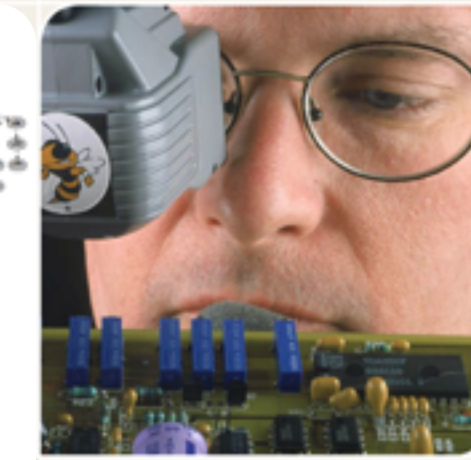


Optimization in Factor Graphs for Fast and Scalable 3D Reconstruction and Mapping

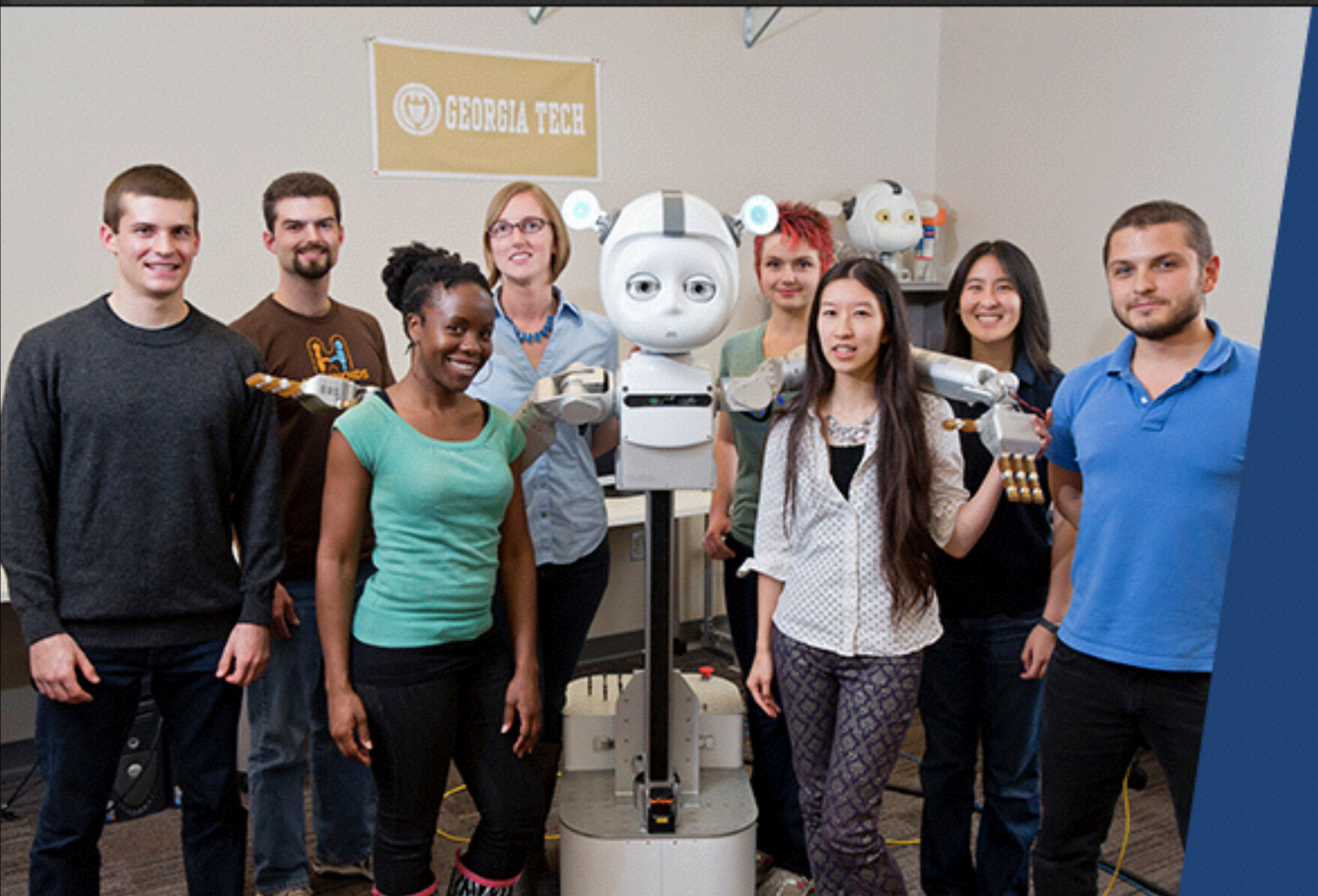
Frank Dellaert, Robotics & Intelligent Machines @ Georgia Tech

Georgia Tech College of Computing

Georgia Tech

Ph.D. Program in Robotics

Home | Program Overview | Program of Study | Admission Requirements | FAQs | Resources | Contact Us

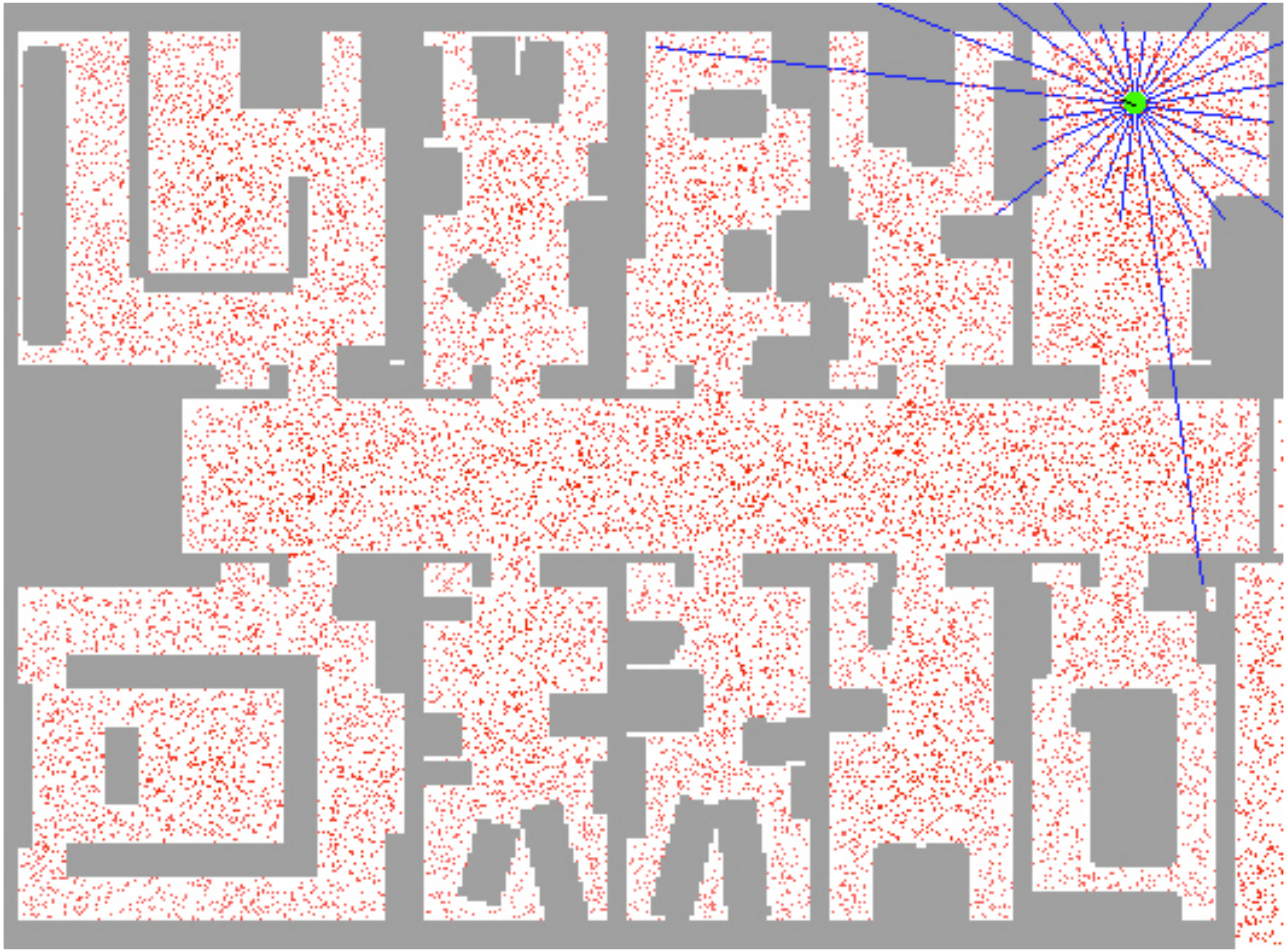


UNLIKE ANY OTHER

Offered jointly by the College of Computing and the College of Engineering, Georgia Tech's Ph.D. Program in Robotics is the first interdisciplinary robotics degree of its kind.

