

Probabilistic Temporal Inference on Reconstructed 3D Scenes

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The World Changes Over Time

How can we reason about time in structure from motion problems?



Temporal Inference Problem

1. When was each photograph taken?
2. When did each building first appear?
3. When was each building removed?

Set of Photographs:

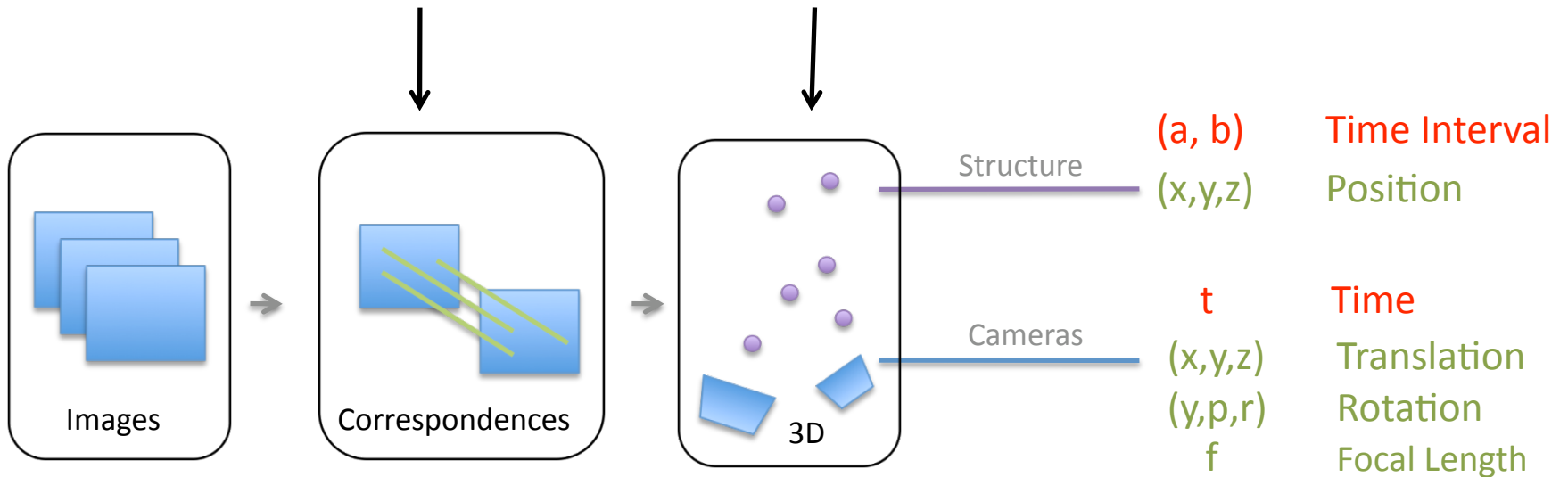


**Set of Objects:
Buildings**

Temporal Inference Problem

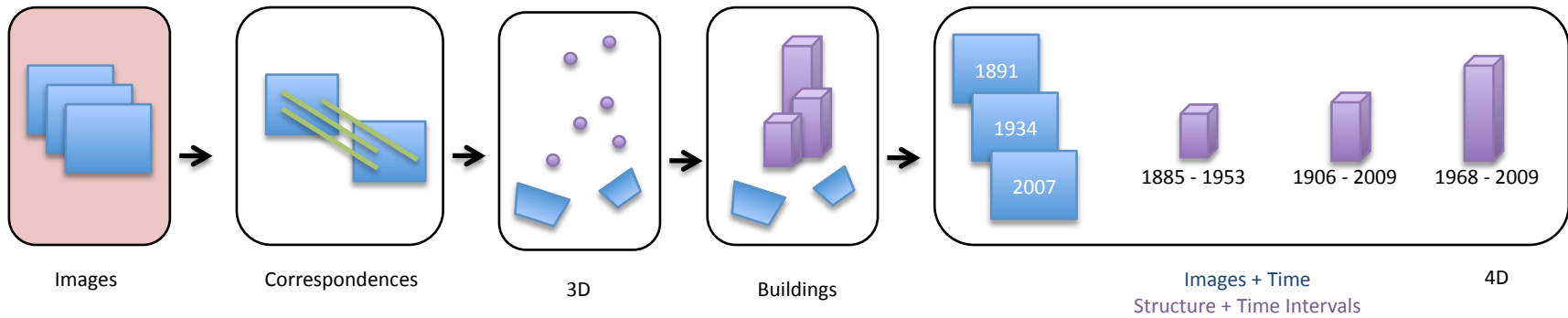
Temporal Inference Problem

Given observations \mathbf{Z} and scene geometry \mathbf{X} , what are the temporal parameters \mathbf{T} ?

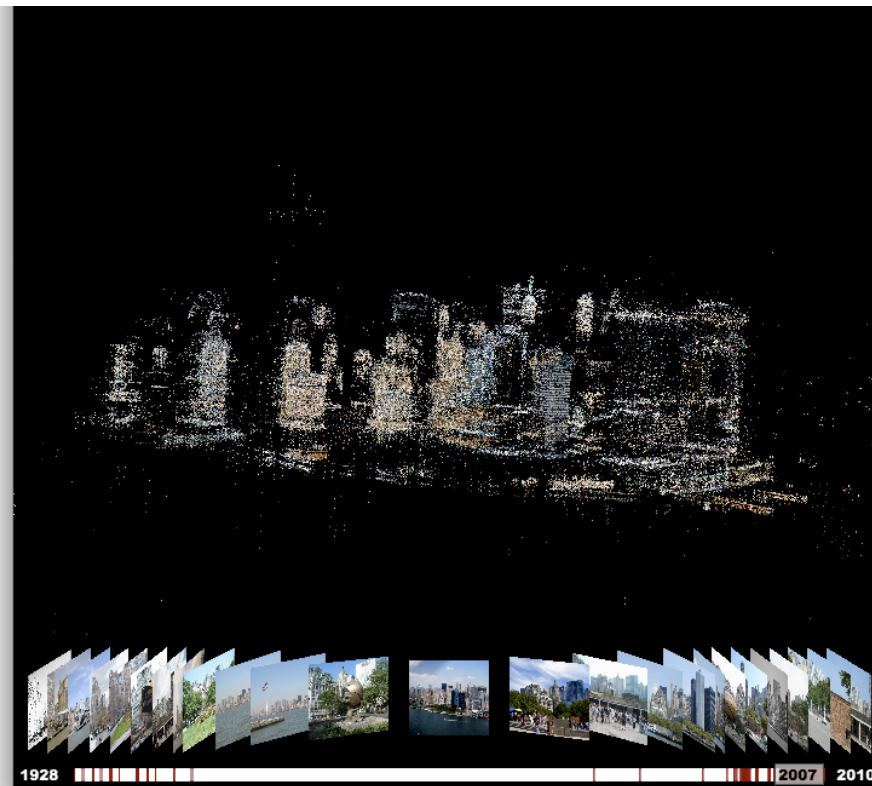
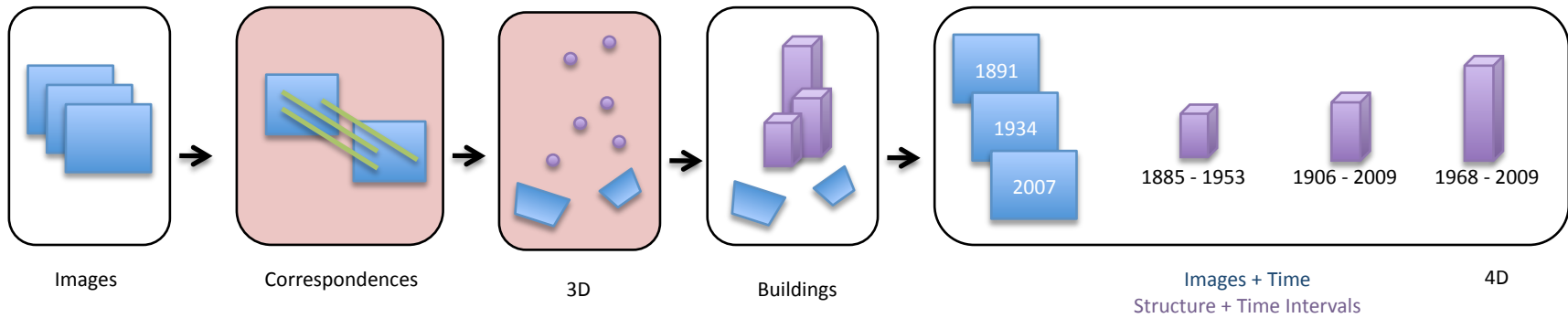


