

# Geometry Beyond 3D

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Google Inc., Cornell University

Bay Area Vision Meeting, 2014

# Are we done with 3D modeling?

- Huge progress in the last 10 years



[Pollefeys et al. IJCV04]



[Snavely et al. SIGGRAPH06]

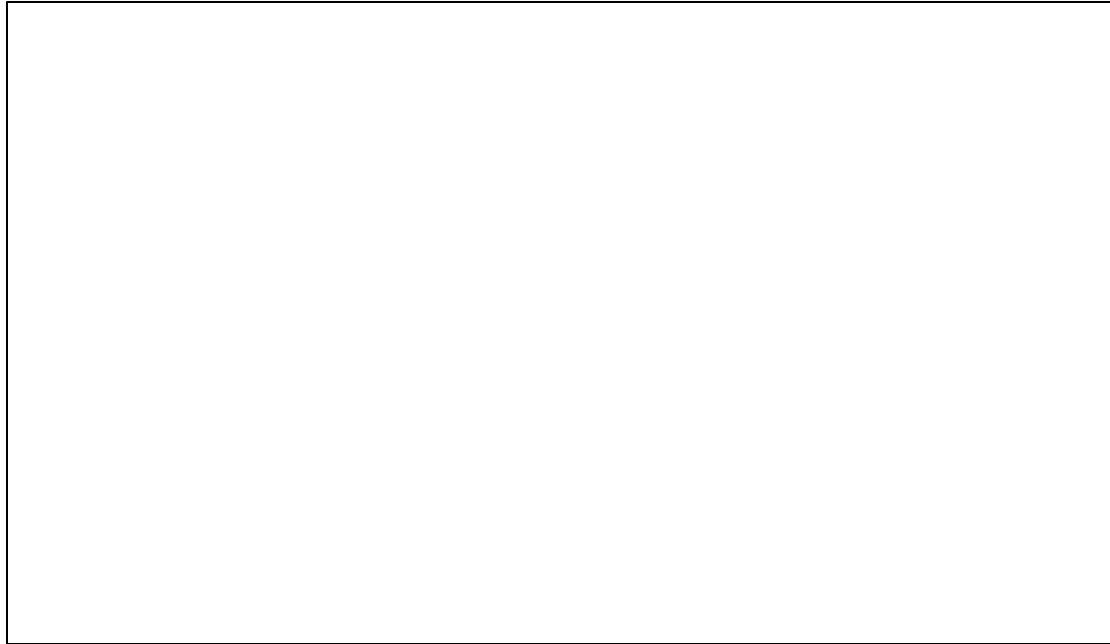


Aerial models

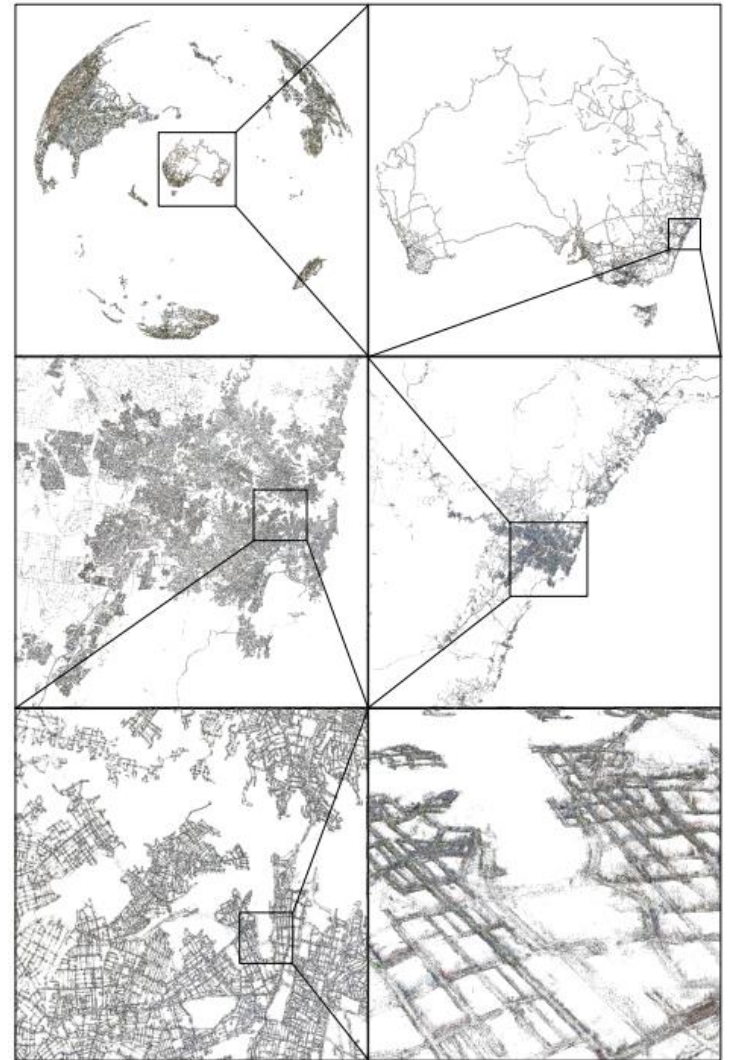


[Zhou & Koltun , SIGGRAPH14]

# Are we done with 3D modeling?



[Agarwal et al. ICCV 2009]



[Klingner et al., ICCV 2013]

# Are we done with 3D modeling?

- Not until we have a fully **realistic, editable, semantically meaningful** model of the entire world
- **Realistic** = correct geometry, materials, lighting; high-resolution; dynamic
- In other words, a model you can feed into your holodeck

# Times Square

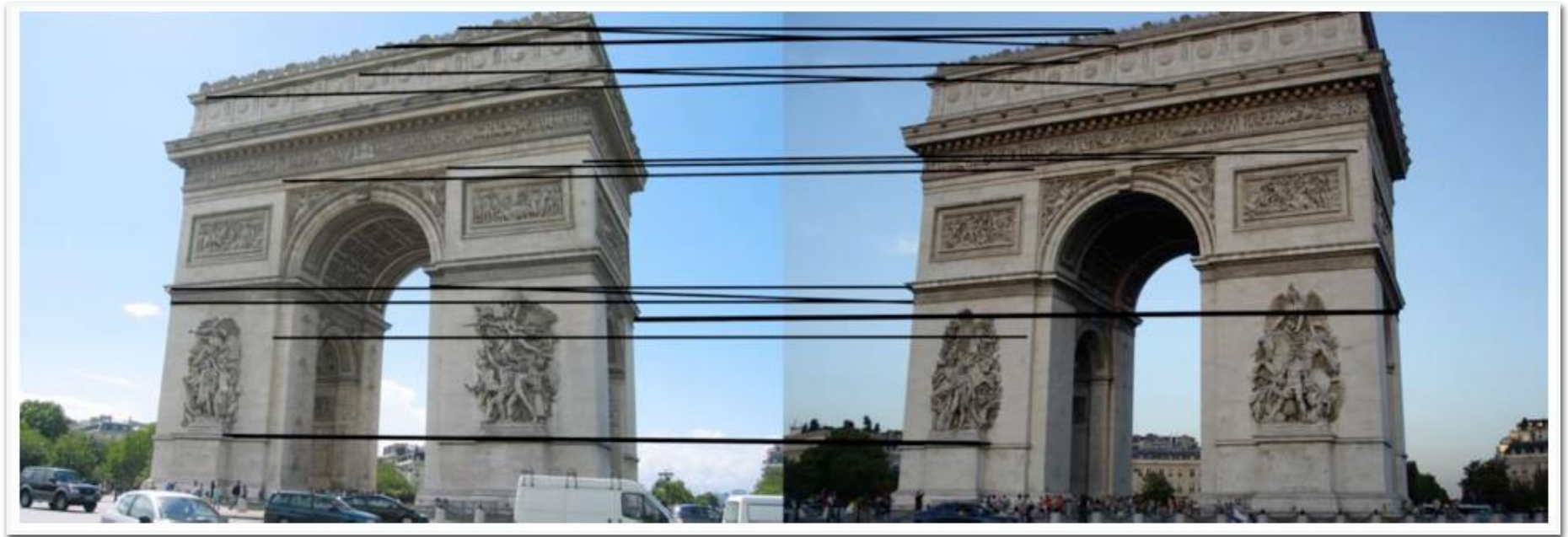


# What are the key challenges?

- Scale – we have made great progress here
- **Robustness**
- **Time**
- **Materials**
- **Semantics / grounding**
- My own biased view

Robustness

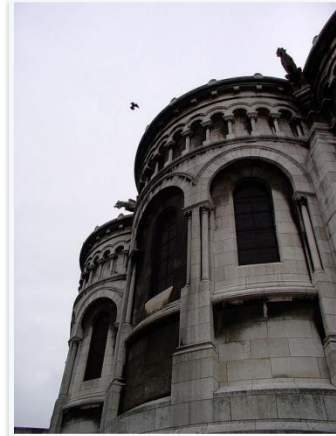
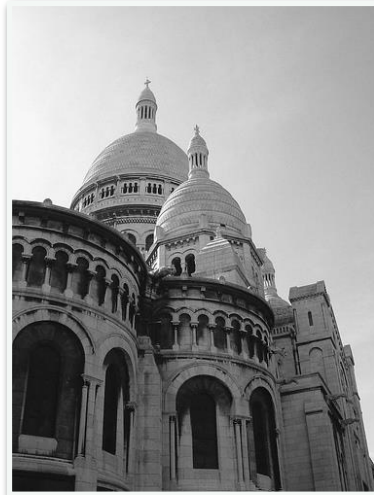
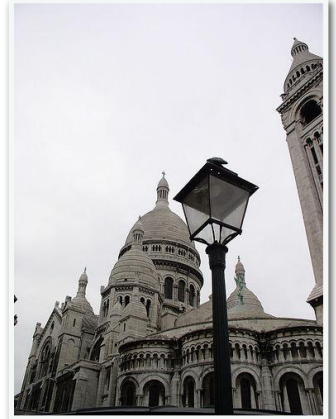
# Are two things the same?