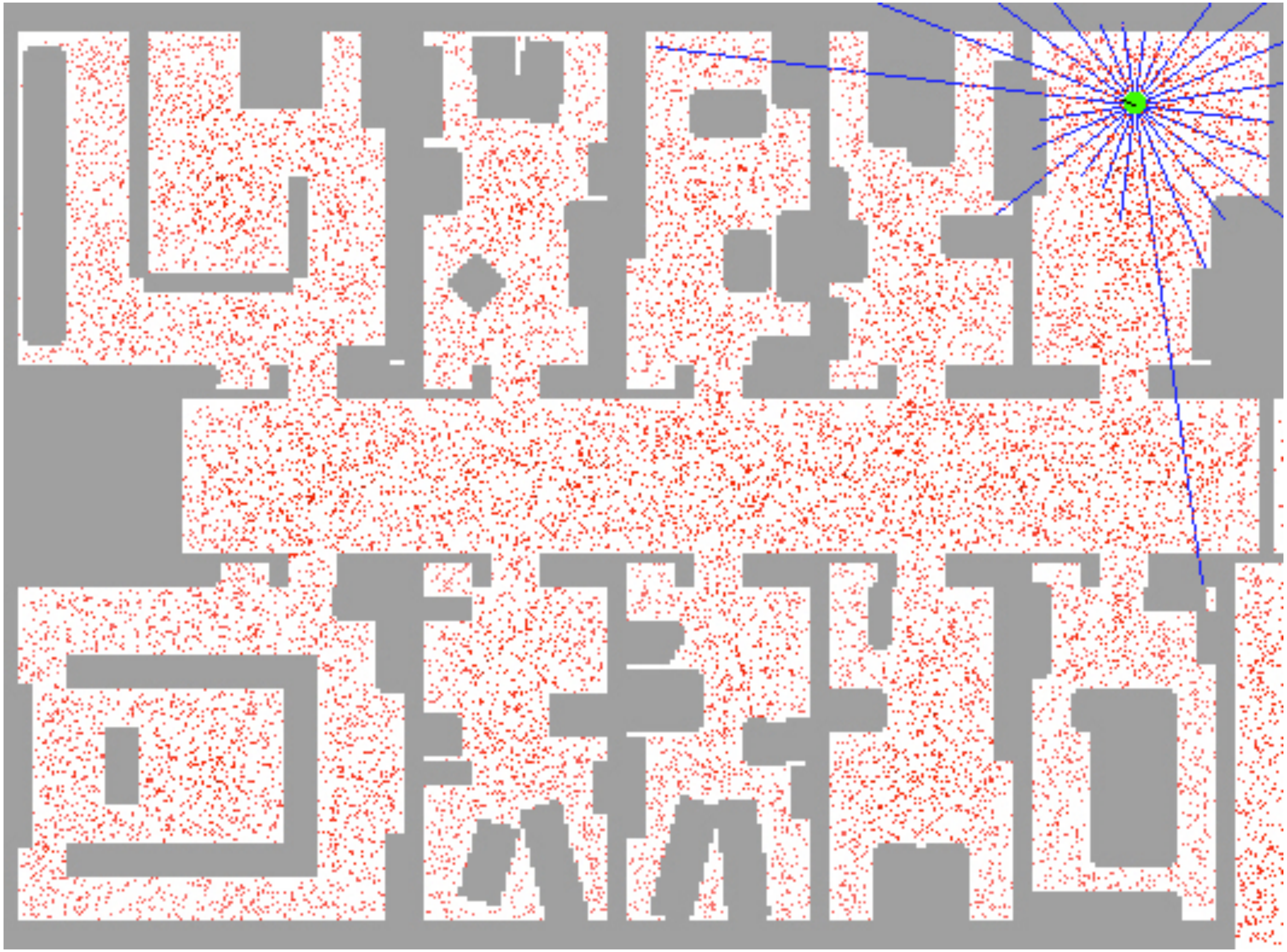
The next application deadline is December 15, 2014

Monte Carlo Localization



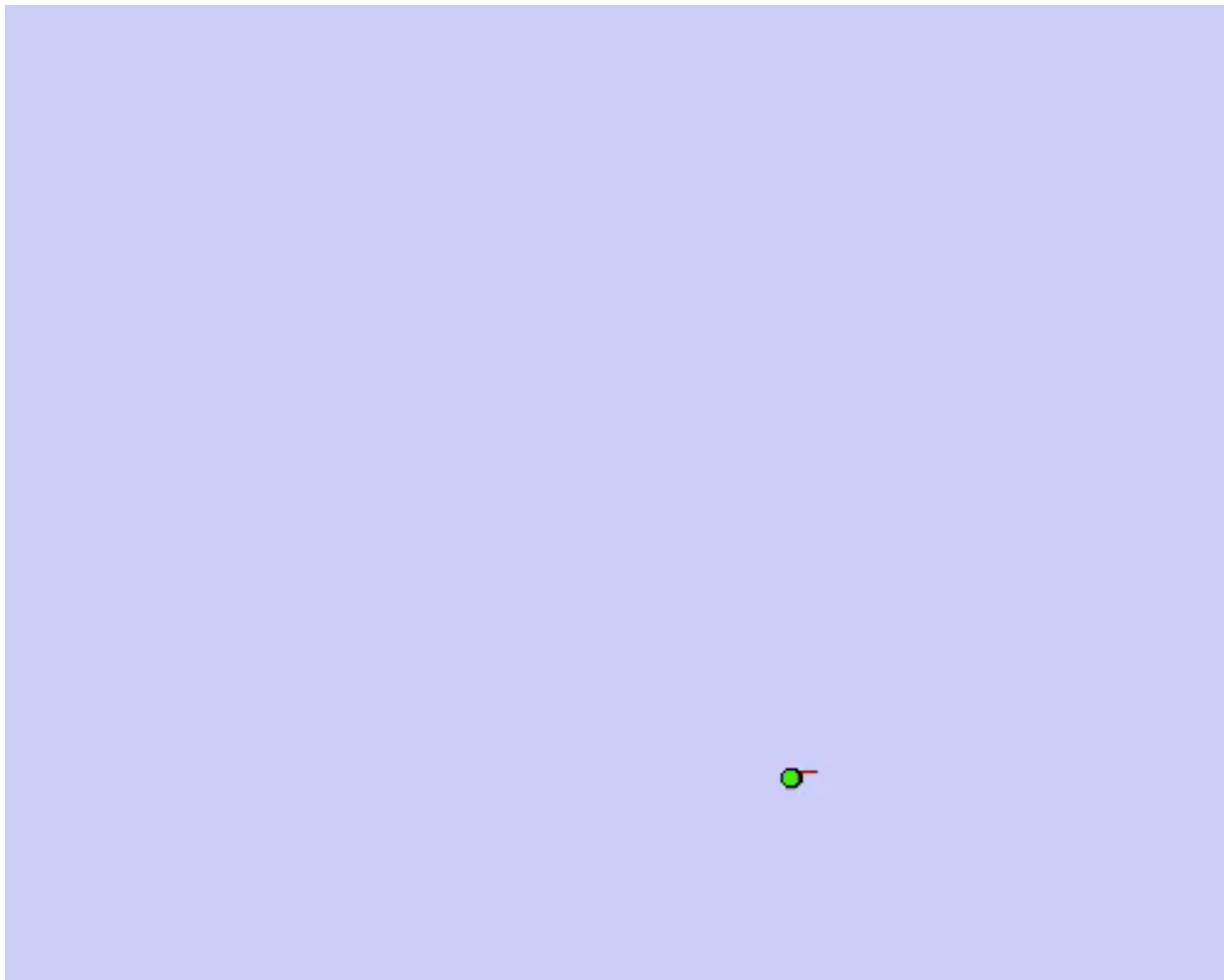
Dellaert, Fox, Burgard & Thrun, ICRA 1999