Structure from Motion

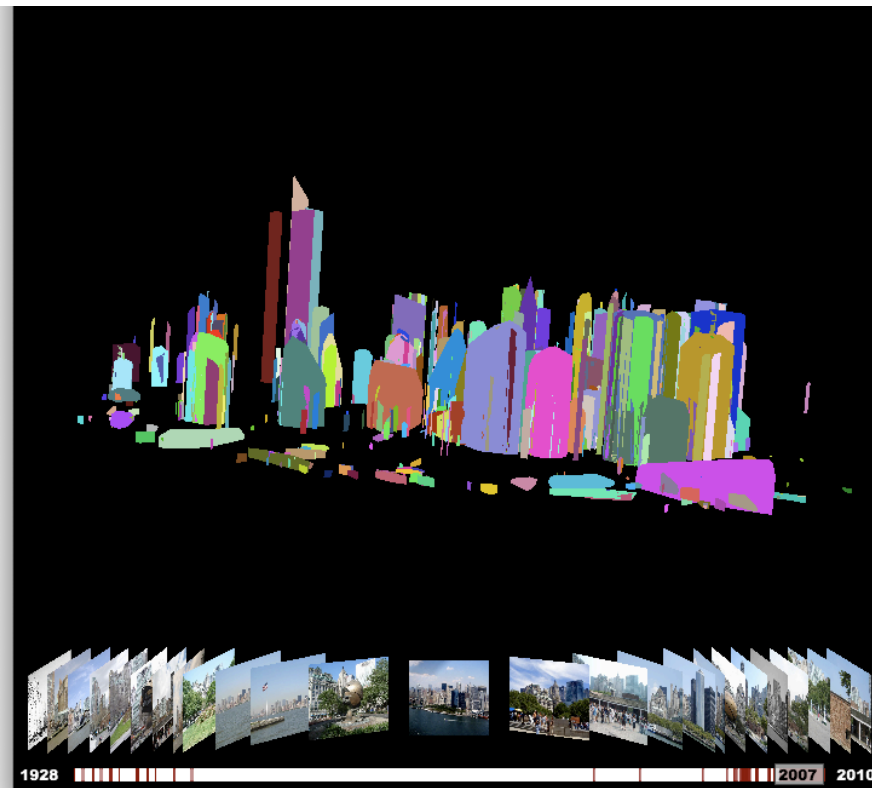
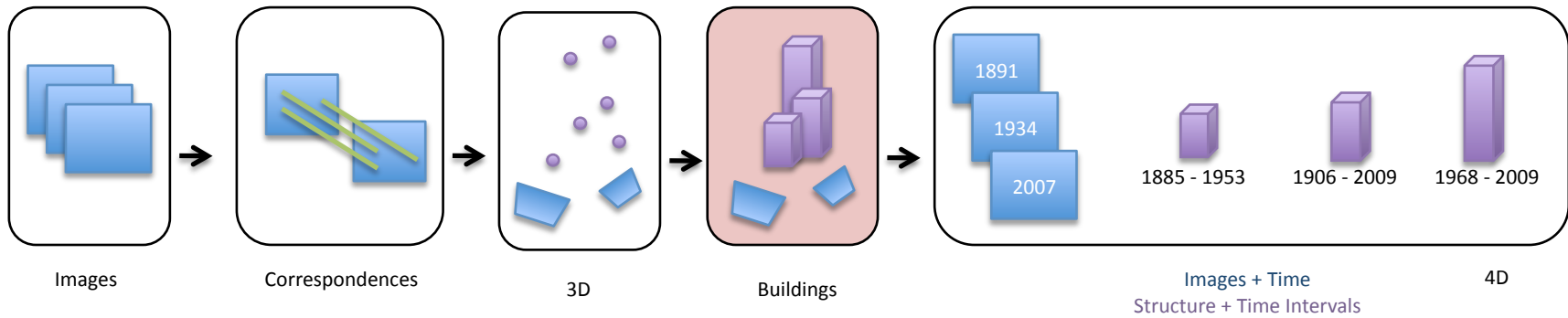
Overview