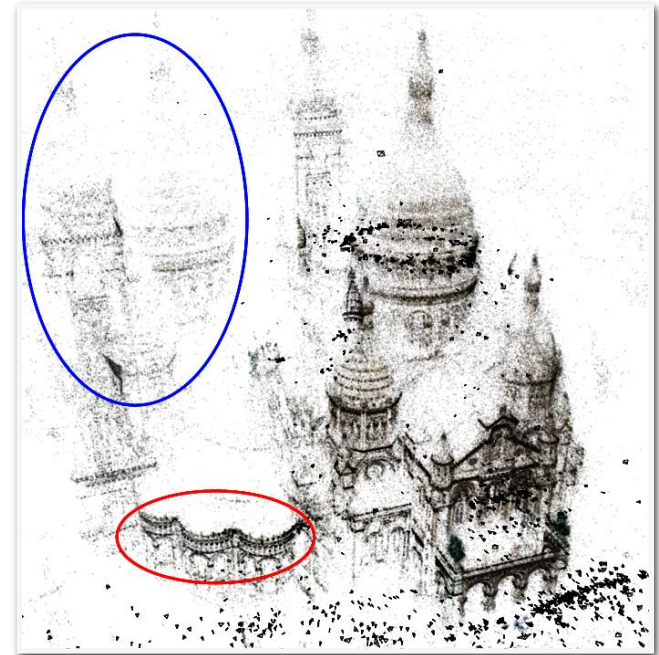
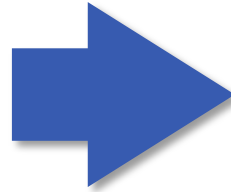
- How do we know what we are looking at is the same or different?