Monte Carlo Localization



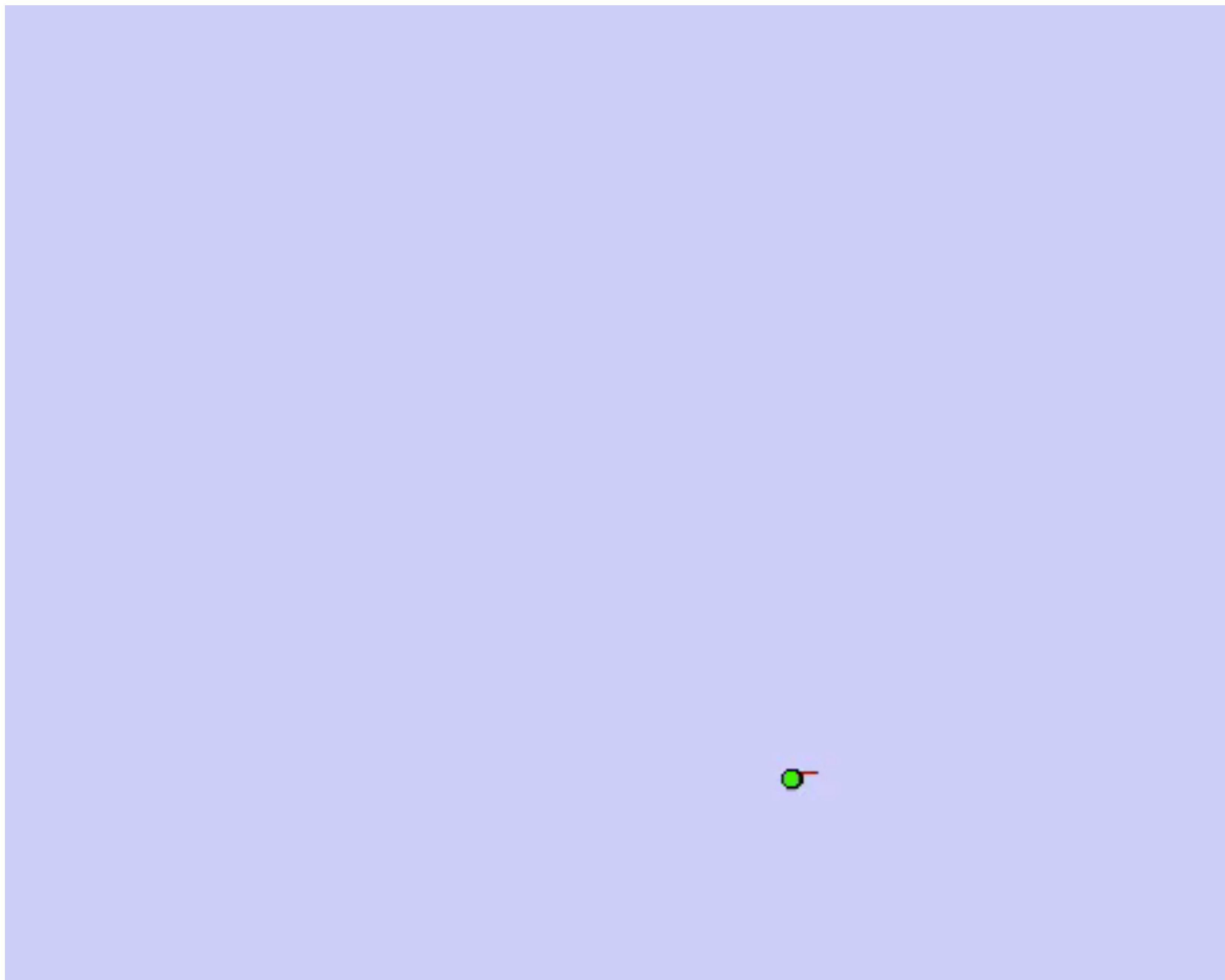
Dellaert, Fox, Burgard & Thrun, ICRA 1999

FastSLAM: Particle Filter on Trajectories



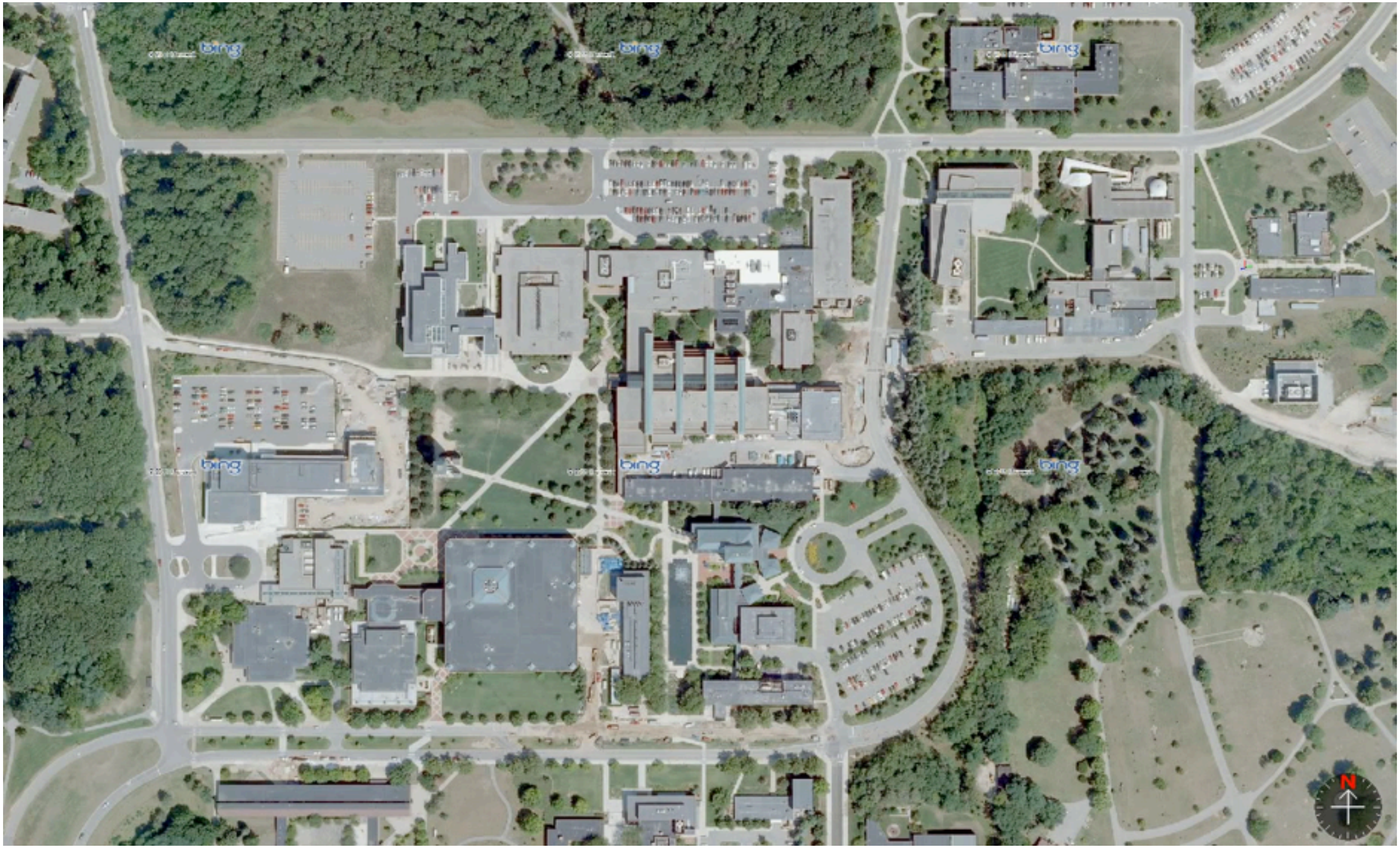
Montemerlo, Thrun, Koller, & Wegbreit, AAAI 2002