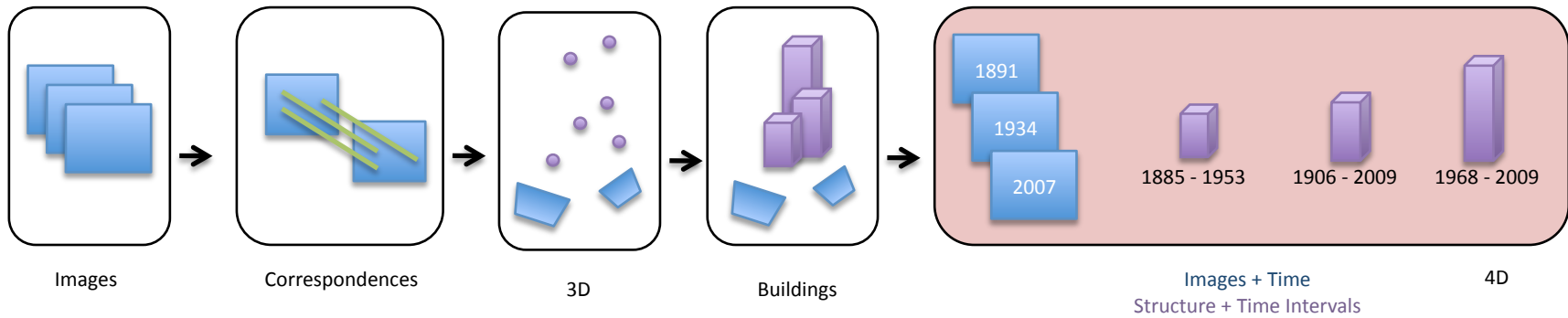
Overview



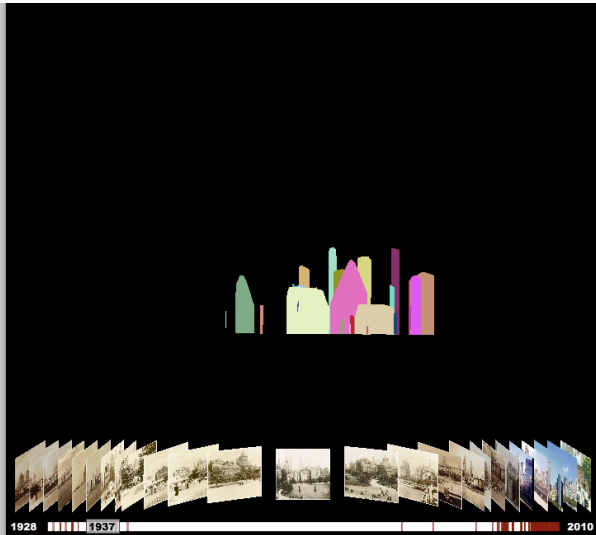
Overview



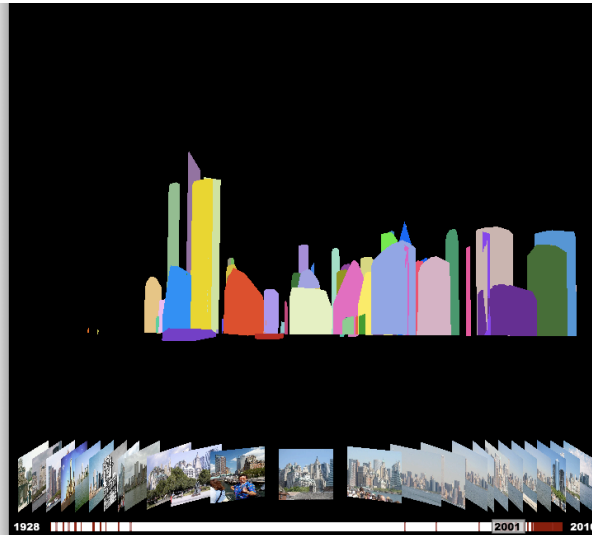
Overview



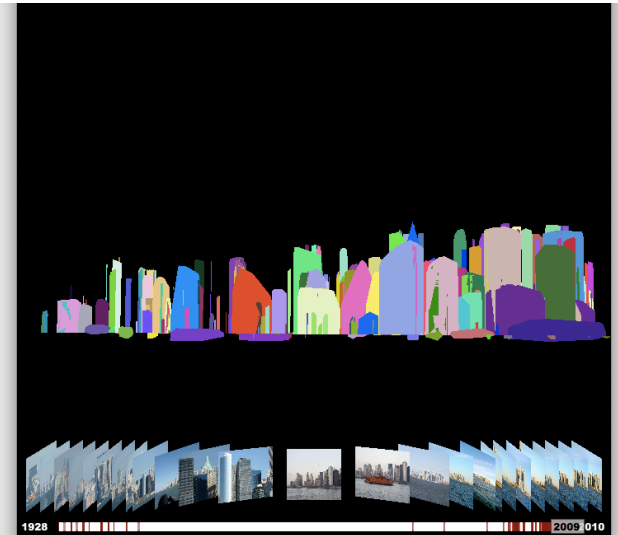
1937



2001



2009

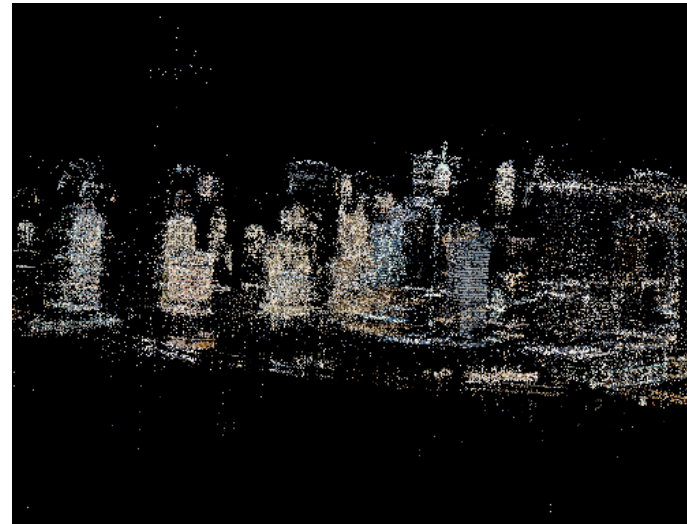


3D Reconstruction

Images

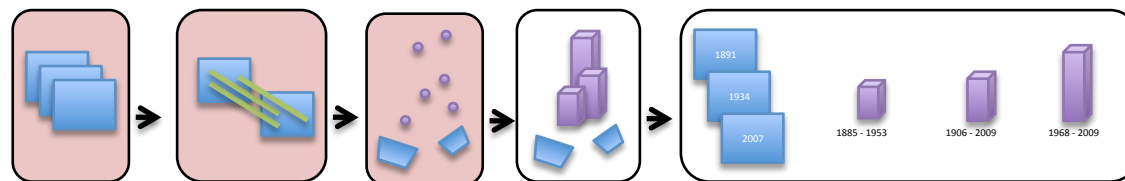


3D Point Cloud



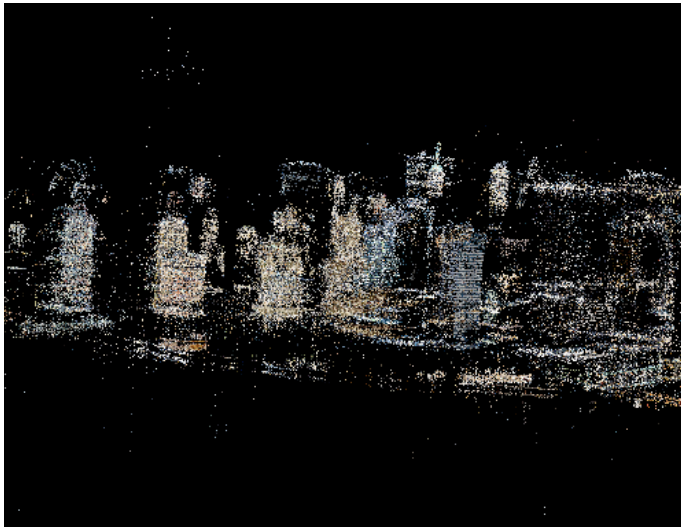
Structure from Motion

Bundler Software by Noah Snavely
(*Snavely et al SIGGRAPH 2006*)