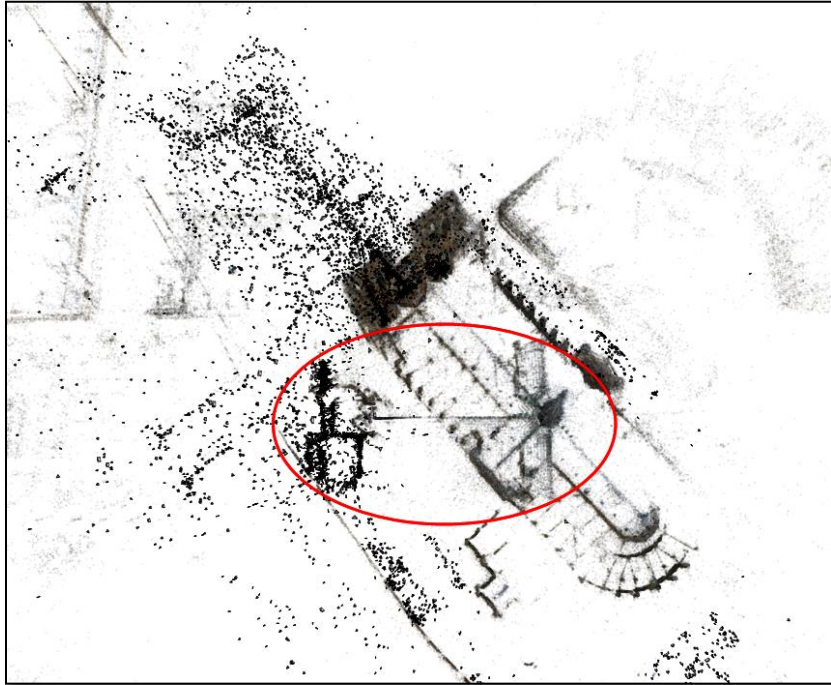
# Structural similarities break SfM



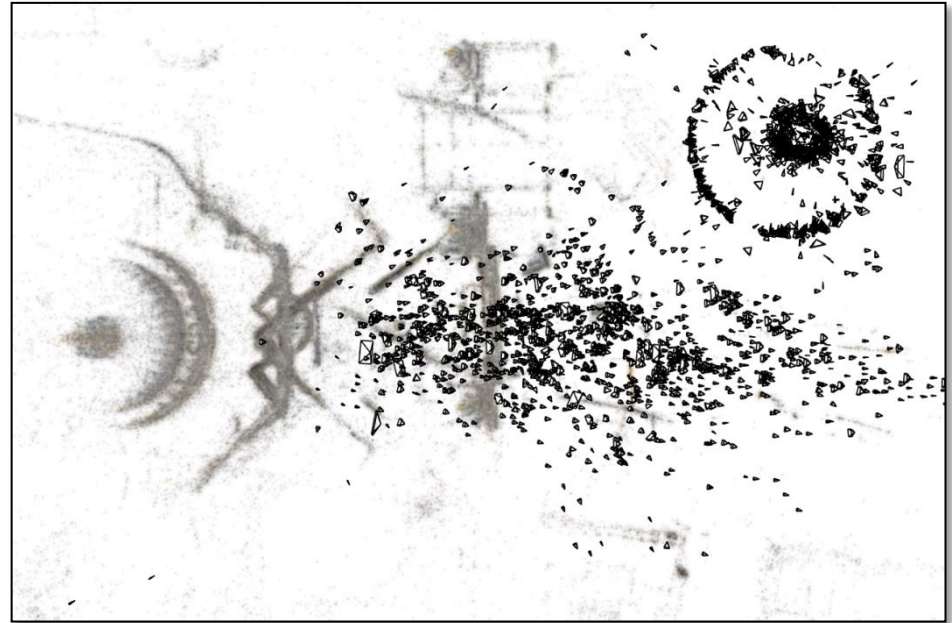
# Structural similarities break SfM



# Other examples

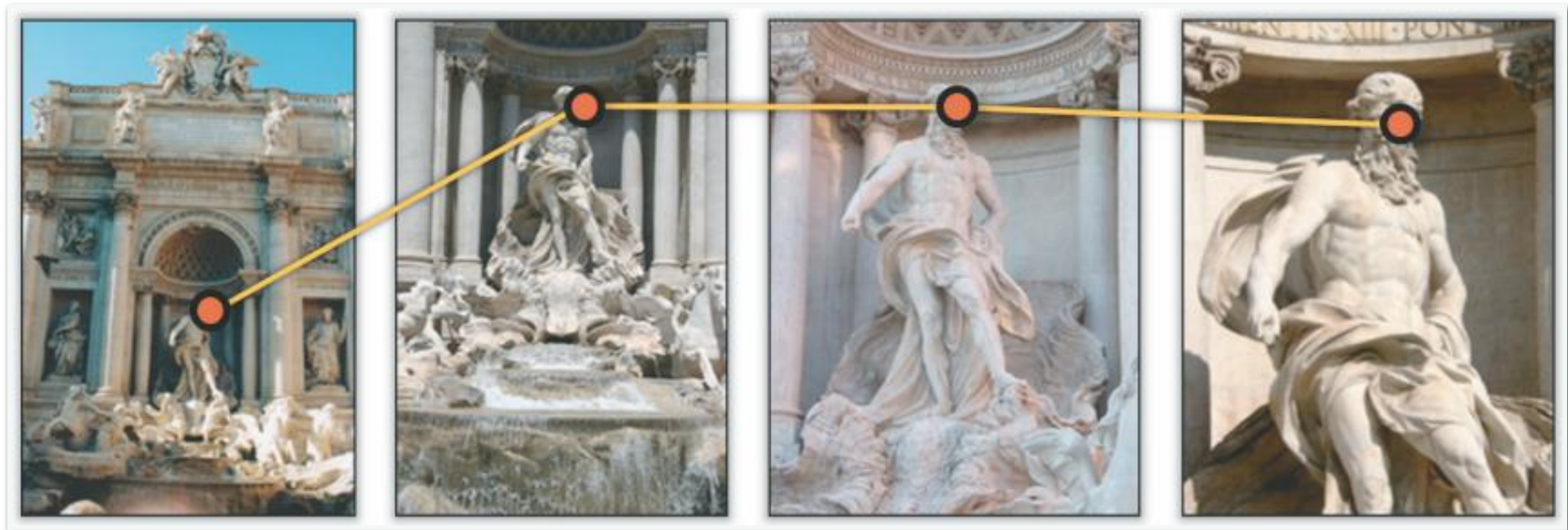


Notre Dame Cathedral

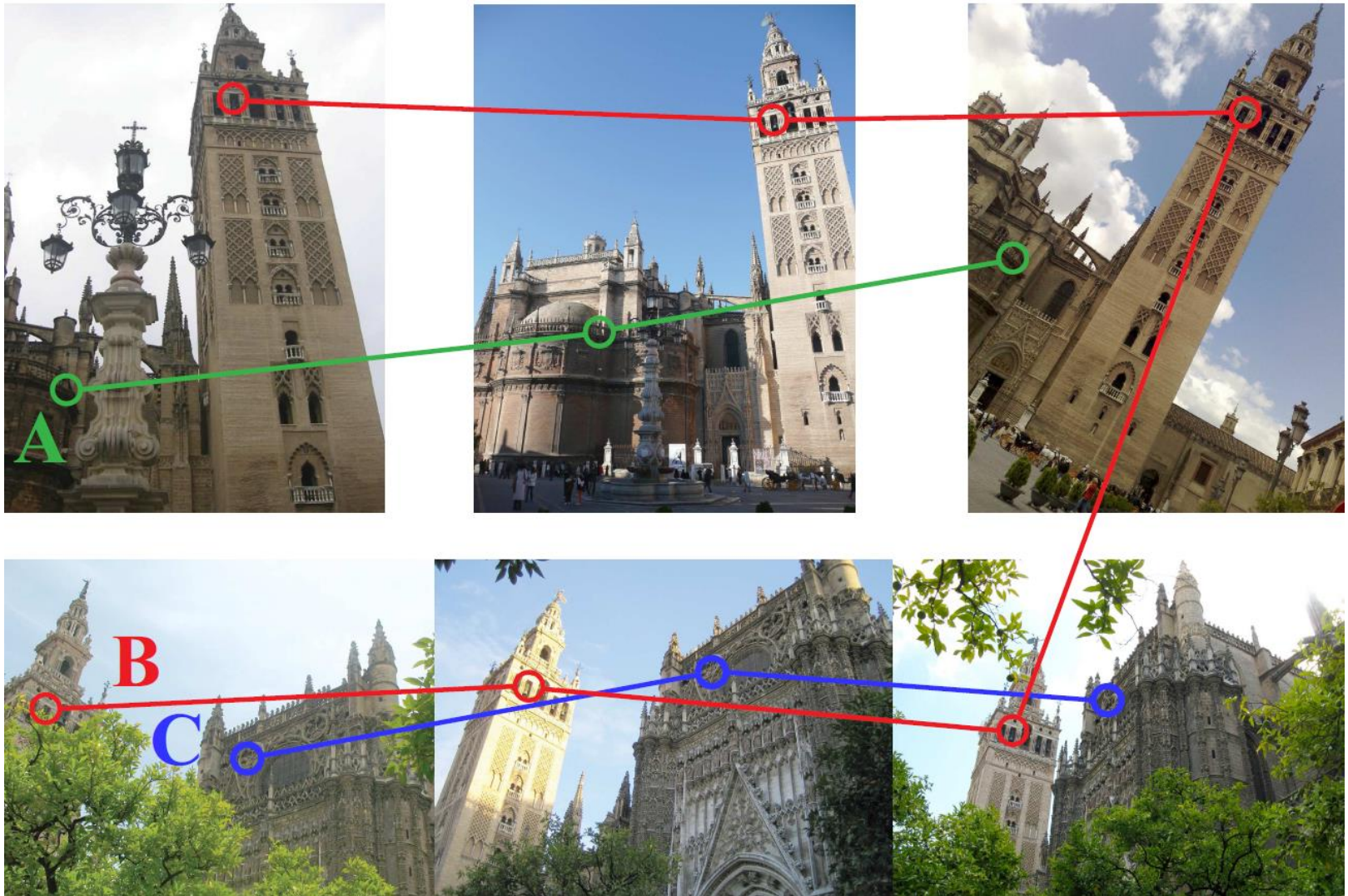


St. Paul's Cathedral

# Tracks should contain one 3D point



# Tracks can conflate distinct points



# SfM Disambiguation

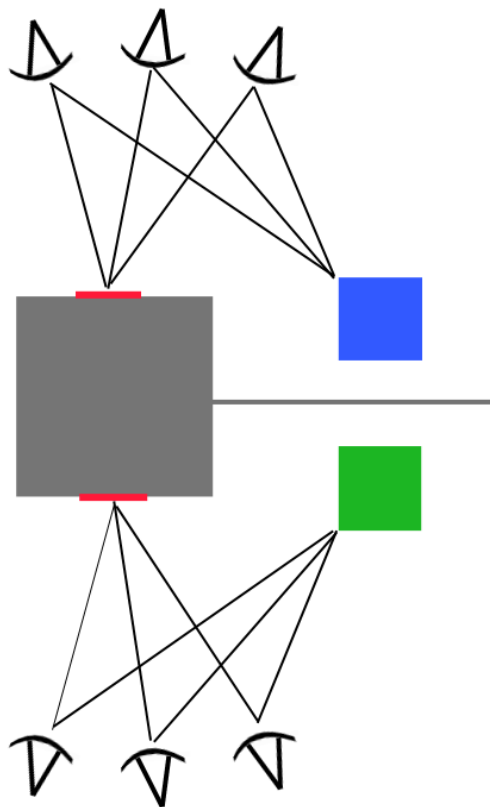
- Most methods reason about inconsistencies across many images
- Inconsistencies in
  - Loops of pairwise geometries
  - Visibility
  - Sequencing
  - Global geometry

[Zach et al., CVPR 2008], [Zach et al., CVPR 2010],  
[Roberts et al., CVPR 2011], [Jiang et al., CVPR 2012]

# SfM Disambiguation in the Large

- We wanted a solution that was
  - As simple as possible
  - Scalable to huge image collections
- Intuition: visibility of points is (often) transitive

# Graph topology is a cue for ambiguities

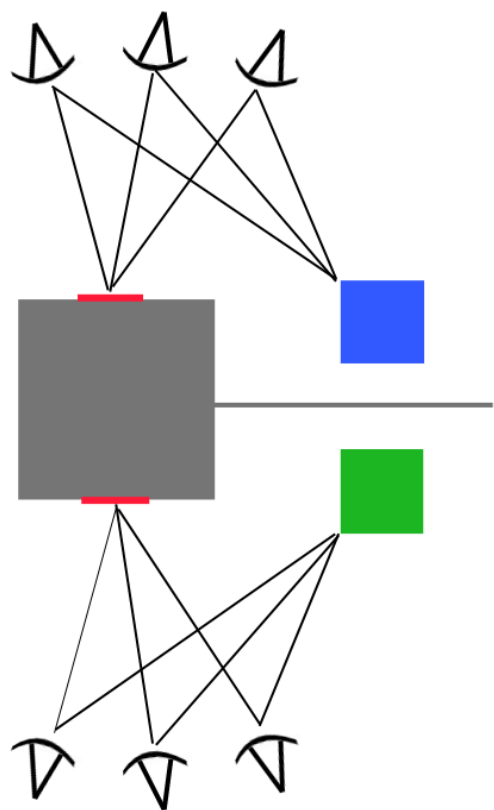


Schematic of a scene with an ambiguous feature (in red)

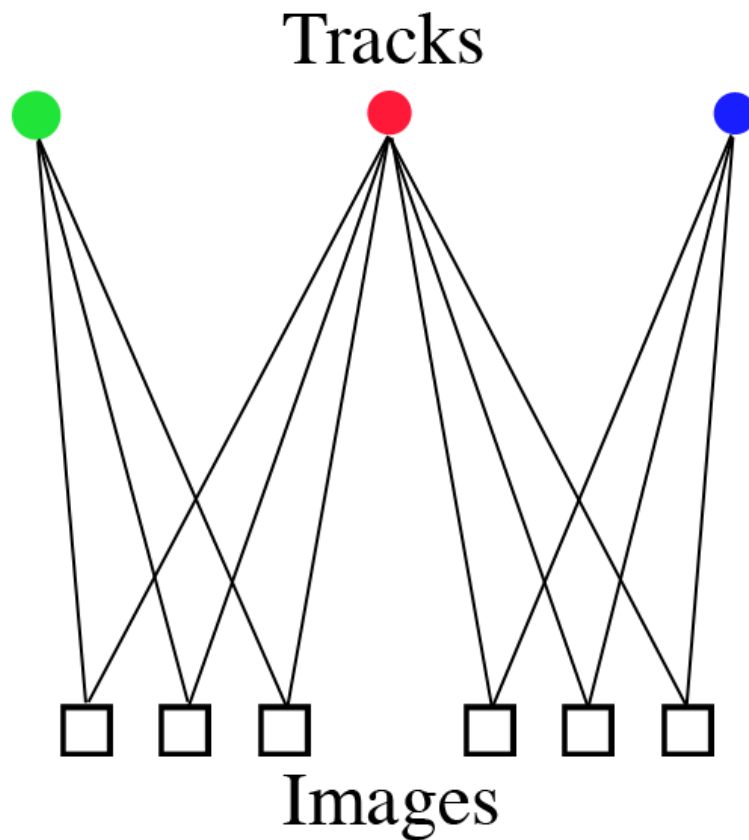
Note that the two sides of the scene have different background (blue and green)



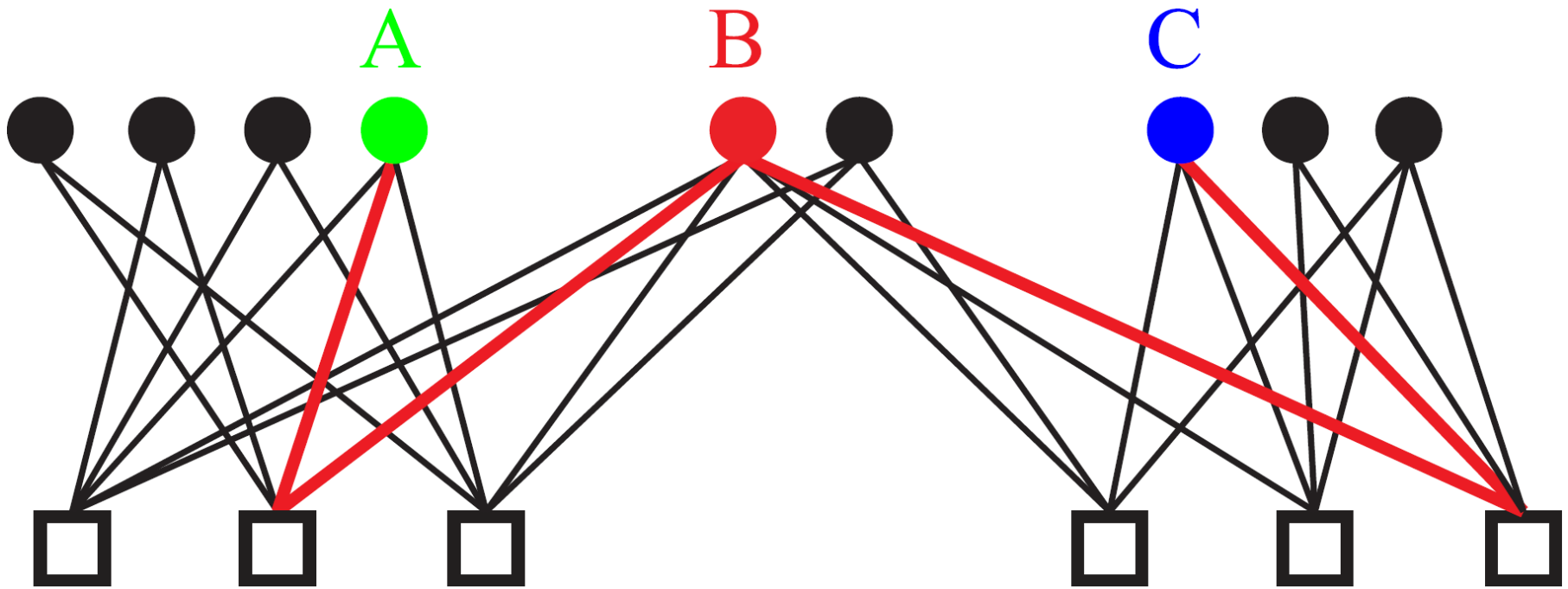
# Graph topology is a cue for ambiguities