FastSLAM: Particle Filter on Trajectories



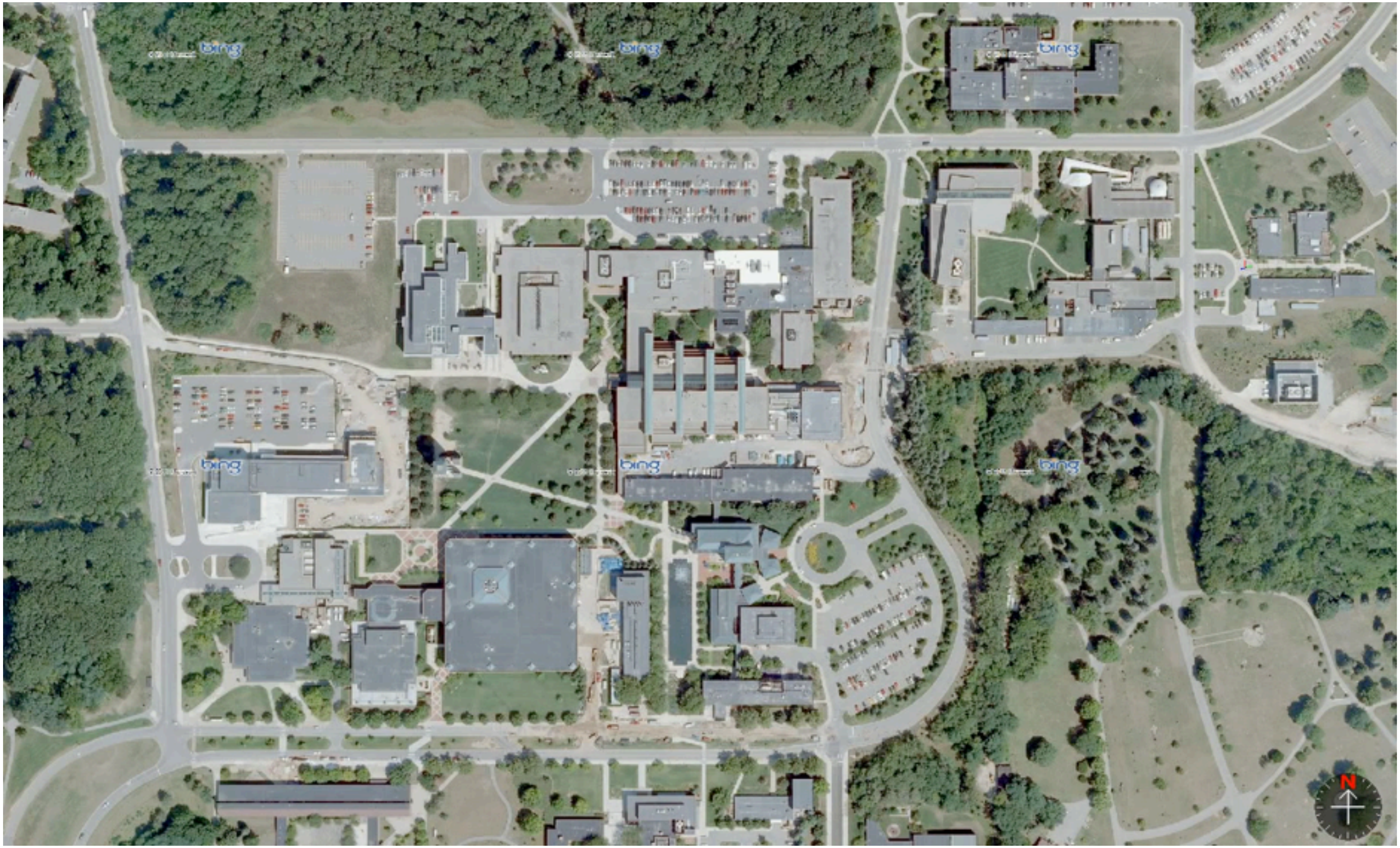
Montemerlo, Thrun, Koller, & Wegbreit, AAAI 2002

2013: Full 3D LIDAR Mapping



Data/Movie by Nick Carlevaris-Bianco and Ryan Eustice (U. Michigan)

2013: Full 3D LIDAR Mapping



Data/Movie by Nick Carlevaris-Bianco and Ryan Eustice (U. Michigan)

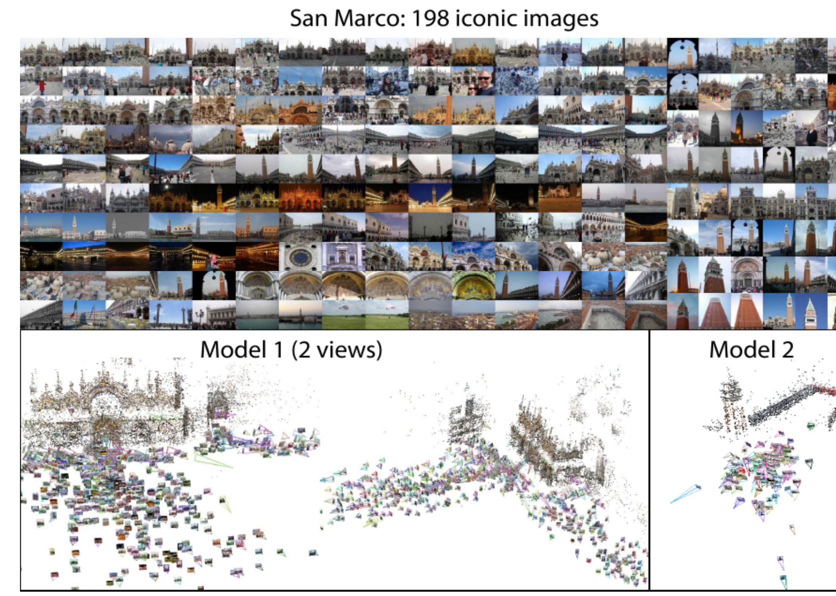
Large-Scale Structure from Motion

Photo Tourism

[Snavely et al. SIGGRAPH'06]

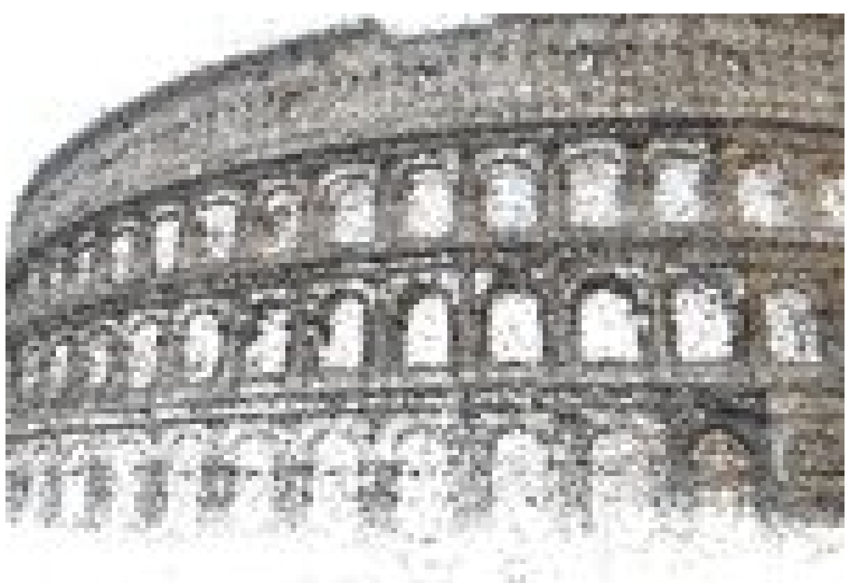
Photosynth

[Microsoft]



Iconic Scene Graphs

[Li et al. ECCV'08]

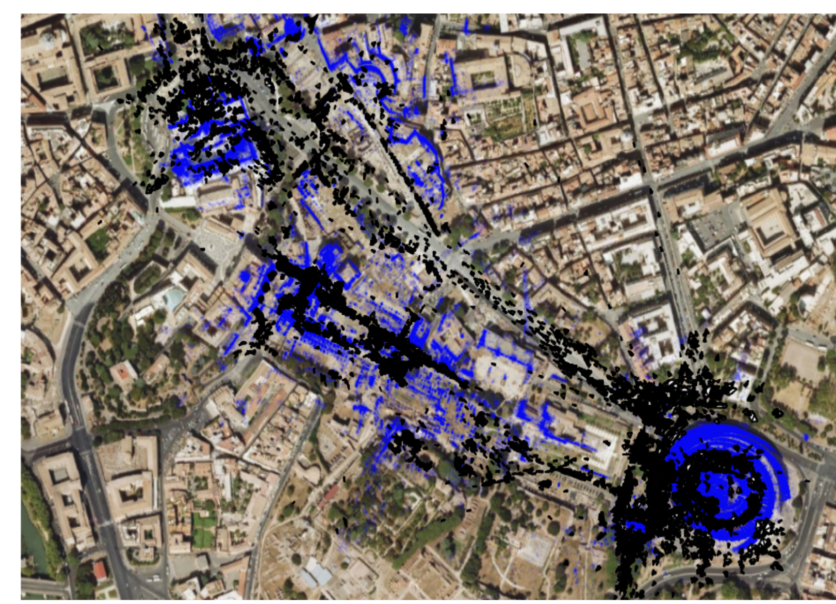


Build Rome in a Day

[Agarwal et al. ICCV'09]

Build Rome on a Cloudless Day

[Frahm et al. ECCV'10]