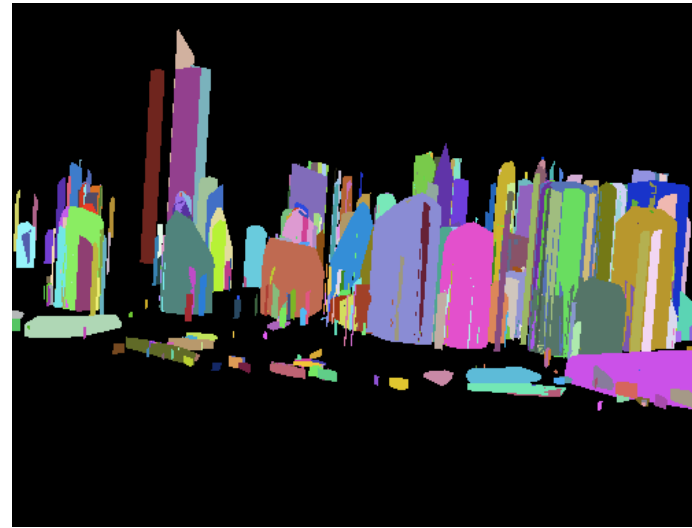


Grouping Points into Buildings

3D Point Cloud



3D Buildings



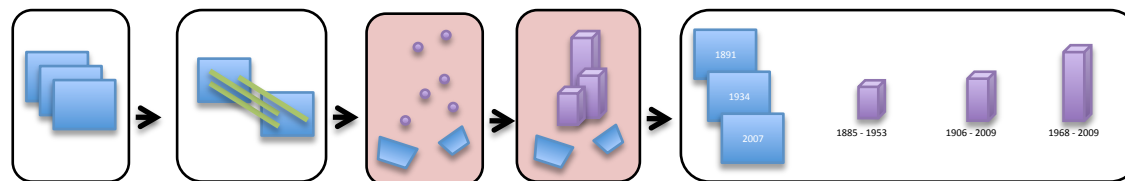
Point Grouping

Group points according to both:

- Distance $<$ threshold in 3D
- Observed simultaneously in 1+ images

Building Geometry

- Convex hull of each group
- Fit ground plane to camera centers
- Extend convex hulls to ground



3D Reconstruction: Points vs. Objects

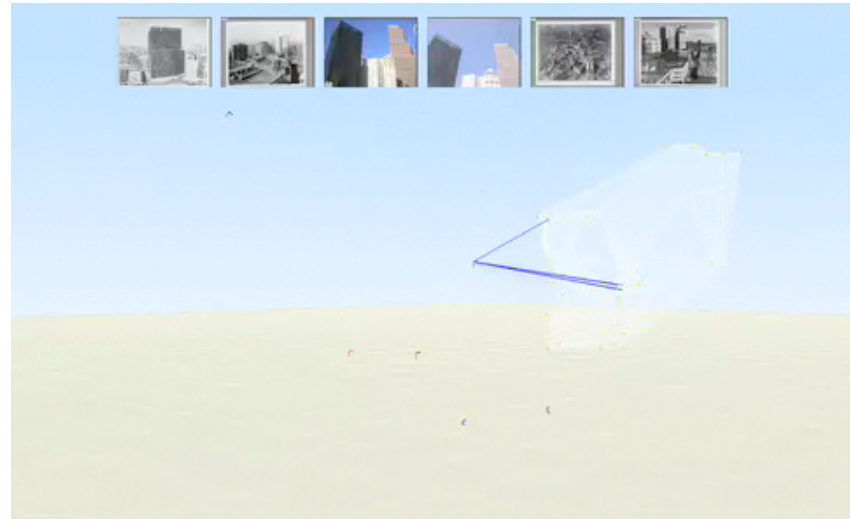
Lower Manhattan



454 images 83,860 points 960 Buildings 1928-2010

Reasoning About Time: From Constraint Satisfaction...

Schindler et al. CVPR 2007.
Inferring Temporal Order of
Images from 3D Structure.



- Key Idea: Visibility of 3D points constrains image ordering
- Disadvantage: Only relative image ordering
- Disadvantage: Perfect observations required
 - rules out fully automatic reconstruction, inherently noisy

...to Probabilistic Temporal Inference

Maximize $P(T|Z, X)$

T = time parameters

Z = observations

X = scene geometry

$$P(T|Z, X) \propto P(Z|T, X)P(T)$$



Observation Probability

Visibility Reasoning



Noisy Building
Observations



Image Date Prior



"Circa 1910"



"Undated"

Uncertain Dates

P(T) - Image Date Prior

Date Sources:

EXIF tags

database annotations

Historical dates often uncertain

Undated: $P(t_j) = \text{Uniform}$

Otherwise: $P(t_j) = N(\mu, \sigma^2)$

↑
Estimated Date

↑
Uncertainty



"May 1970"



"Undated"



"Circa 1910"

Observation Probability Model

$$P(Z|T, X) = \prod_{z_{ij} \in Z} P(z_{ij}|T, X)$$

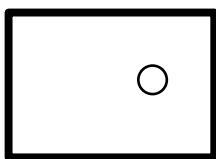
Time Parameters Hypothesized

Geometry Known

Binary variable:

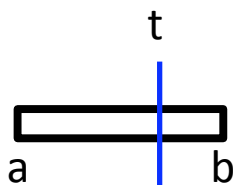
Was object i observed in image j ?

X
only



Viewability: Is object i within the field of view of camera j ?

T
only



Existence: Did object i exist at the time image j was captured?

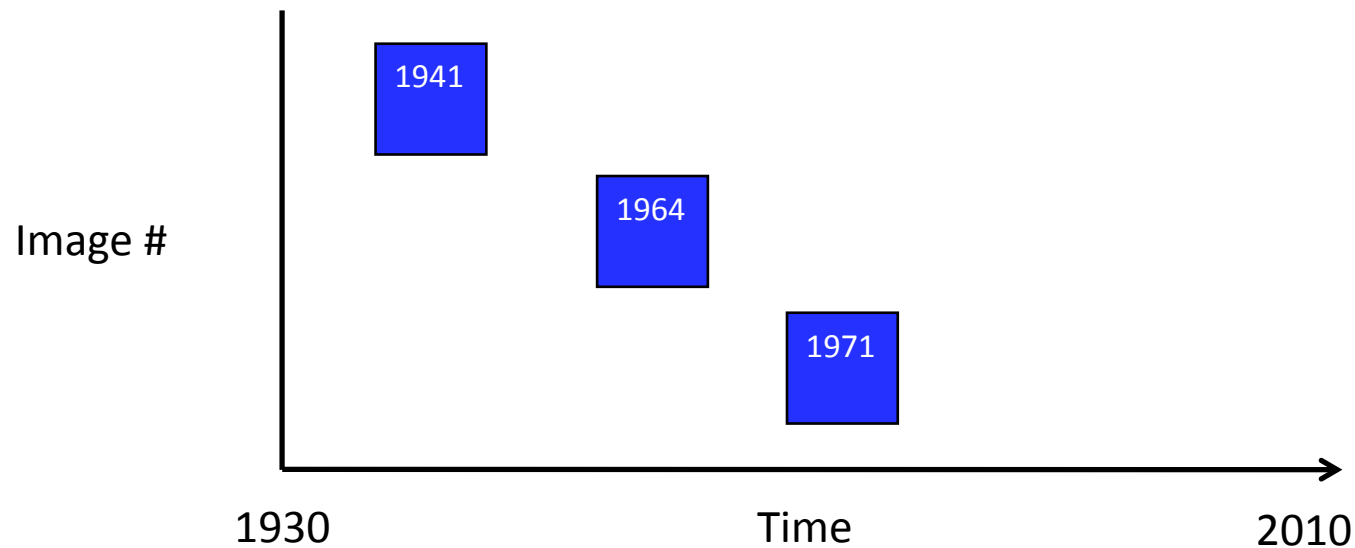
X & T



Occlusion: Is object i occluded by some other object(s) in image j ?

