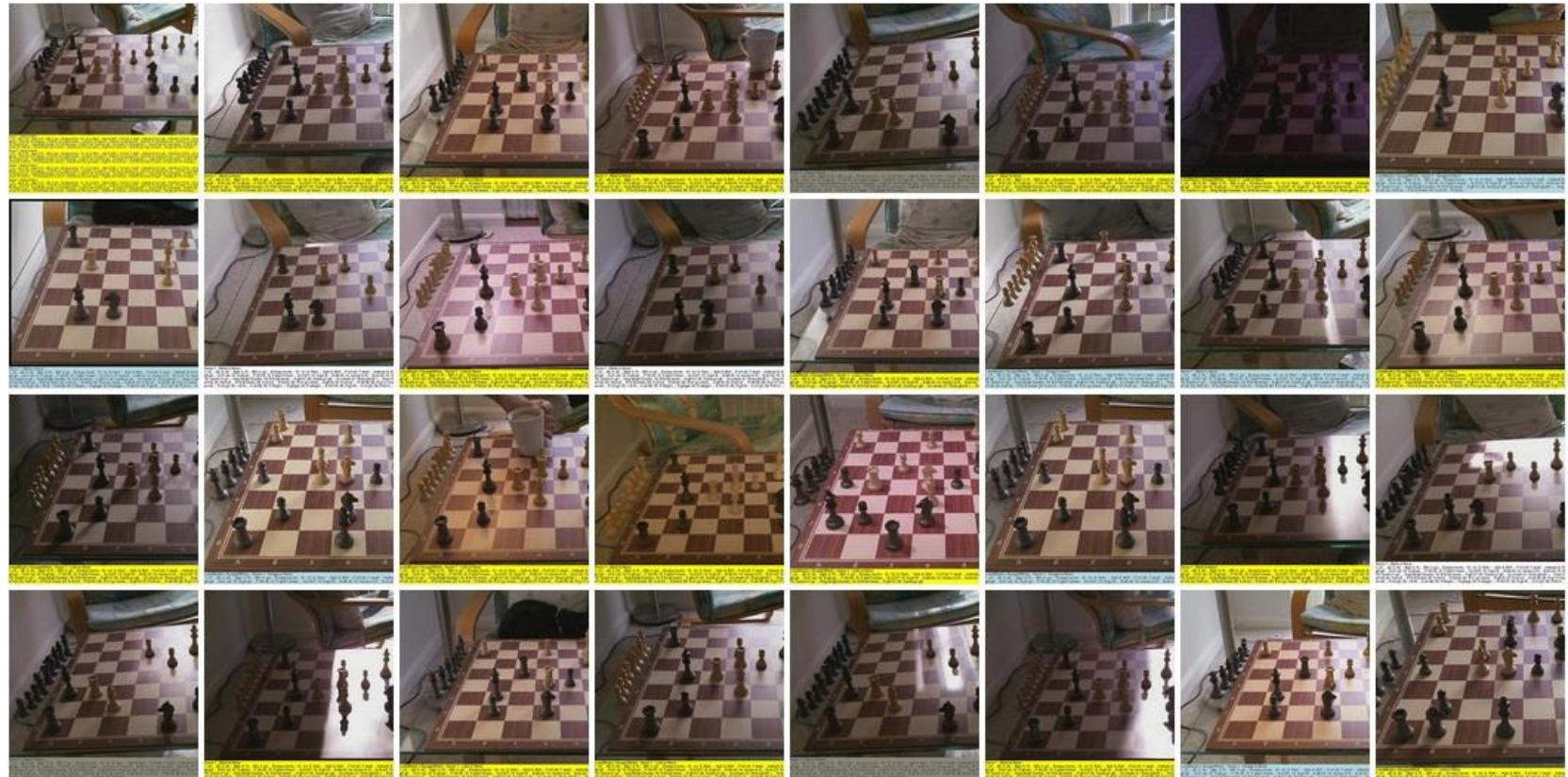
Microsoft

URCV

Large-scale 3D Modeling from Crowdsourced Data

170

Results



ETH zürich



Microsoft URCV

Large-scale 3D Modeling from Crowdsourced Data

171

Outline

- Challenges and opportunities of crowd-sourced data
- Image retrieval and indexing
- Connected component discovery
- Reconstruction of connected components
- Design of a real pipeline
- Lessons learned



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

172

Lessons Learned

- 1-in-a-million bugs hurt
- Engineering matters
- Ask questions and dig into code
- Expect and handle data of all forms
- Create visualizations whenever possible



ETH zürich



Microsoft **URCV**

Large-scale 3D Modeling from Crowdsourced Data

173

Questions?



ETH zürich



Microsoft **URCV**