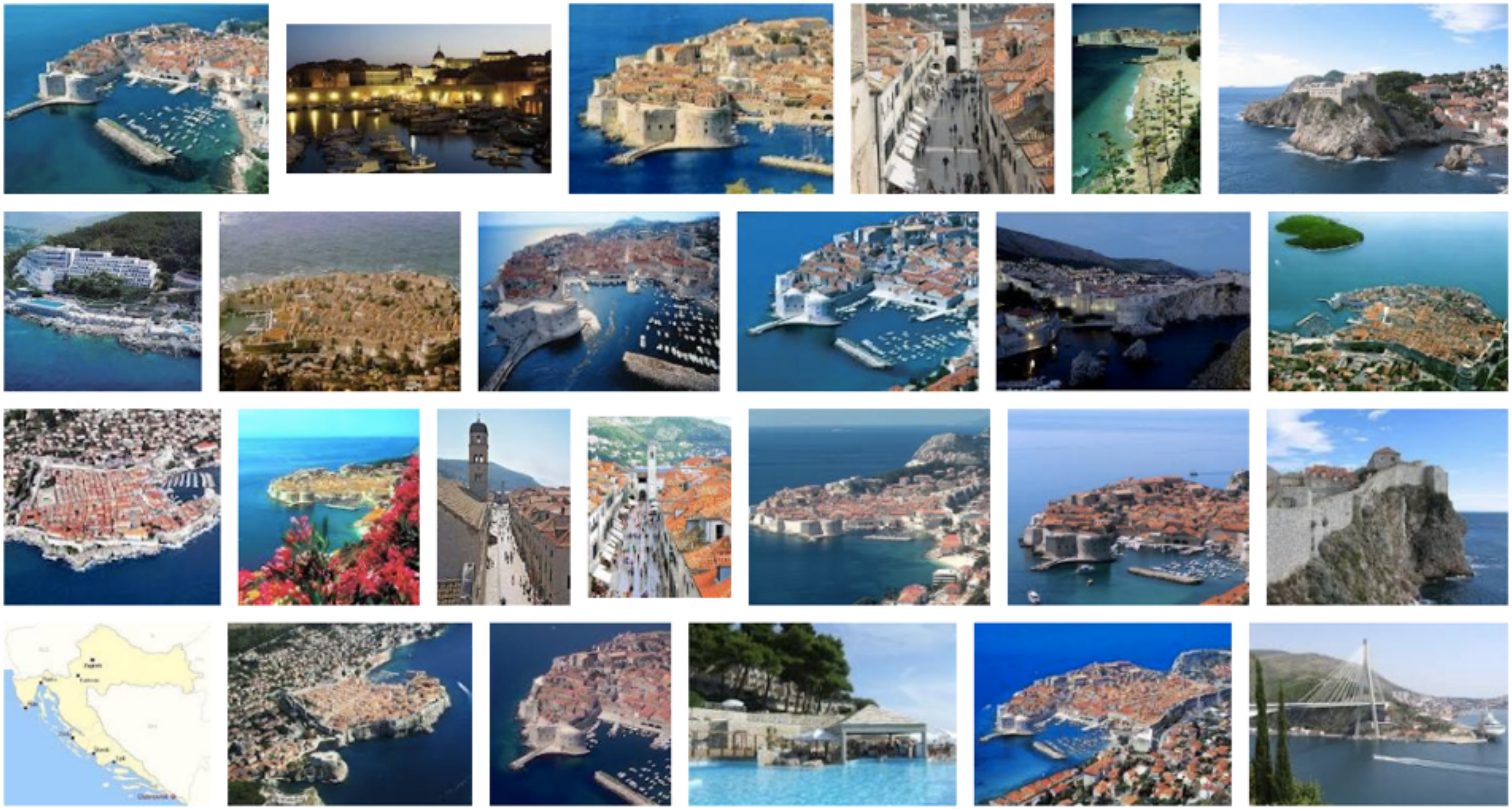


Discrete-Continuous Optim.

[Crandall et al. CVPR'11]

3D Models from Community Databases

- E.g., Google image search on “Dubrovnik”