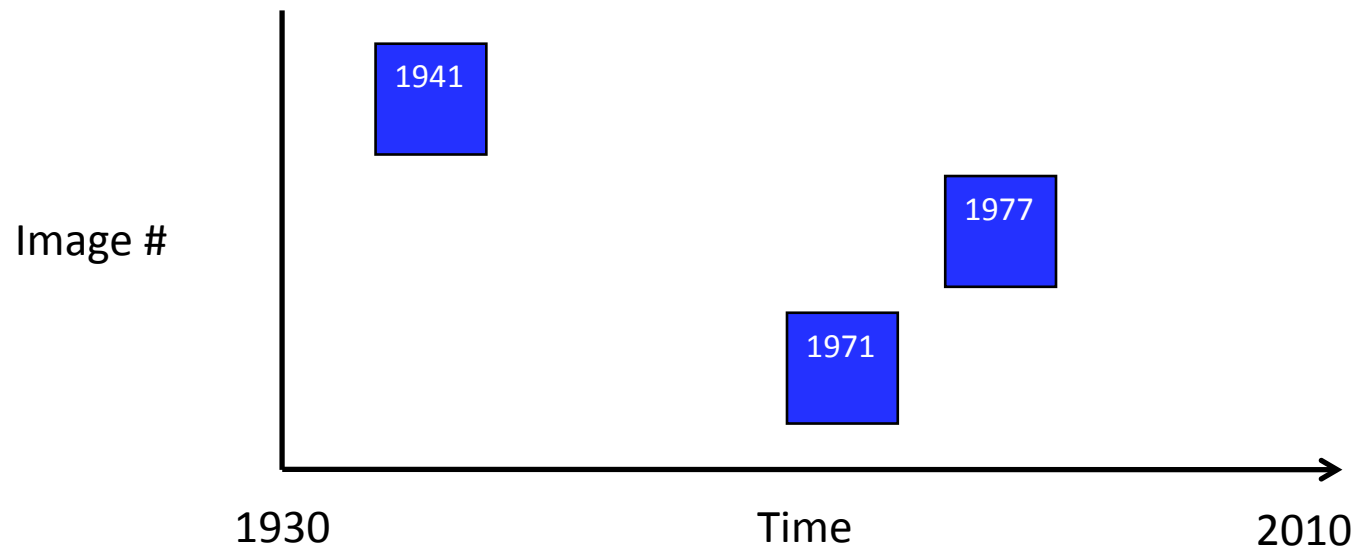
Optimizing Temporal Parameters

- Markov Chain Monte Carlo (MCMC) Sampling
 - Propose to move an image date
 - Analytically solve building date intervals
 - Evaluate $P(T|Z,X)$
 - Accept or reject move