This structure can  
be seen in the  
*visibility graph*

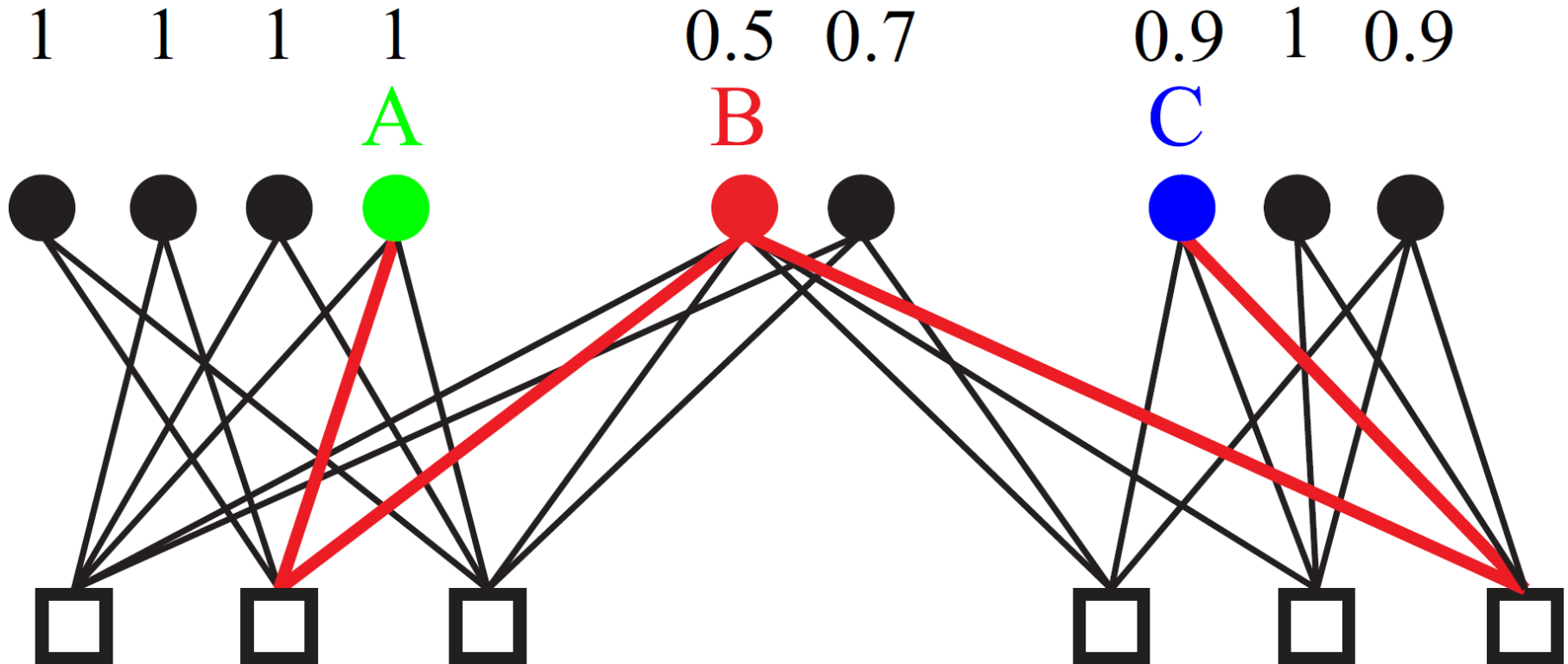


# Larger example



Bad tracks have more than one cluster of context. Measure this with the bipartite local clustering coefficient.

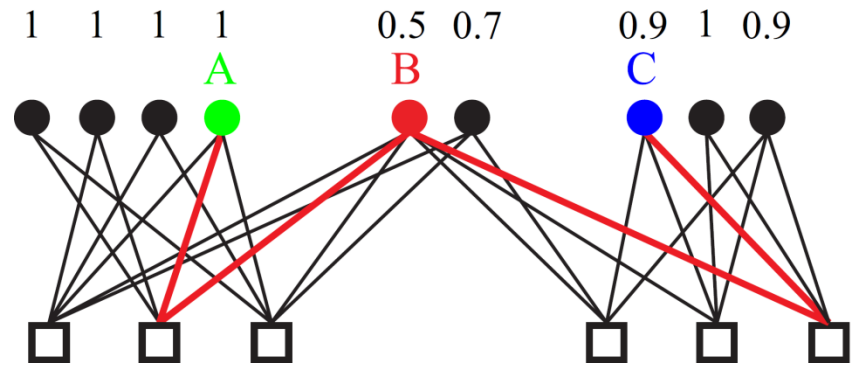
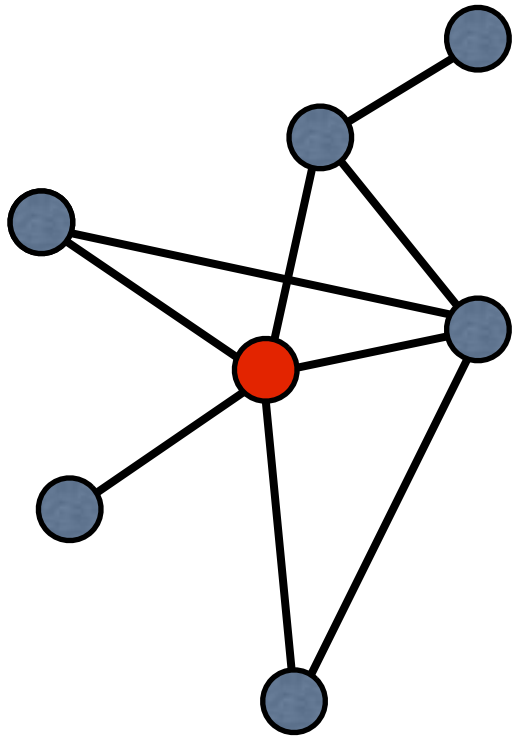
# Larger example



Bad tracks have more than one cluster  
of context. Measure this with the  
bipartite local clustering coefficient.

# *blcc* is analagous to the local clustering coefficient

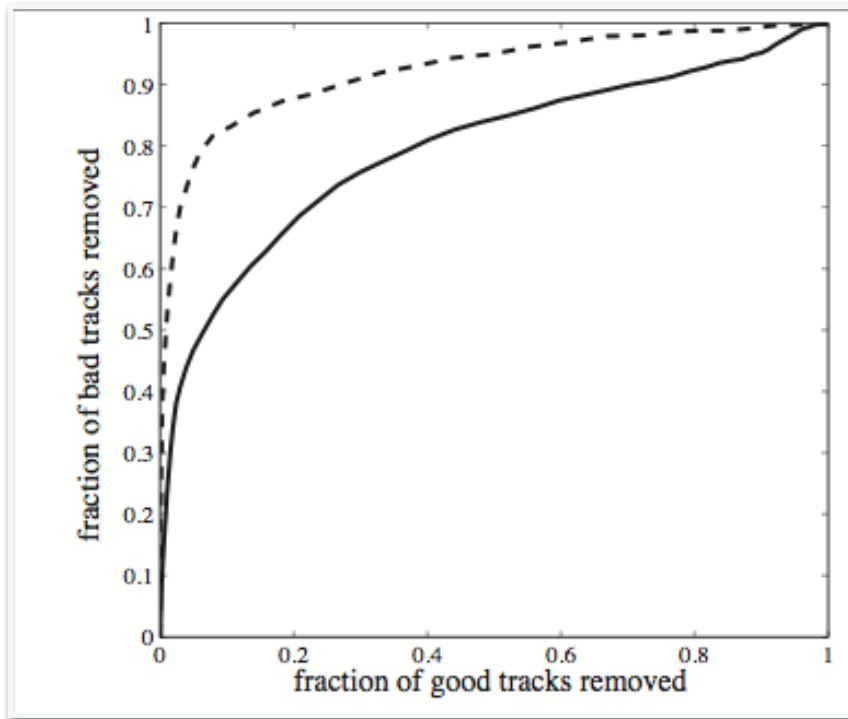
$$lcc(\text{red node}) = \frac{\text{closed triangles}}{\text{possible triangles}} = \frac{3}{10}$$



$$blcc(\text{red node}) = \frac{\text{closed 6-paths}}{\text{possible 6-paths}}$$