3D Models from Community Databases

Agarwal, Snavely et al., University of Washington

http://grail.cs.washington.edu/rome/

5K images, 3.5M points, >10M factors

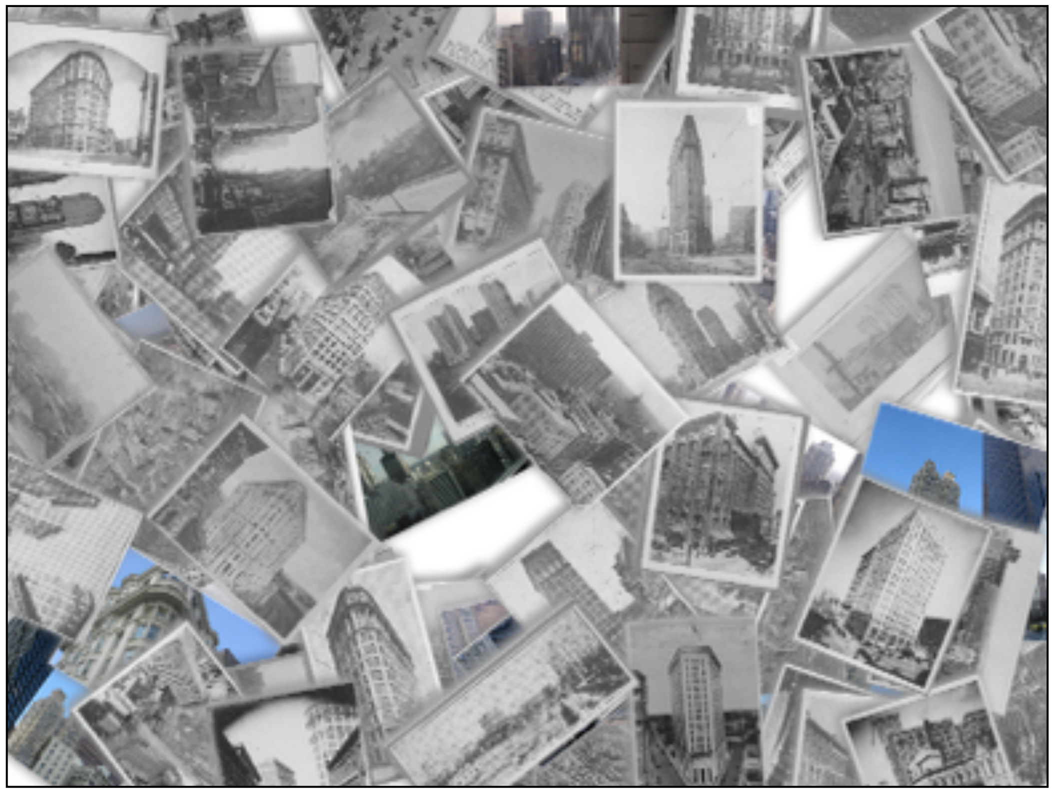
3D Models from Community Databases

Agarwal, Snavely et al., University of Washington

http://grail.cs.washington.edu/rome/

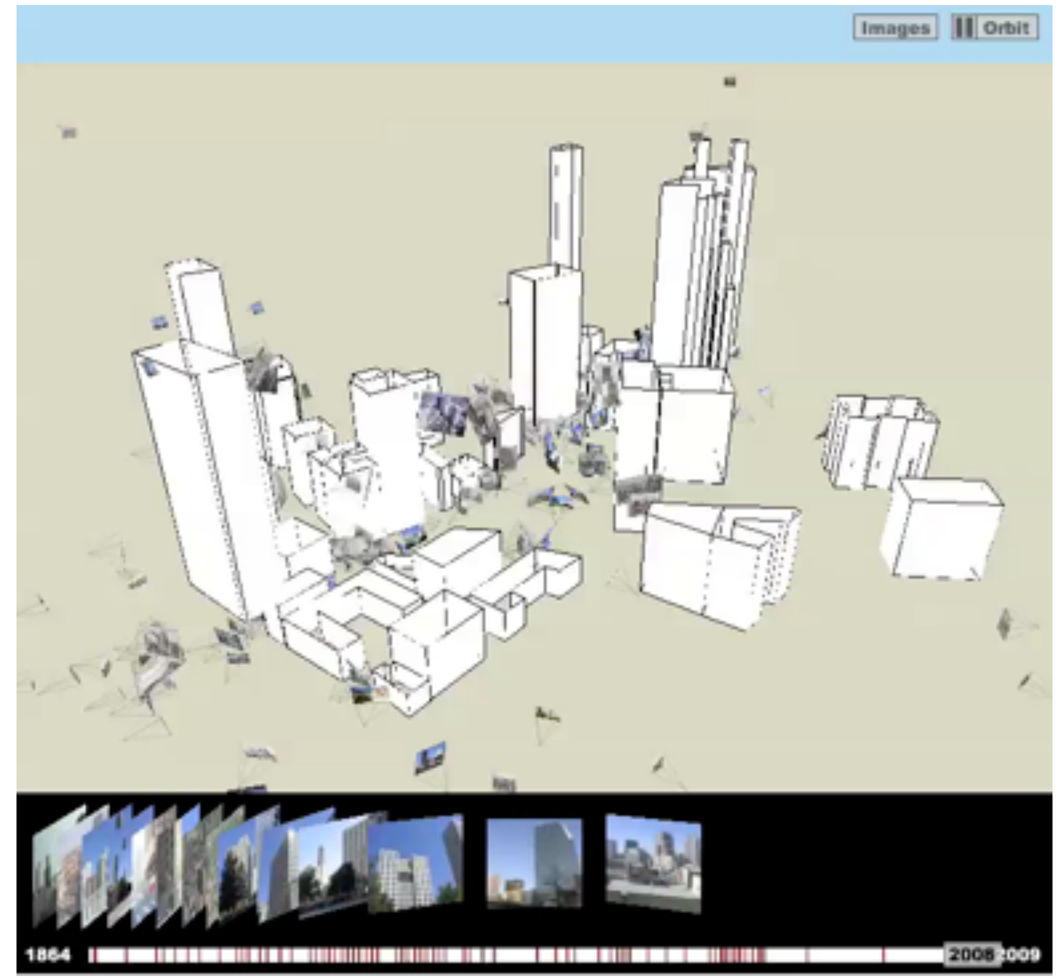
5K images, 3.5M points, >10M factors

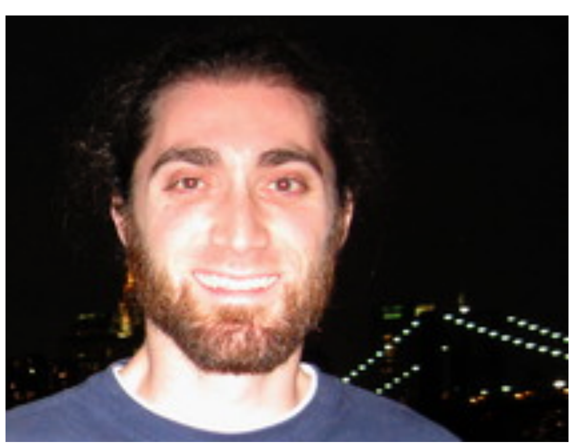
4D Reconstruction



Historical Image Collection

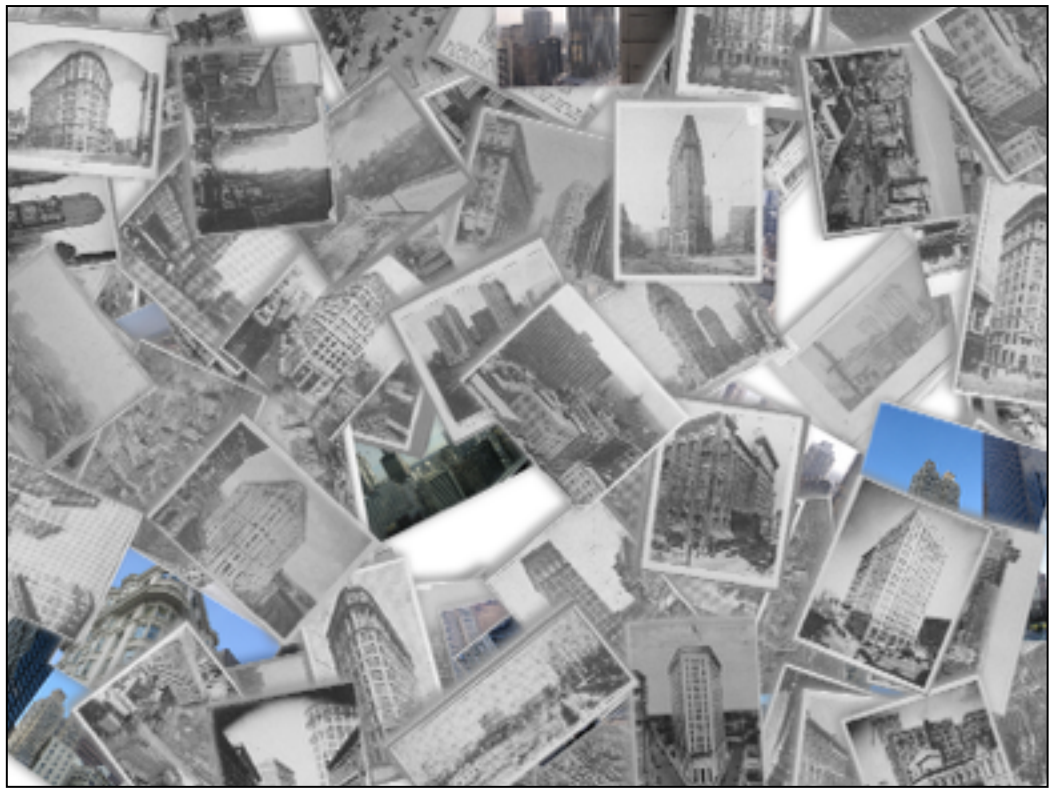
4D Cities: 3D + Time





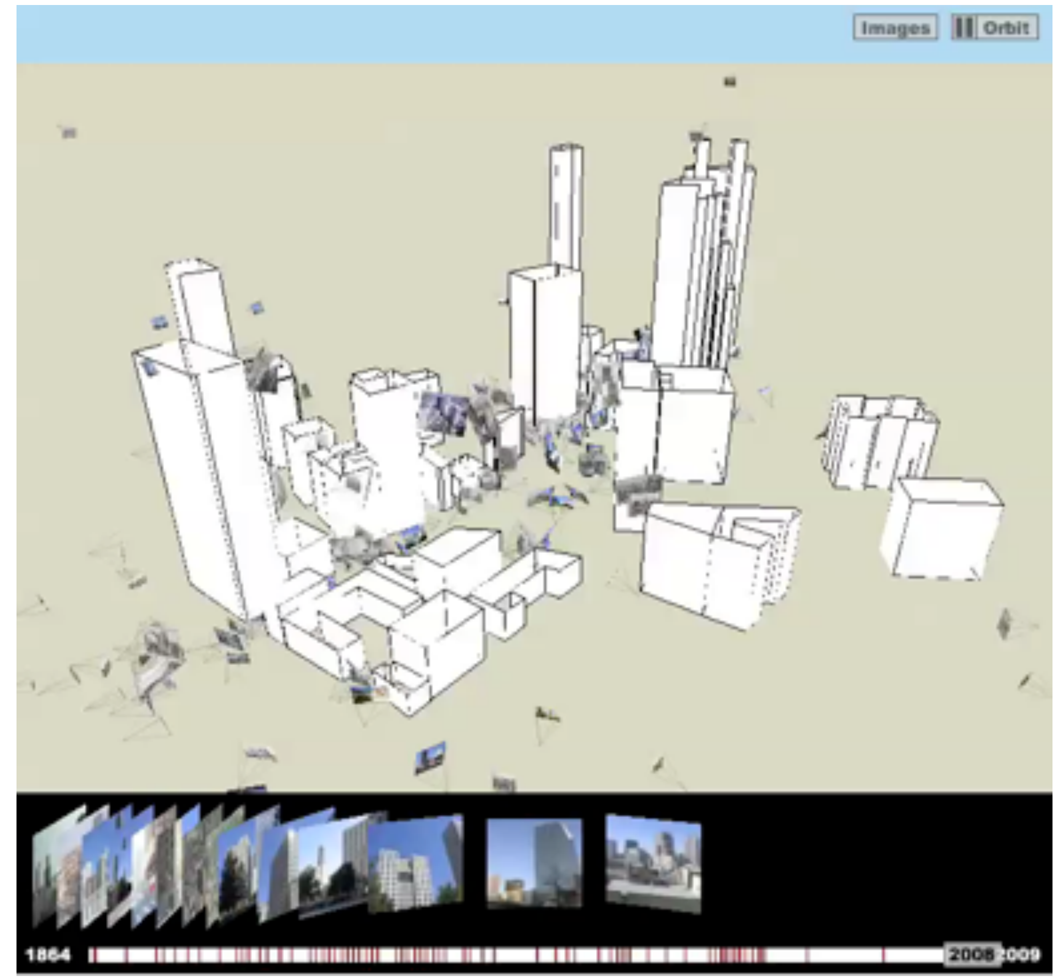
Grant Schindler

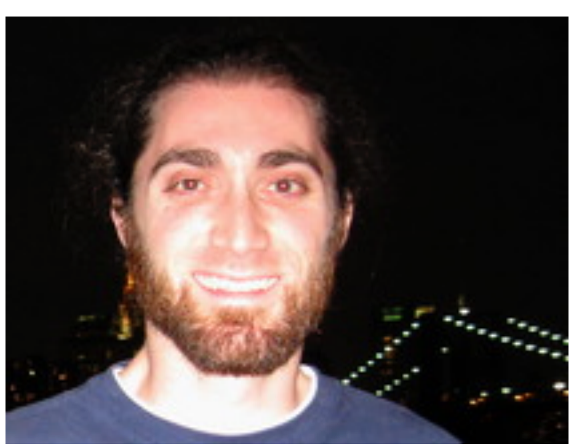
4D Reconstruction