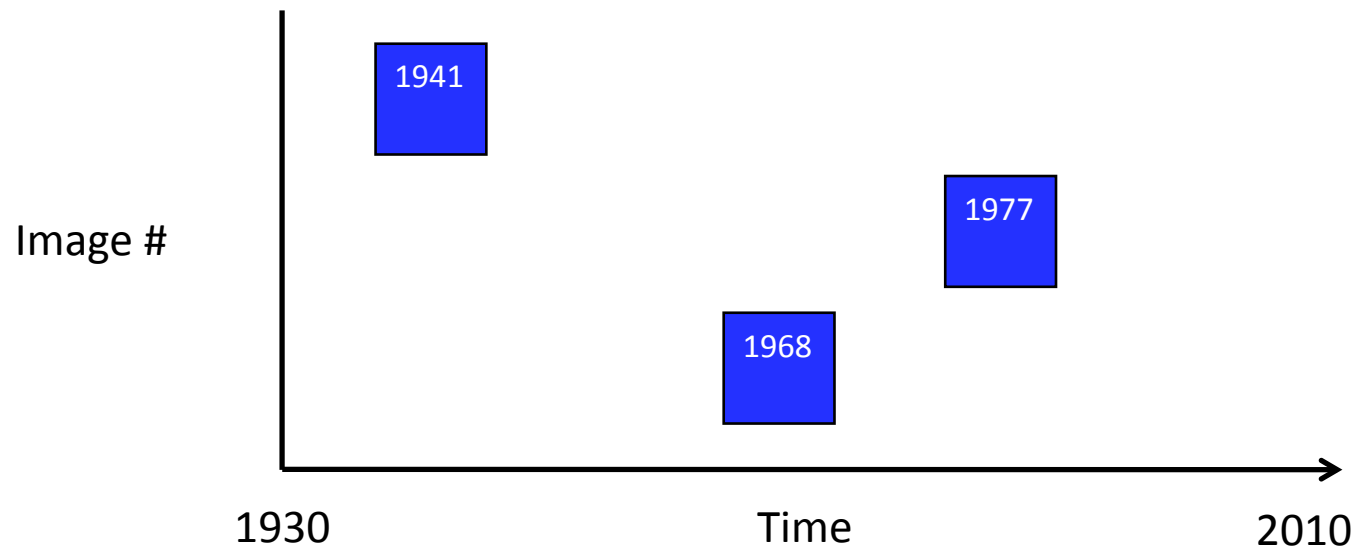
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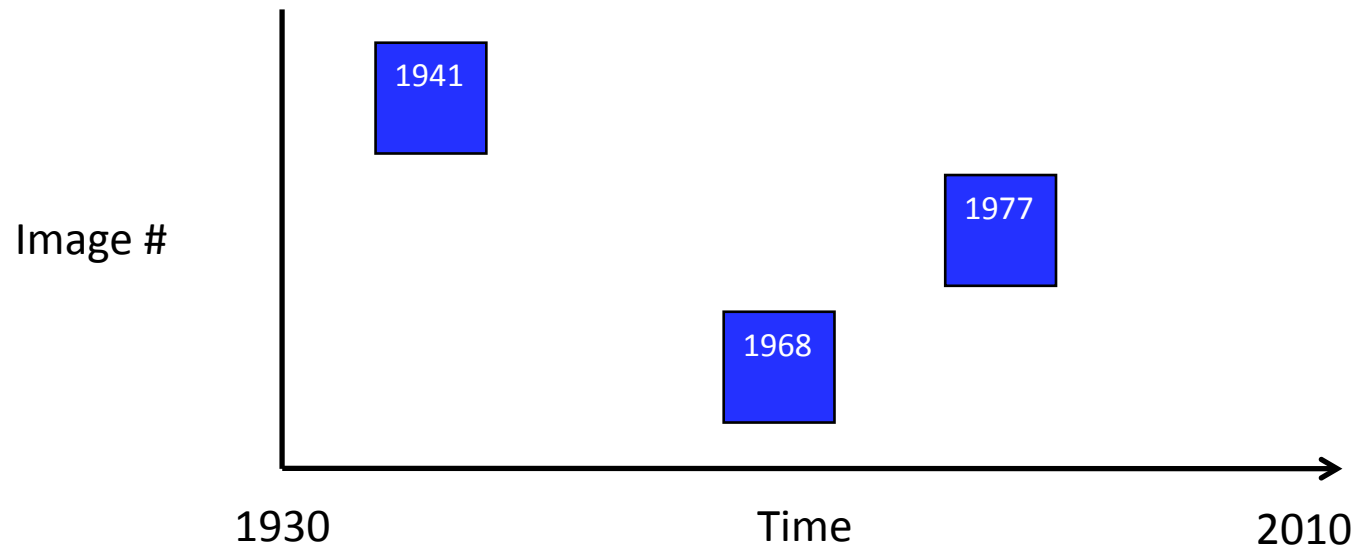
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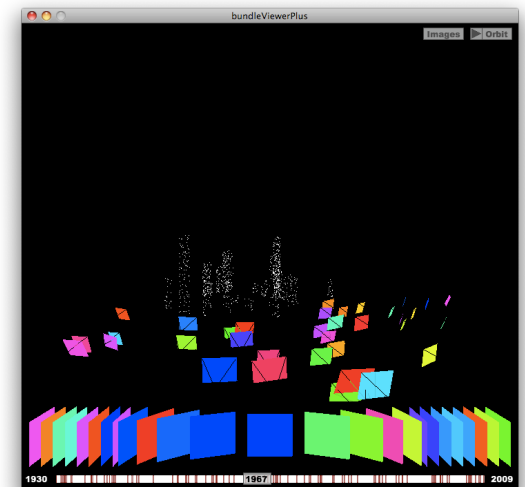
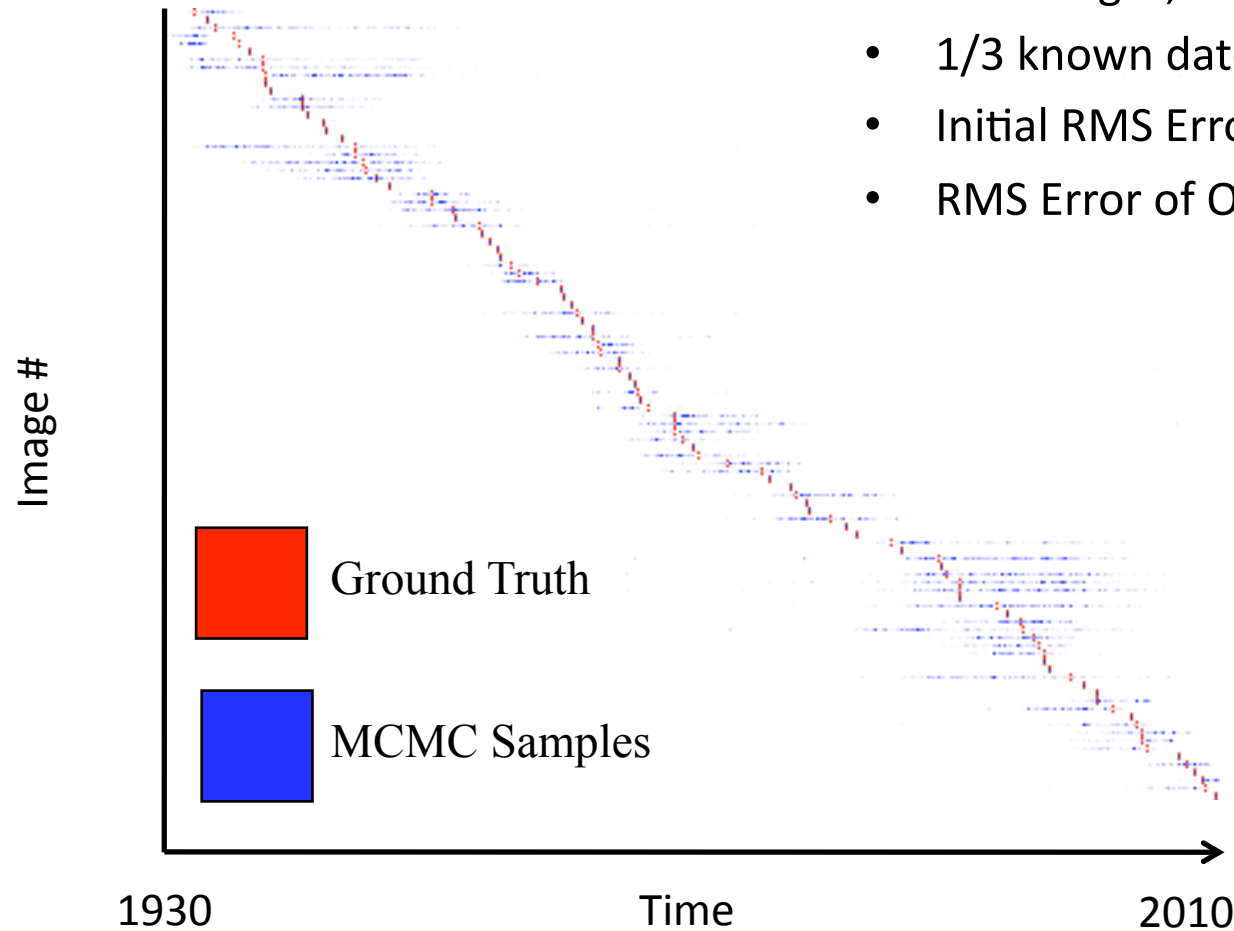
80,000 samples = 1.3 hours
for scene with 100 images