# Filtering by *blcc* removes bad tracks

ROC curve for classifying bad tracks

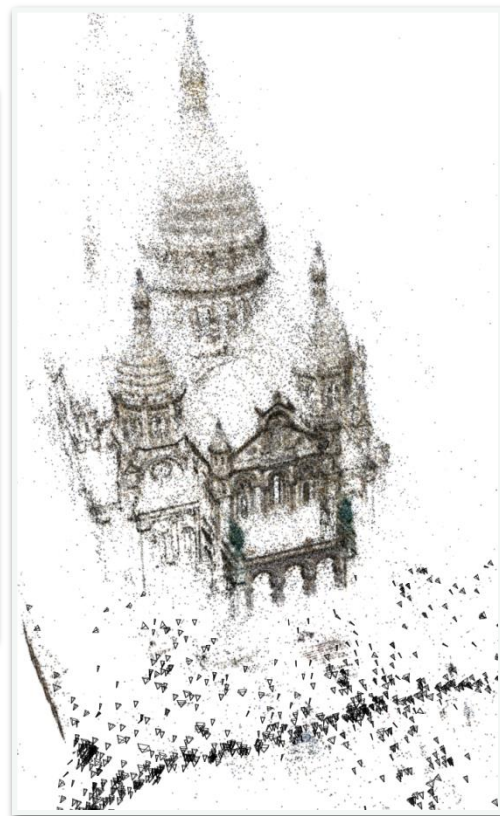
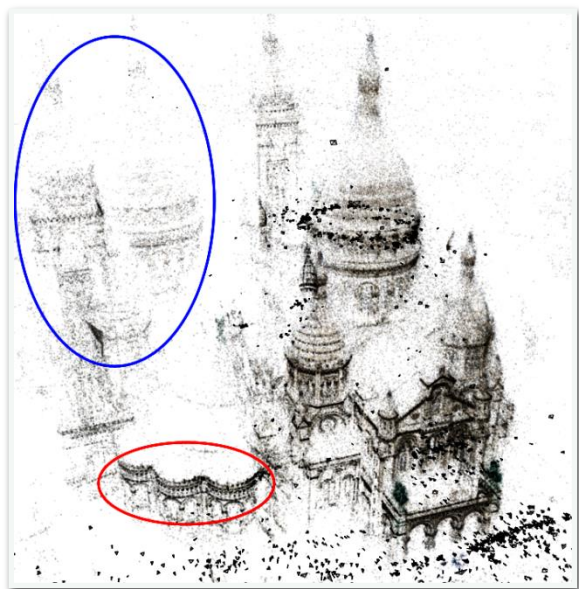


Solid line: thresholding tracks on *blcc*.  
Dotted line: same, but on a more uniform subgraph.

## Algorithm:

1. Compute a covering subgraph
2. Compute *blcc* for each track
3. Remove tracks lower than a threshold  
Use lowest threshold that separates the graph into a user-predetermined number of components.
4. Reconstruct each component separately
5. Rigidly merge components if possible

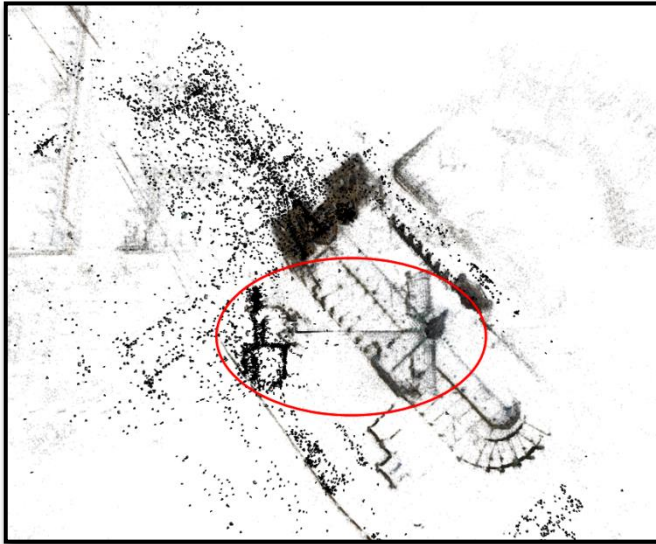
# Disambiguation results



Sacre Coeur Basilica, Paris

# Disambiguation results

Before

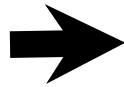


After



Notre Dame Cathedral, Paris

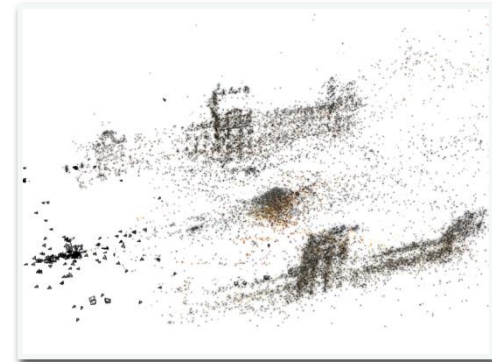
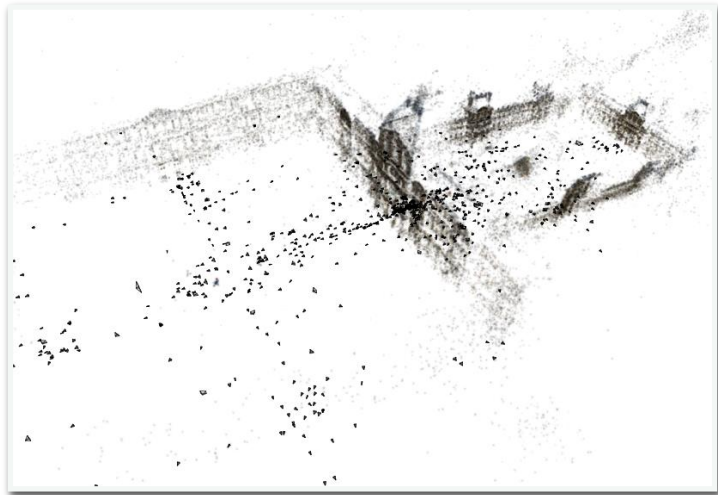
# Disambiguation results



Seville Cathedral



# Disambiguation results



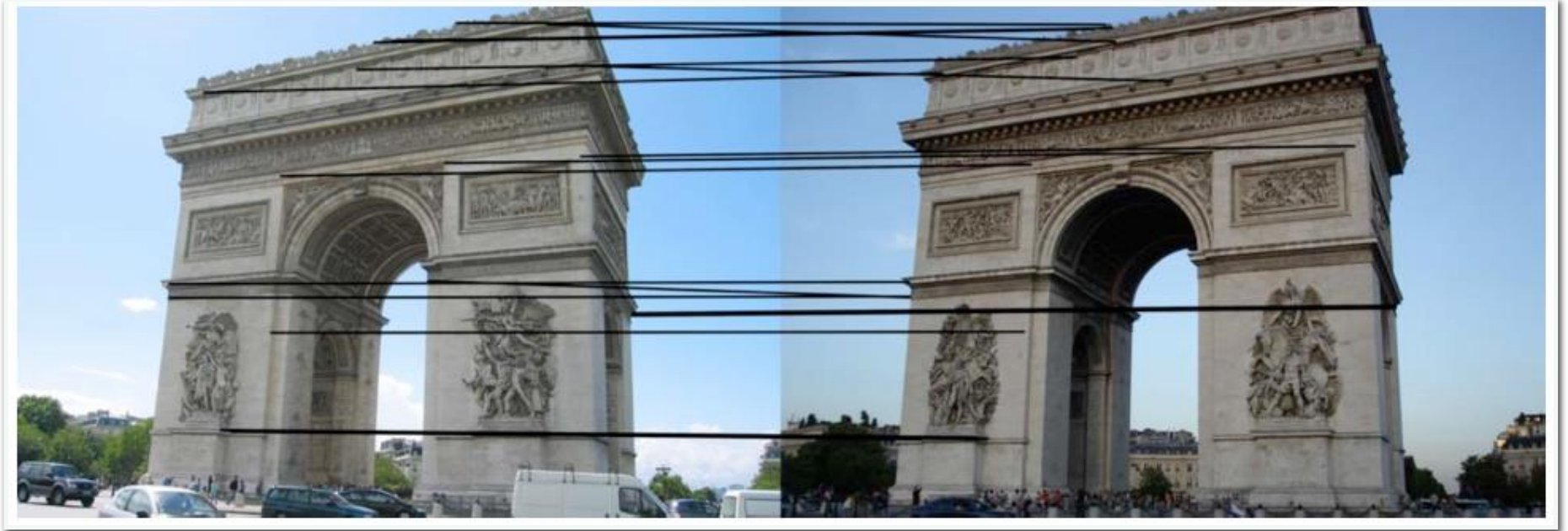
Outside the Louvre, Paris

# Network Principles for SfM

- + Extremely fast method
- + Based on simple local reasoning
- + Very simple to implement
- Can sometimes oversegment models
- Theoretical guarantees?

See also [Heinly et al. ECCV 2014]

# Feature matching as recognition



- Can't we just solve this problem using appearance alone?
- Better features or image metrics?

Time

# Places are dynamic



# 5pointz, Queens



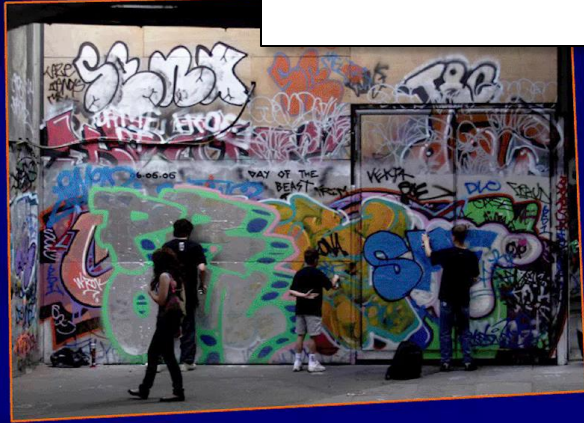
# 5pointz

**GRAFFITI ARCHAEOLOGY**   about   credits   links   news   faq   submit   donate

Locations & Walls.

- ▼ bluxome:
  - eastA
  - eastB
  - eastC
- ▼ undercroft:
  - panel2
  - panel3
- ▶ cavern:
- ▶ harveys:
- ▶ olympia:
- ▶ 22nd:
- ▶ 19th:
- ▶ candle:
- ▶ florida:
- ▶ ghost:
- ▶ cove:
- ▶ belmont:
- ▶ 25th:
- ▶ williams:

How do we model these time-varying scenes?



Zoom. Navigator.   Timeline.