Historical Image Collection

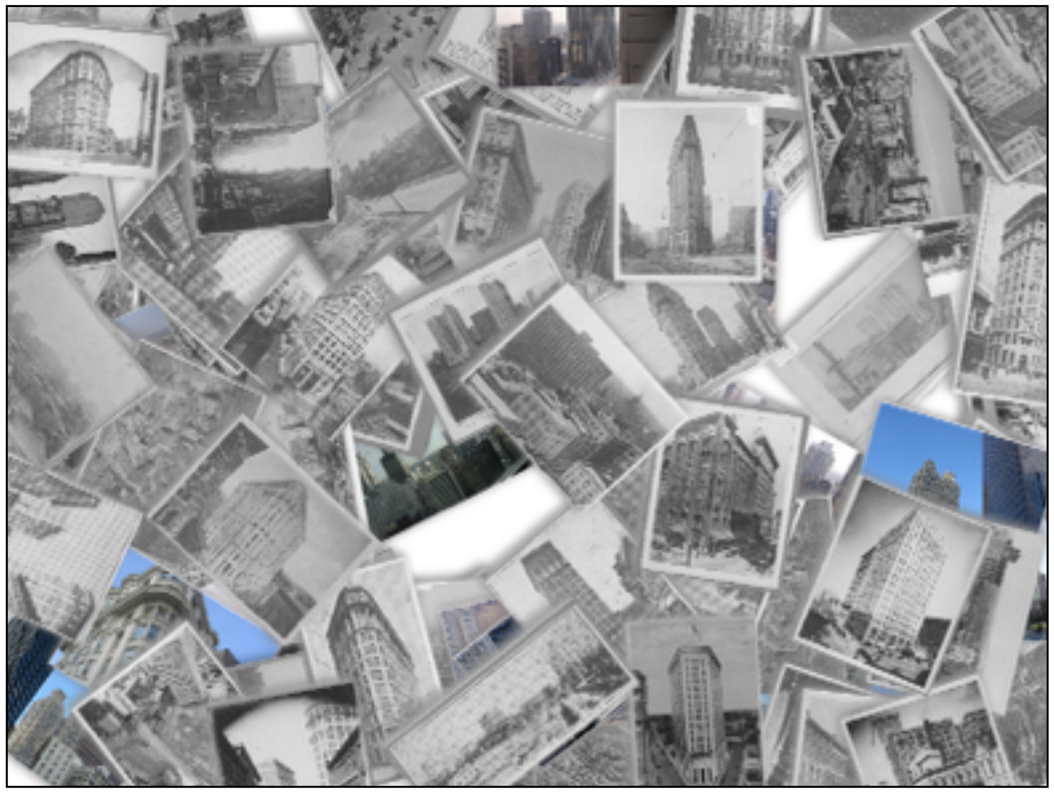
4D Cities: 3D + Time





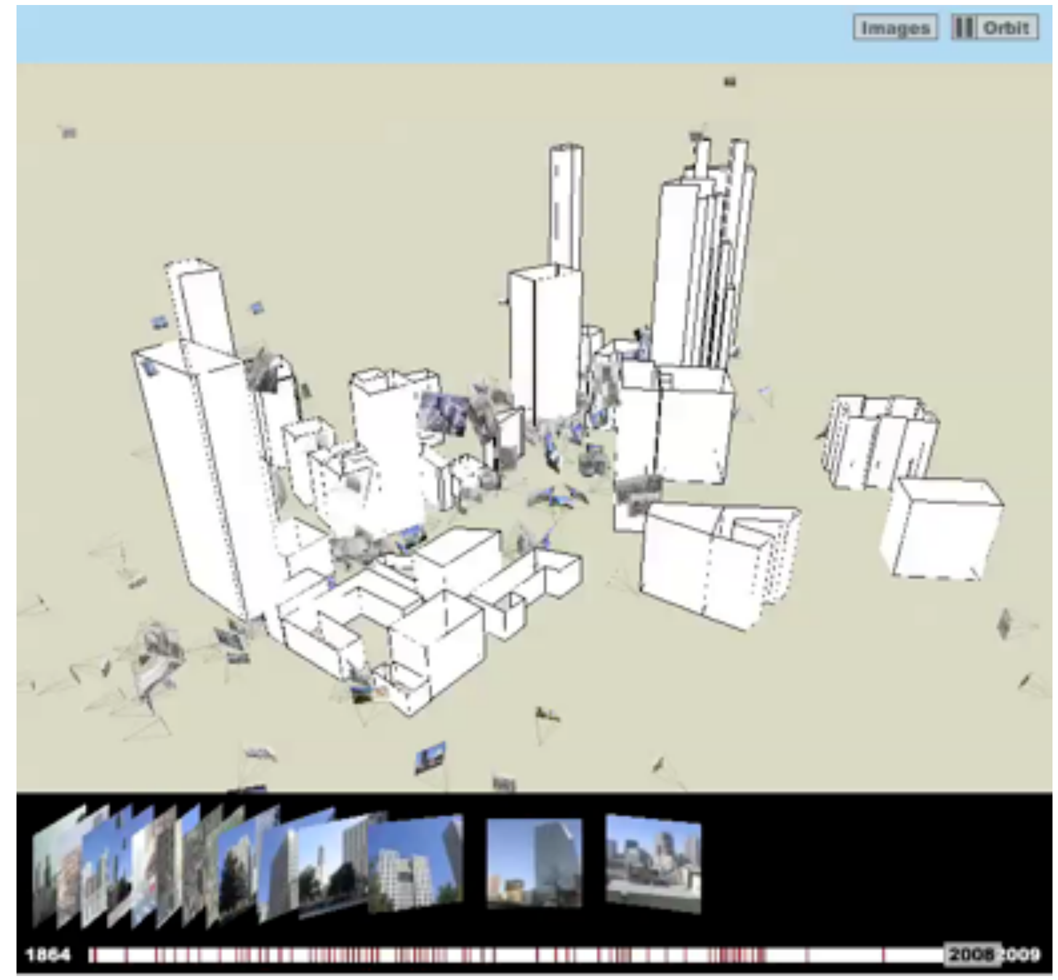
Grant Schindler

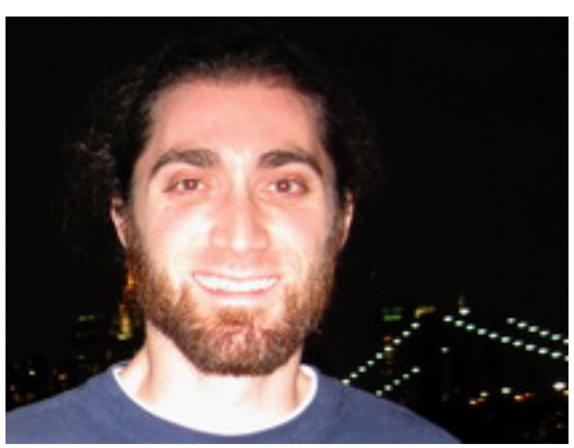
4D Reconstruction



Historical Image Collection

4D Cities: 3D + Time





Grant Schindler

trimensional

3D Scanner for iPhone

3D Reconstruction

Probabilistic Temporal Inference on Reconstructed 3D Scenes, G. Schindler and F. Dellaert, IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR), 2010.

3D Reconstruction

Probabilistic Temporal Inference on Reconstructed 3D Scenes, G. Schindler and F. Dellaert, IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR), 2010.