Results: Full Temporal Optimization

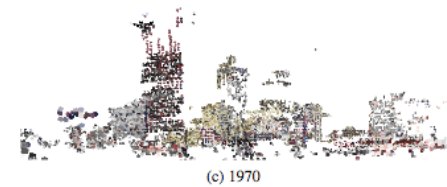
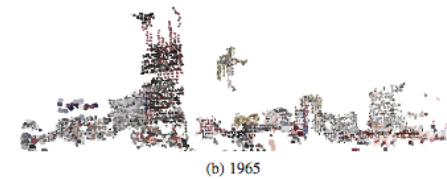
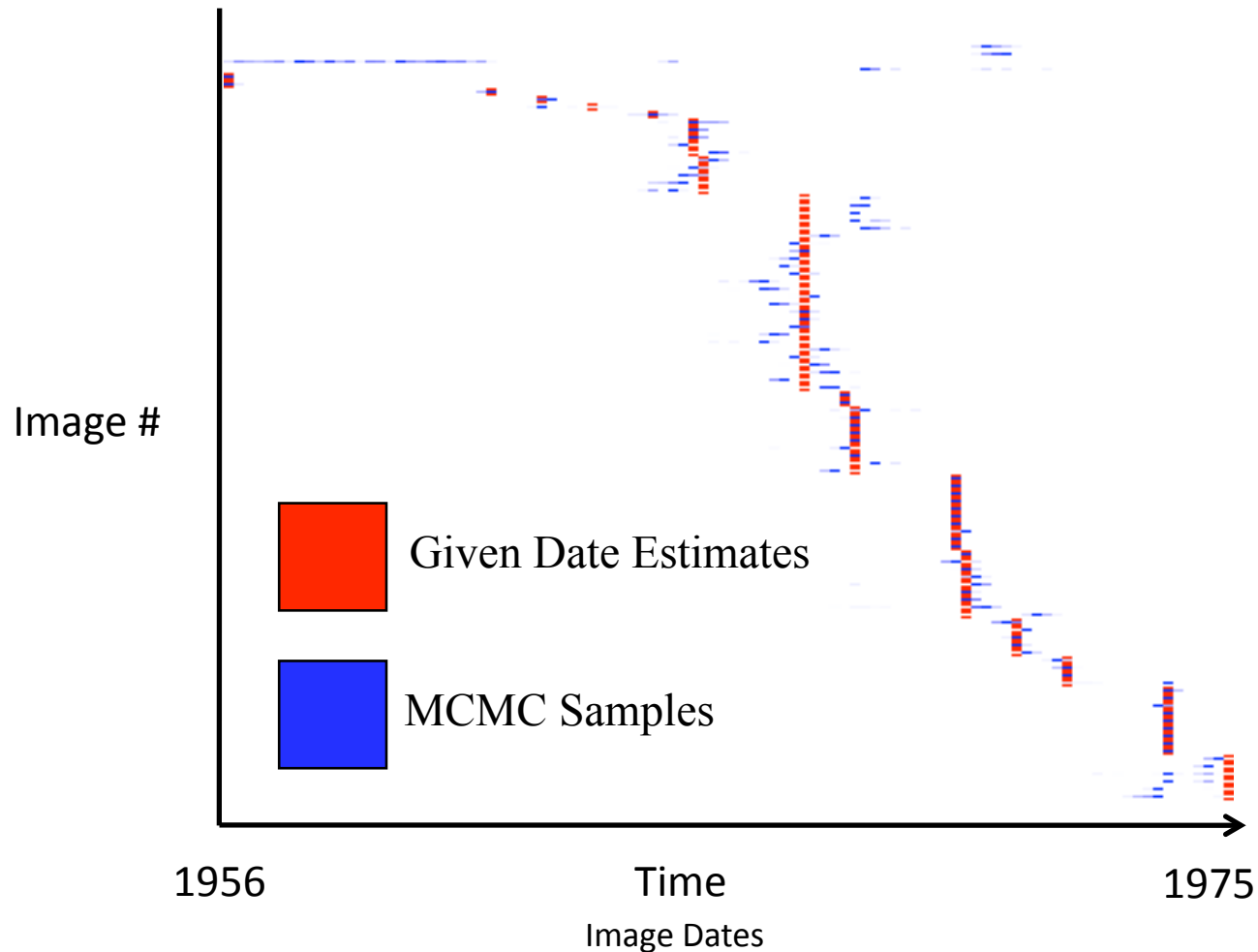
Synthetic Scene

- 100 images, 30 buildings, 80 years
- 1/3 known date, 1/3 “circa”, 1/3 unknown
- Initial RMS Error: 19.31 years
- RMS Error of Our Solution: **2.87 years**



Results: Full Temporal Optimization

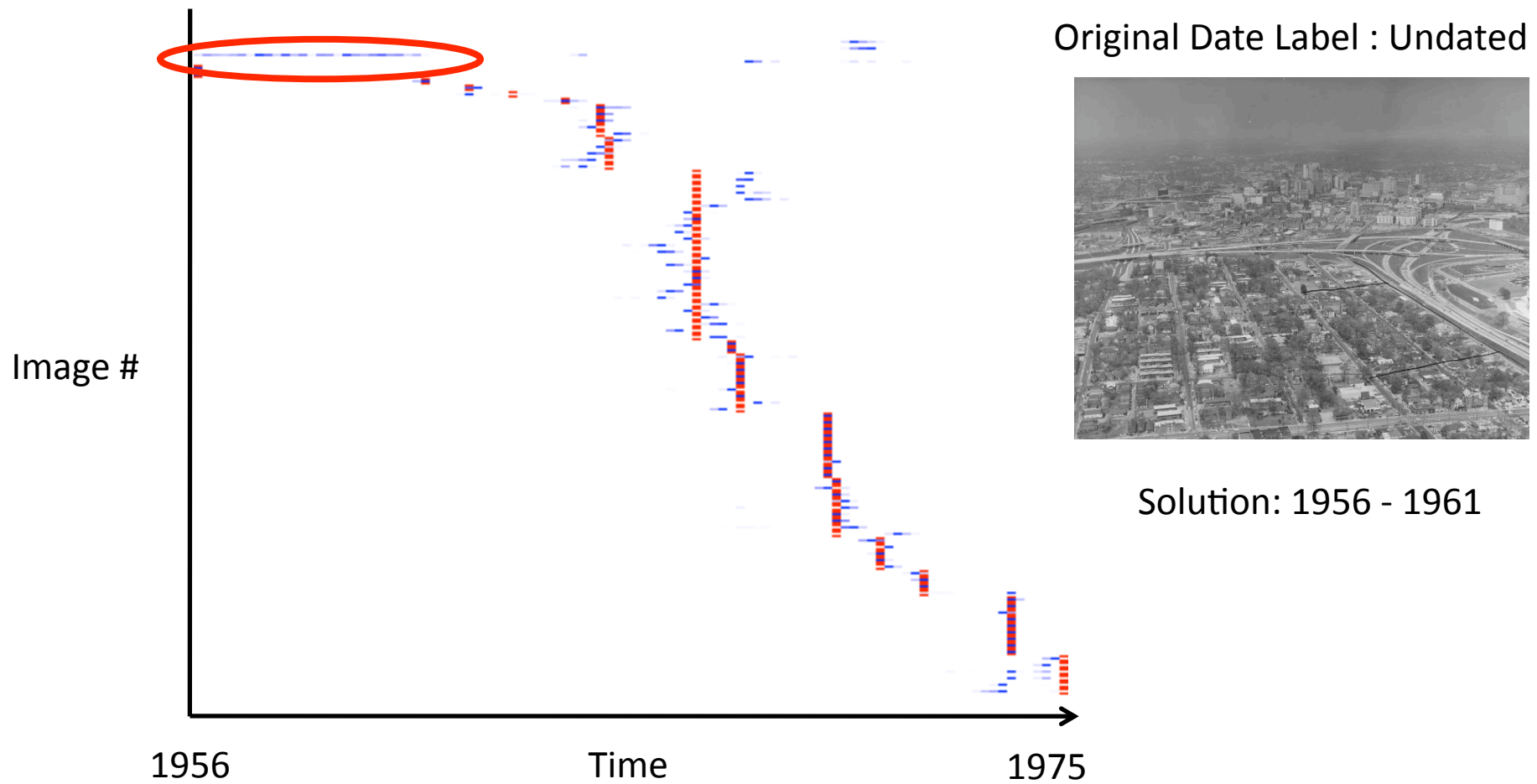
Downtown Atlanta (102 Images)