2006   2007   2008

1 2 3 4 5 6 7 8 9 1 11 12 13 1 1 16 17 1 1 20 21 22 23 2 2 26 27 2 29 3 3 32

VS

[Graffiti Archaeology, Cassidy Curtis]

# 4D Cities



[Frank Dellaert, Grant Schindler, et al.]



# Scene Chronology

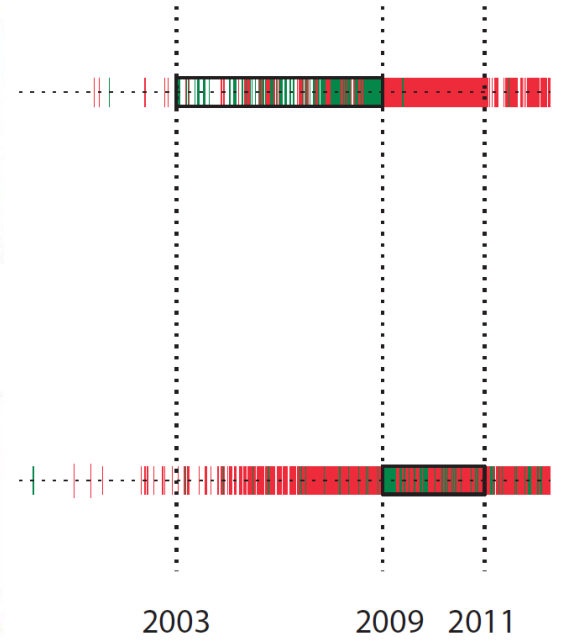
**Step 1:** Download photos from Flickr

**Step 2:** Reconstruct a single 3D model with all times mixed up together

**Step 3:** Recover the *chronology* of the scene



Single 3D Model (from ~100,000 images)



Per-Point Time Observations



CATHERINE ZETA-JONES ANGEL LABSBUR  
*A Little Night Music*

SEX AND THE CITY  
CARRIE ON MAY 27  
HBO  
SEXANDTHECITYMOVIE.COM

CIRQUE DU SOLEIL  
BANANA SQUEEL  
LIMITED ENGAGEMENT

COME WITHE  
YANGKE STAMINK

THE CROWD WILL  
LOVE OUT  
JERSEY BOYS  
BEST MUSICAL  
2010 TONY AWARD  
HAIR  
BEST MUSICAL REVIVAL - 2009 TONY AWARD

WINNER! 7 TONY AWARDS  
BEST MUSICAL REVIVAL  
RODGERS & HAMMERSTEIN'S  
SOUTH PACIFIC  
DIRECTED BY BARRY COHEN  
LINCOLN CENTER

WEST SIDE STORY  
TICKETMASTER.COM / 212-307-4100

CHICAGO  
CALIENTE - INCONTOURNABLE - 熱的 · F  
THE INTERNATIONAL  
TELECHARGE.COM / CHICAGO  
CHICAGO THE MUSICAL.COM © AMBASSAD

Tonight belongs to...  
PHANTOM OF THE OPERA  
@MAJESTIC

WEST SUITE

WEST SIDE STORY

WEST SIDE STORY

FUEL

THE CHAN

sharbo sharro sharro

SO EXCITING IT MAKES YOU SOB WITH PLEASURE

WEST SIDE STORY  
MONDAY TO SATURDAY 10 A.M. - 8 P.M.

IT WILL BLOW YOU AWAY



CARIE KIRBY ZETA-JONES ANGEL LABSBERG  
*A Little Night Music*

SEX AND THE CITY  
CARRIE ON MAY 27  
HBO  
SEXANDTHECITYMOVIE.COM

CIRQUE DU SOLEIL  
**BANANA Shteel**  
LIMITED ENGAGEMENT

COME WITHE YANKEE STAMINK

THE GROVE WILL  
**HAIR**  
BEST MUSICAL REVIVAL - 2009 TONY AWARD

7 TONY AWARDS  
BEST MUSICAL REVIVAL  
**SOUTH PACIFIC**  
DIRECTED BY BARRY COHEN  
LINCOLN CENTER

PALACCE

**WEST SIDE STORY**  
TICKETMASTER.COM / 212-307-4100

**CHICAGO**  
CALIENTE - INCONTOURNABLE - 熱的  
THE INTERNATIONAL  
TELECHARGE.COM / CHICAGO  
CHICAGOthemusical.com @ AMBASSADOR

Tonight belongs to...  
**PHANTOM OF THE OPERA**  
#MUSICITY

**WEST SUITE**  
westsuitemanhattan.com

**WEST SIDE STORY**

**WEST SUITE**

**FUEL**

**THE CHAN...**

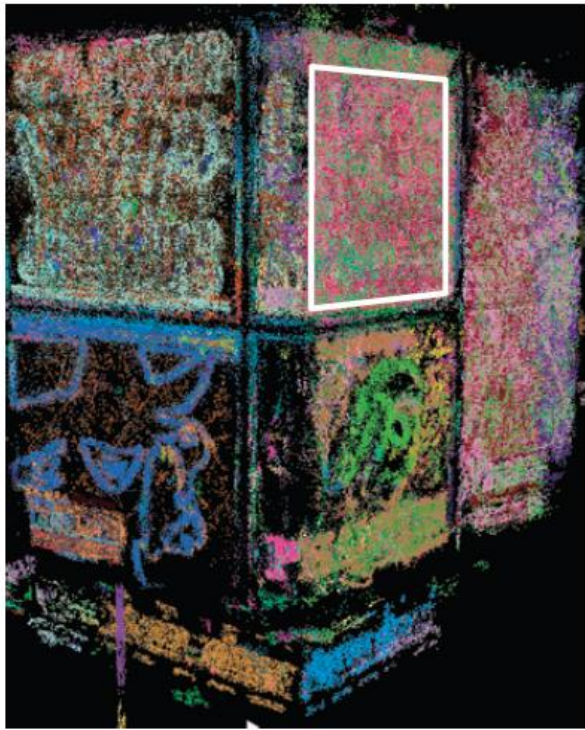
Gifts  
GIFTS

sharbo sharro sharro

SO EXCITING IT MAKES YOU ASKE WITH PLEASURE

IT WILL BLOW YOU AWAY  
**WEST SIDE STORY**  
MONDAY TO SATURDAY 10 A.M. - 8 P.M.

THE GUEST SUITES



Space-Time Point Clustering



Exploded View across Time



**5Pointz - Queens, New York City**

# Re-time-stamping

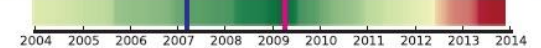
March 2008 - Late 2007



January 2005 - Early/Mid 2007



April 2007 - 2008/2009



Blue: original timestamp

Red: our predicted timestamp



Physics



Weather



People



Times Square, 1922



Eisenstadt, 1945



# Materials



Glass  
Window

Ceiling



Wall



Sofa

Fabric

Fabric

Leather



Plastic  
Chair

Mat  
Fur

Wood  
Floor

living room



# OpenSurfaces

Sean Bell, Paul Upchurch, Noah Snavely, Kavita Bala  
Cornell University

## Statistics

	Good	All
Labeled Scenes	25,357	91,876
Whitebalanced Photos	17,839	24,771
Segmentations	70,005	103,513
Planar Segmentations	36,482	70,005
Named Materials	56,625	68,761
Named Objects	31,697	42,203
Rectified Textures	16,829	22,219

## Materials



## Reflectances



## Textures



Sean Bell, Paul Upchurch, Noah Snavely, Kavita Bala, SIGGRAPH 2013

<http://opensurfaces.cs.cornell.edu/>



Query



Results: wood floors in kitchens, sorted by diffuse color



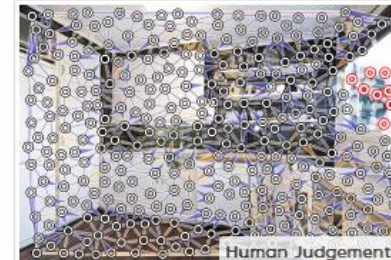
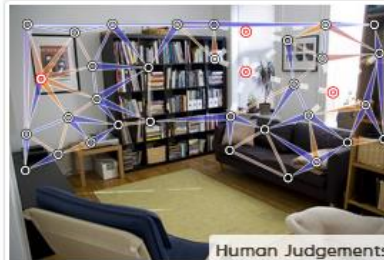
Query



Results: fabric sofas in living rooms, sorted by diffuse color similarity

# Intrinsic Images in the Wild

Sean Bell, Kavita Bala, Noah Snavely  
Cornell University



Sean Bell, Kavita Bala, Noah Snavely, SIGGRAPH 2014, <http://intrinsic.cs.cornell.edu>

# Semantics / Grounding

# Every image tells a story...

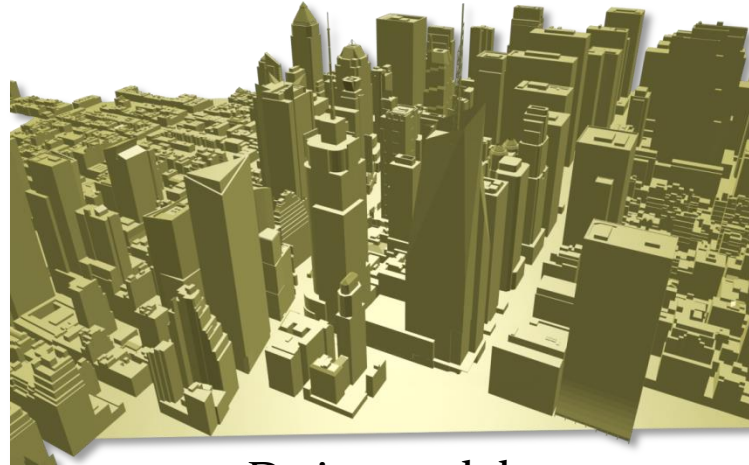




# Grounding vision in the world



OpenStreetMap



3D city models

**NOAA NATIONAL CLIMATIC DATA CENTER**  
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Home Climate Information Data Access Customer Support About NCDC

Quick Links

- Land-Based Station
  - Datasets
  - Find a Station
  - Station Metadata
  - Climate Data Online
  - Data Publications
- Satellite
- Radar
- Model
- Weather Balloon
- Marine / Ocean
- Paleoclimate
- Severe Weather

HOME > DATA ACCESS

### Land-Based Station Data

Land-based (*in situ*) observations are collected from instruments sited at locations on every continent. They include temperature, dew point, relative humidity, precipitation, wind speed and direction, visibility, atmospheric pressure, and types of weather occurrences such as hail, fog, and thunder. NCDC provides a broad level of service associated with *in situ* observations. These include data collection, quality control, archive, and removal of biases associated with factors such as urbanization and changes in instrumentation through time. Data on sub-hourly, hourly, daily, monthly, annual, and multiyear timescales are available.