Building Date Intervals

Results: Full Temporal Optimization

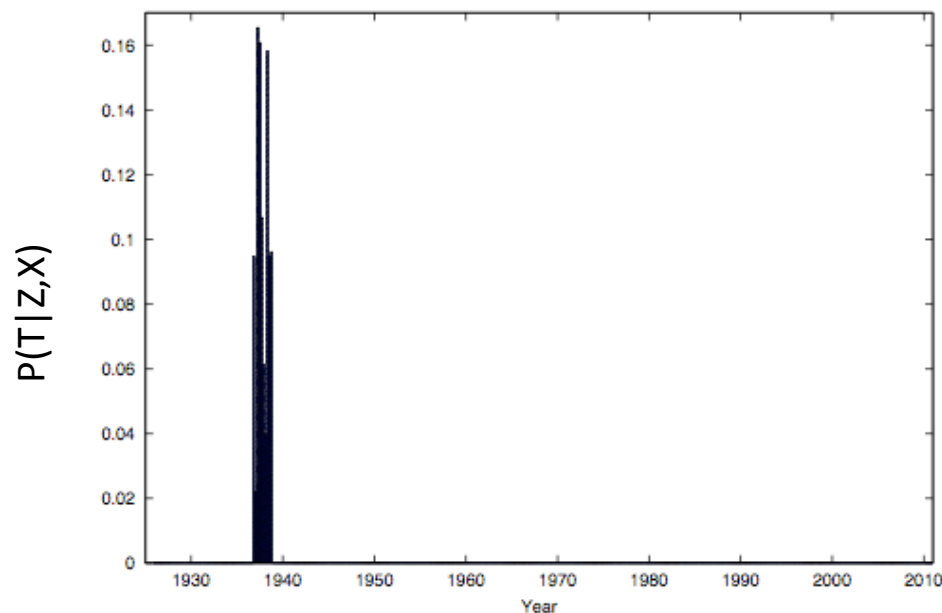
Downtown Atlanta



Results: Leave-One-Out Image Dating

Lower Manhattan

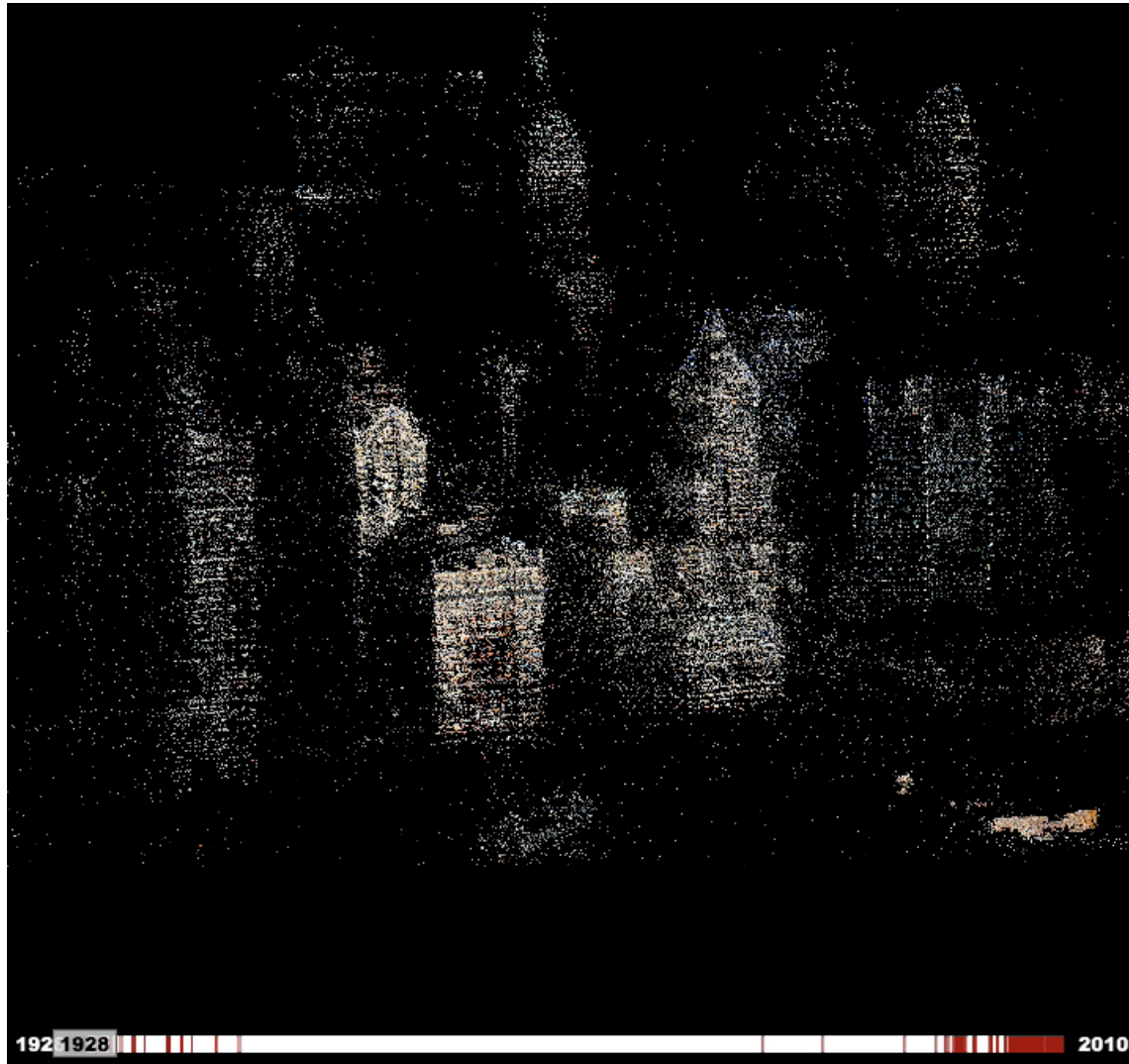
Error < 5 years for 48% images



Estimated Date: 1937.2

Given Date: 1935

Results: Building Date Intervals



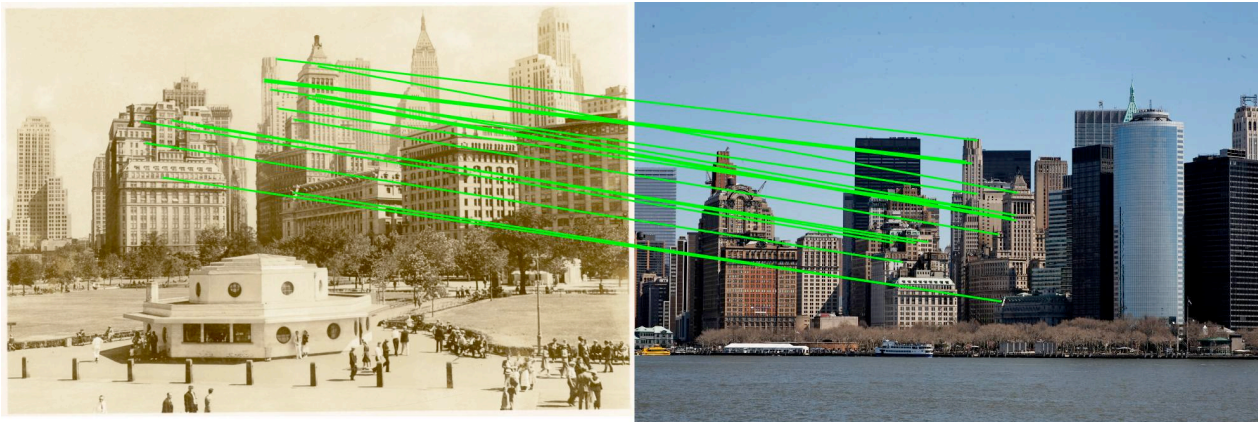
Conclusions and Future Work

- Automatic, probabilistic temporal inference method
- Results for synthetic scene and 2 challenging real data sets

Future Work:

Feature correspondence across time challenging

- Find more data, densely sampled in space and time
- Design time-invariant features



Thank you!