- Datasets and Products
  - Access NCDC's land-based datasets directly.
- Find a Station
  - Locate a station by using either a map tool or a location and data search tool.
- Station Metadata

Measuring instruments used for current observations and data reporting

Weather data

**MAP LEGEND**

- Makes all regular stops.
- SNOW route/Ruta para casos de nieve.
- TIME POINT/INTERMEDIAS: Street intersection used for time schedule reference point listed at the top of time columns to estimate bus arrival and trip times.
- TRANSFER POINT/LUGAR DE TRASBORDO: Route intersection for transferring to the connecting route or routes indicated.
- TIME POINT/TRANSFER POINT, INTERMEDIAS/LUGAR DE TRASBORDO.
- PARK & RIDE: Designated free parking area with direct bus service to major commercial centers.
- LANDMARK: A significant geographical reference point.

**University District Transfer Point**

Bay	NE 41st St
Bay 4	12:00 AM
Bay 3	12:00 AM
Bay 2	12:00 AM
Bay 1	12:00 AM

Bus schedules

## Search & Browse Datasets and Views

Name	
1.	<b>311 Service Requests from 2010 to Present</b> Social Services 311, 311 service requests, 2010, 2011, 2012, ... All 311 Service Requests from 2010 to present. This information is automatically updated daily.
2.	<b>Electric Consumption by ZIP Code - 2010</b> Environment electricity, energy, environment, planning, power, ... 2010 electricity consumption in kWh and GJ, by ZIP code, building type, and utility company.
3.	<b>Zip Codes Map</b> Social Services geographic, location, map, cartography, zip, code, ... Polygon representing the boundary of the zip codes in the city.
4.	<b>MTA Data</b> Transportation traffic, vehicles, route, schedules, clean web Information pertaining to MTA (Metropolitan Transportation Authority of the State of New York) subways, buses, commuter rail,
5.	<b>Restaurant Inspection Results</b> Health restaurant inspection results, ... NYC restaurant inspection results
6.	<b>Basic Description of Colleges and Universities</b> Education doitt gis, geographic, location, map, cartography, ... Location of colleges and universities with basic descriptive information.
7.	<b>SAT (College Board) 2010 School Level Results</b> Education lifelong learning New York City school level College Board SAT results for the graduating seniors of 2010. Records contain 2010 College-bound
8.	<b>Mapped In NY Companies</b> Business jobs, tech, jobs and economic mobility Raw data which powers the Mapped In NY site at <a href="http://www.mappedinny.com/">http://www.mappedinny.com/</a>
9.	<b>Filming Locations (Scenes from the City)</b> Business film, movie, scene, scenes from the city List of filming locations mentioned in the book <i>Scenes from the City</i>
10.	<b>2012 NYC Noise Complaints - Heat Map</b> Other 311, 311 service requests, 2010, 2011, ... NYC Noise complaints for 2012

<https://nycopendata.socrata.com> (<https://data.sfgov.org/>, <https://data.seattle.gov/>, ...)

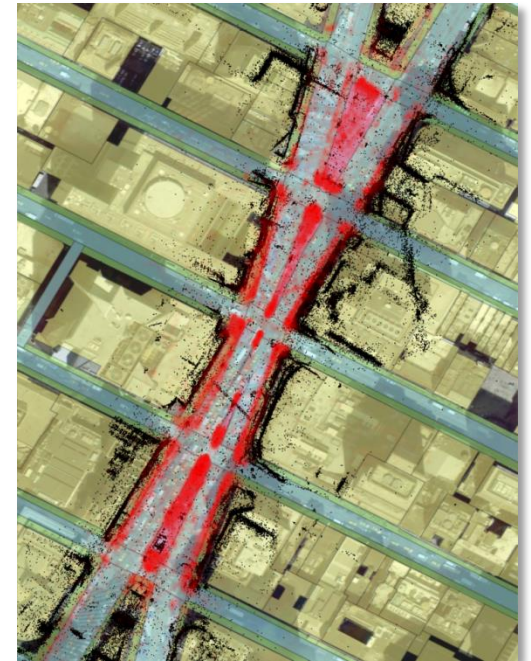
# Grounding vision in the world



- Which direction is north?
- What is the shape of the buildings?
- What was the weather like?
- Where are streets?
- What is the #51 bus schedule in Rome?

**Goal:** Integrate images into this ecosystem of geographic data

# First steps: NYC<sub>3</sub>DCars



# NYC OpenData Roadbeds



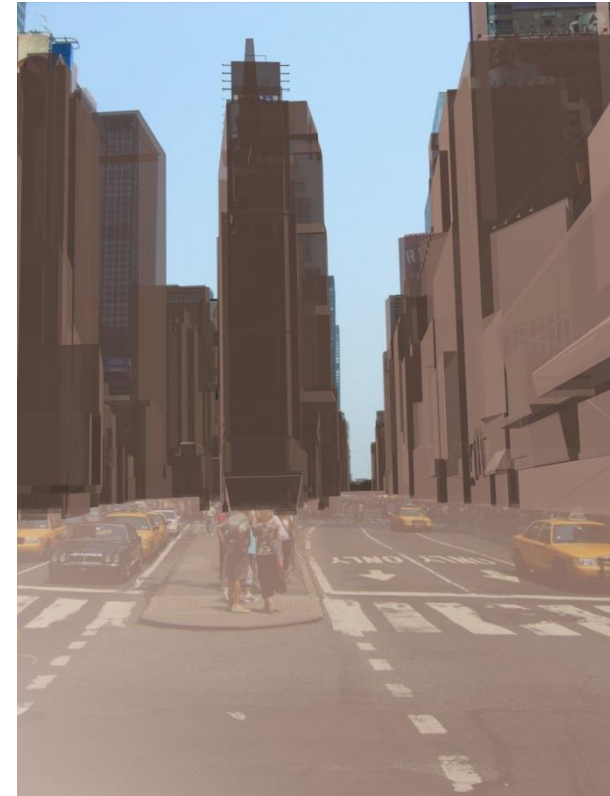
# Vision grounded in the real world



Input photo



Overlaid GIS data  
(roads / sidewalks / medians)



Overlaid Google Earth models

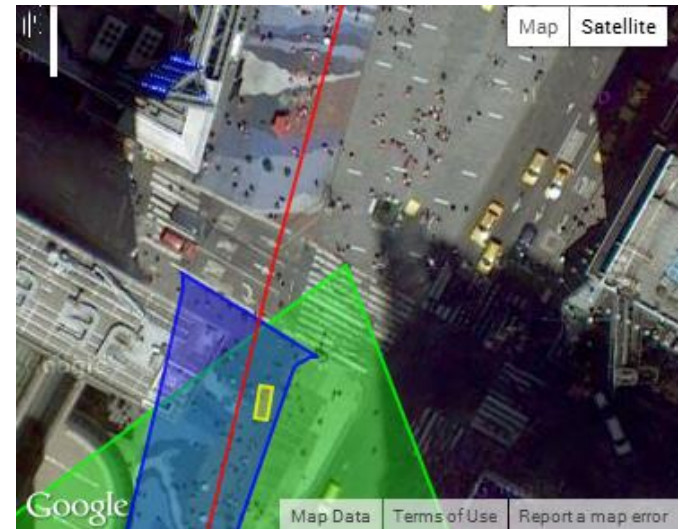
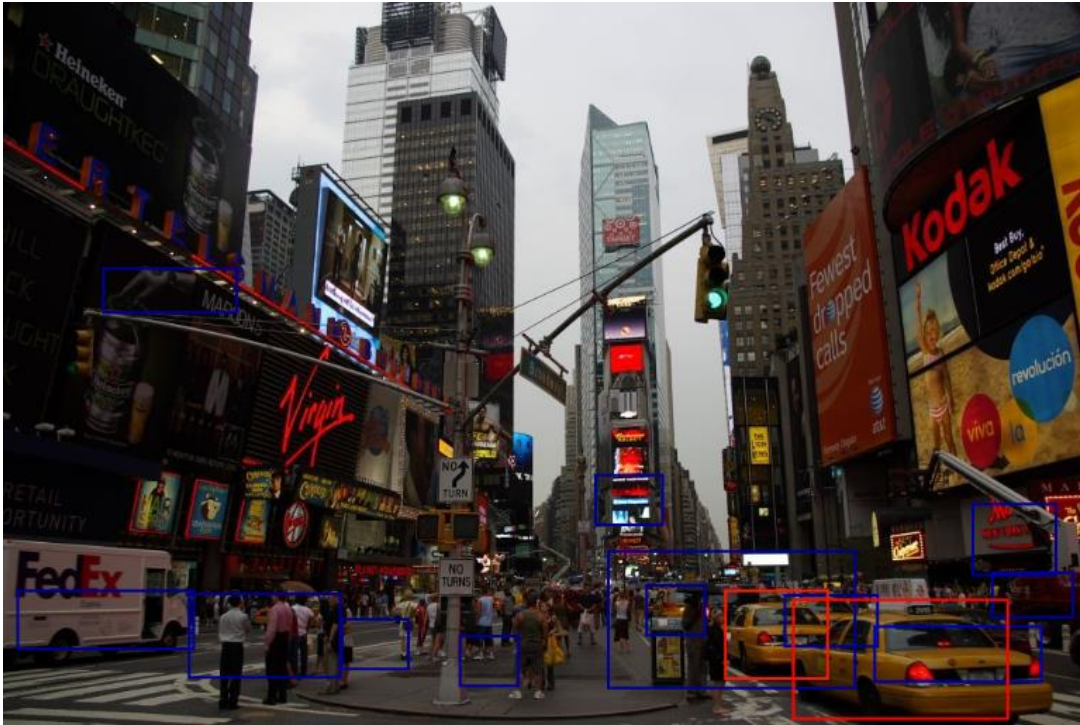
# Annotated 3D Vehicles



Video

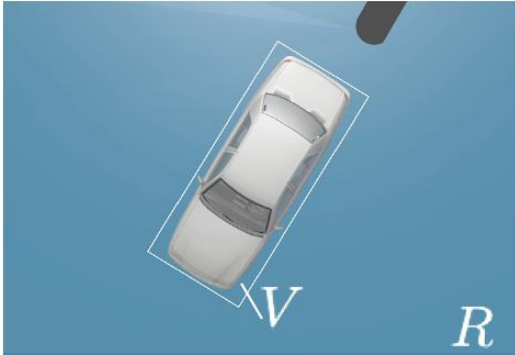


# 3D Detection

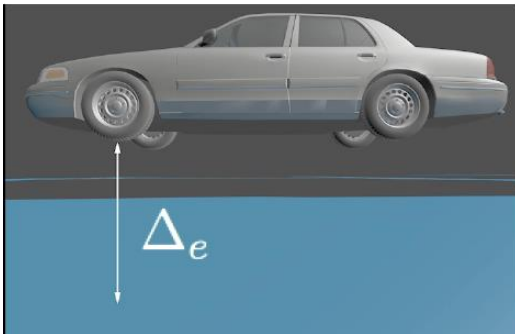




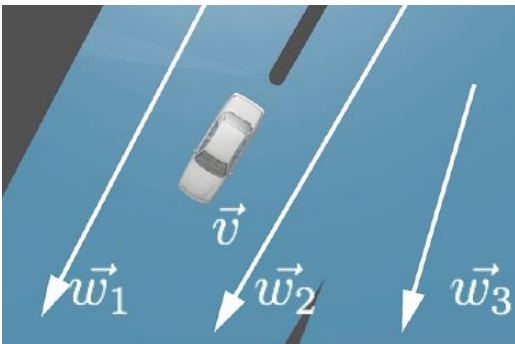
Appearance score



Ground coverage score

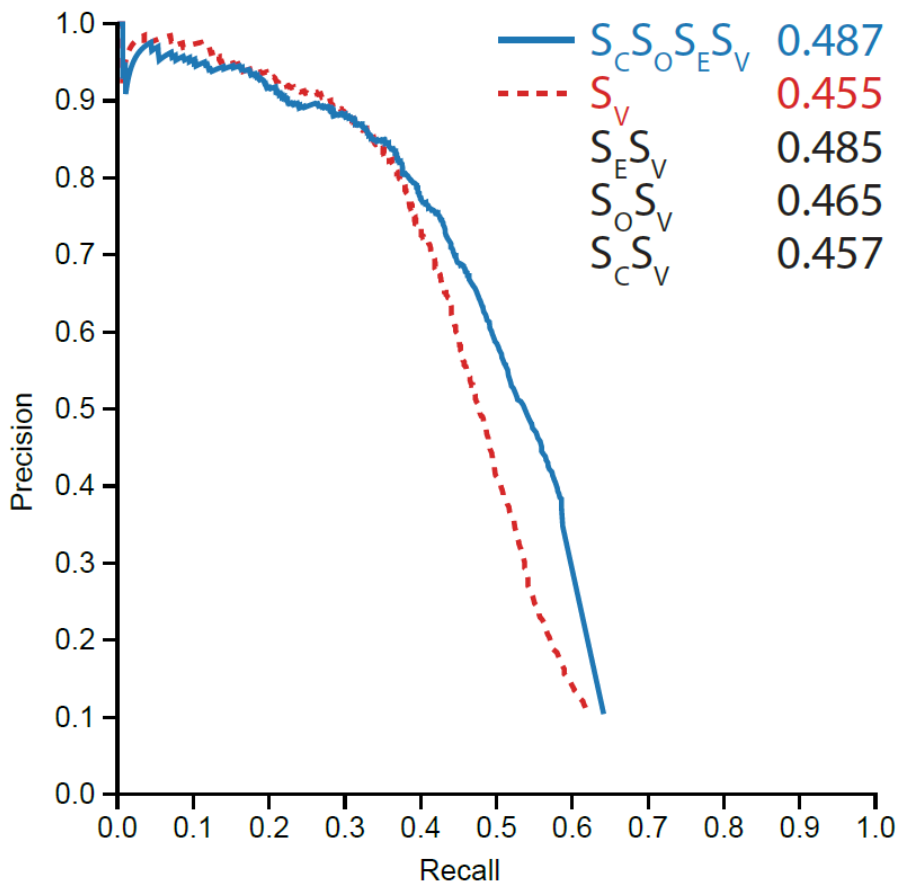


Elevation score

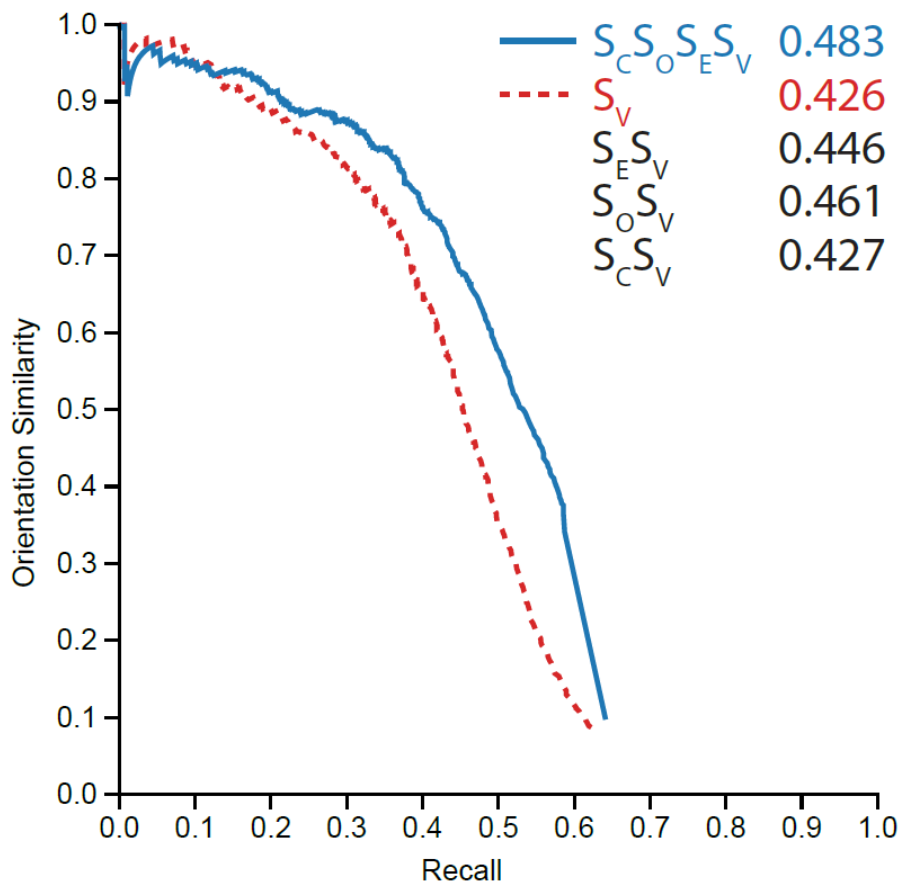


3D orientation score

# Results



**Precision / Recall**



**Orientation similarity / Recall**



A vehicle detection database for vision tasks set in the real world.



### 3D Reconstructions

Each photograph in NYC3DCars has been geo-registered to the Earth, providing full camera intrinsics and extrinsics in an Earth-Centered, Earth-Fixed coordinate system enabling seamless integration with existing geospatial data.



### Geographic Data

Companion databases such as those provided by [OpenStreetMap](#) and [NYC OpenData](#) have been integrated for easy access to geographic features such as road, sidewalk, and median polygons as well as road network connectivity.



### Vehicle Annotations

Human annotators have provided detailed descriptions for vehicles contained in the database. Annotations include a full 6 degree of freedom vehicle pose, vehicle type, 2D vehicle bounding box, and approximate photo time of day.

<http://nyc3d.cs.cornell.edu/>

# Summary

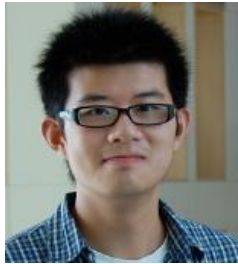
- Many interesting challenges in modeling the world
- Contributions from every area (cf. much wonderful recent work):
  - Scene understanding, object detection, material recognition, illumination modeling, ...
  - Learning?

# Acknowledgements

## Students



Sean Bell



Song Cao



Daniel Hauagge



Kevin Matzen



Paul Upchurch



Chun-Po Wang



Scott Wehrwein



Kyle Wilson

## Collaborators



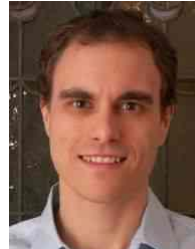
Kavita Bala



Dan Huttenlocher



Yunpeng Li



Dave Crandall

- National Science Foundation
- Intel Center for Science and Technology – Visual Computing
- Amazon AWS for Education

# Thank you!

More information at

<http://www.cs.cornell.edu/~snave/>