4D Structure over Time

4D Structure over Time

Outline

Intro

Factor Graphs

On Graphs & Matrices

Graph-Inspired Methods

Support Subgraphs

Future Directions

End

Acknowledgements

- Provided Materials: Michael Kaess & John Leonard (MIT), Ryan Eustice & Ed Olson (Michigan), Tim Barfoot (Toronto), Pratik Agarwal (Freiburg)
- Sponsors: NSF, DARPA, ONR, ARO/ARL, Microsoft Research, Samsung, Intel
- Noah Snavely, Sameer Agarwal, and Steve Seitz for cool data/videos

Outline

Intro

Factor Graphs

On Graphs & Matrices

Graph-Inspired Methods

Support Subgraphs

Future Directions

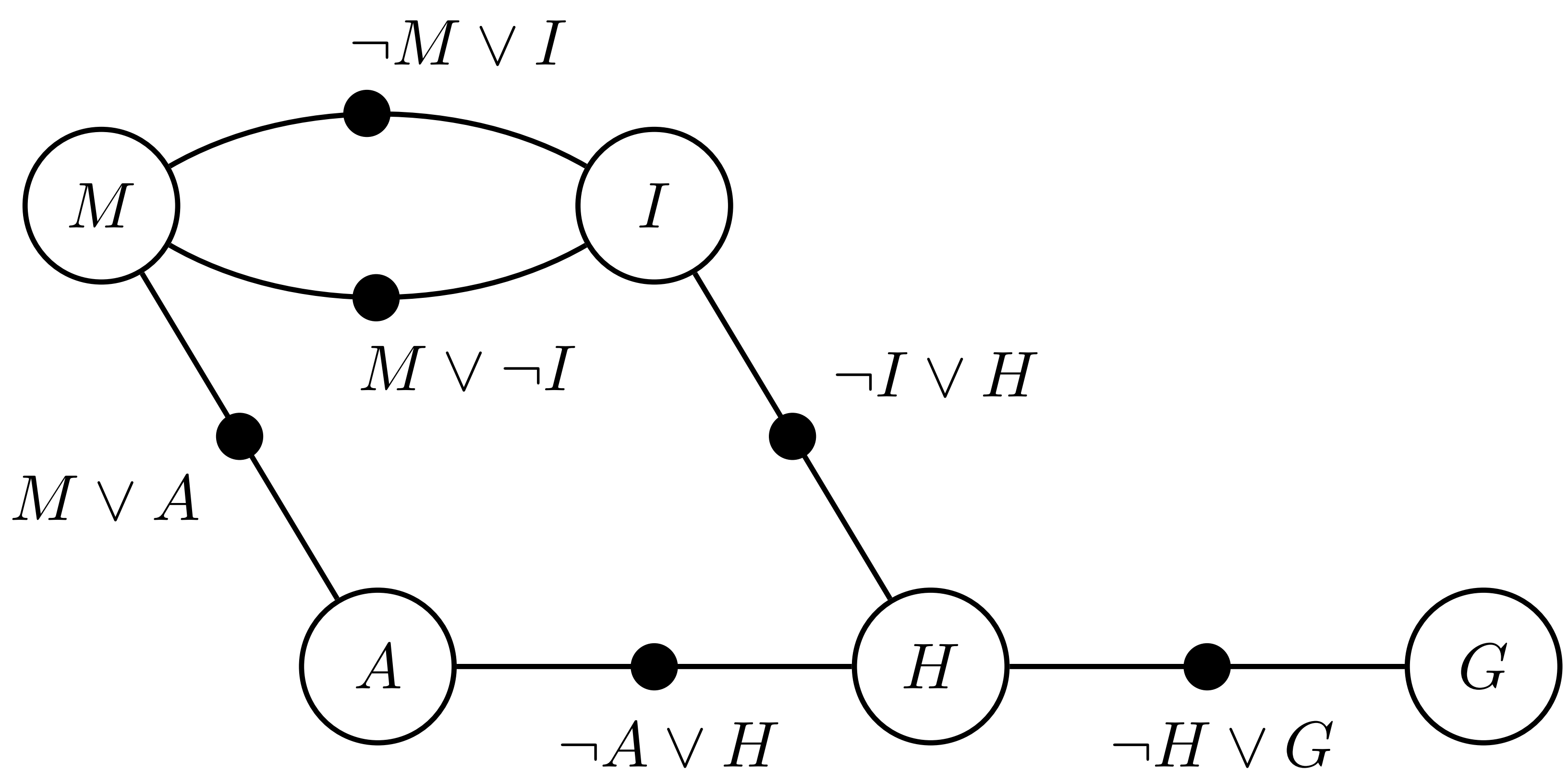
End

Boolean Satisfiability

$$(\neg M \vee I) \wedge (M \vee \neg I) \wedge (M \vee A) \wedge (\neg I \vee H) \wedge (\neg A \vee H) \wedge (\neg H \vee G)$$

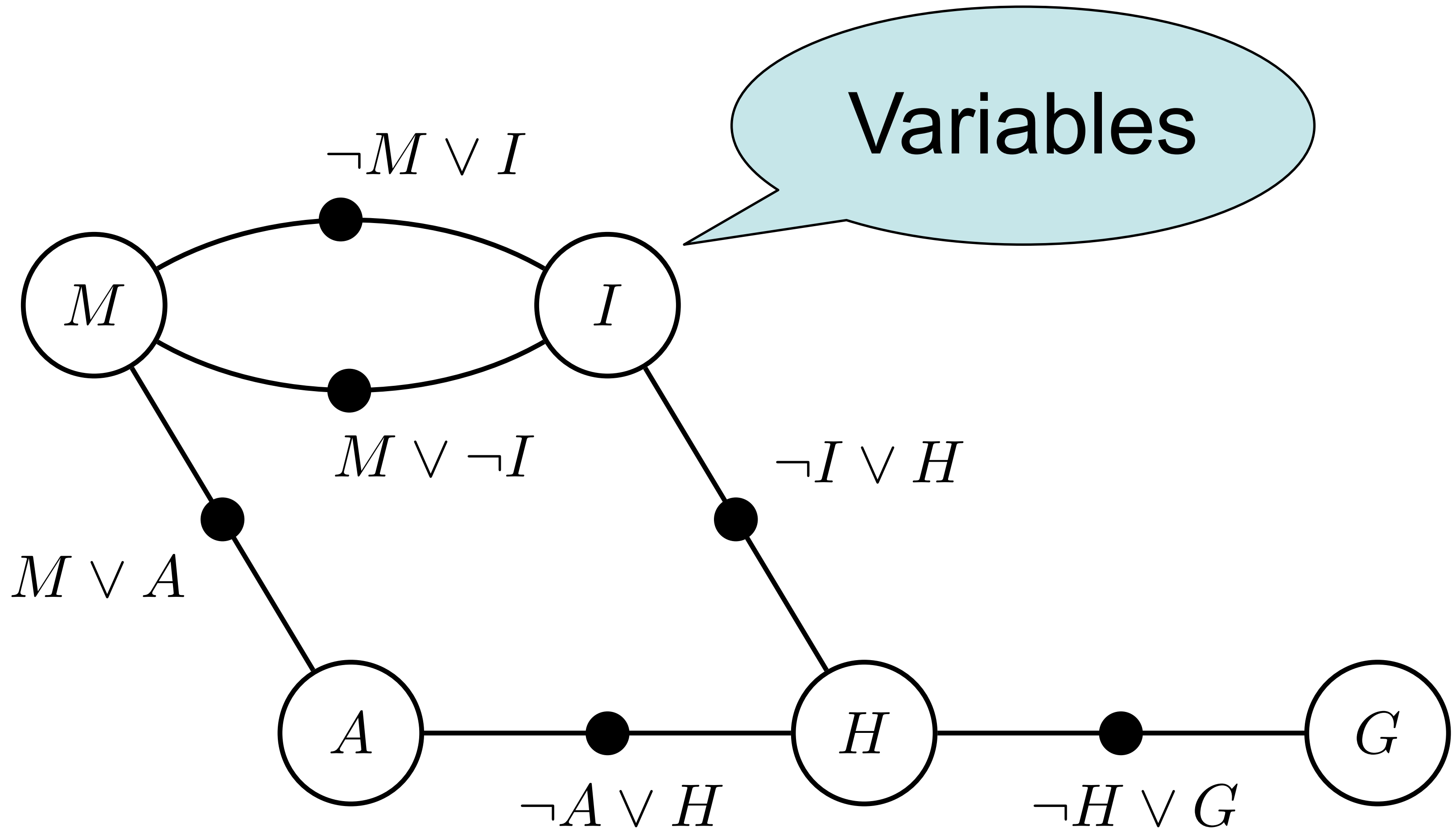
Boolean Satisfiability

$$(\neg M \vee I) \wedge (M \vee \neg I) \wedge (M \vee A) \wedge (\neg I \vee H) \wedge (\neg A \vee H) \wedge (\neg H \vee G)$$



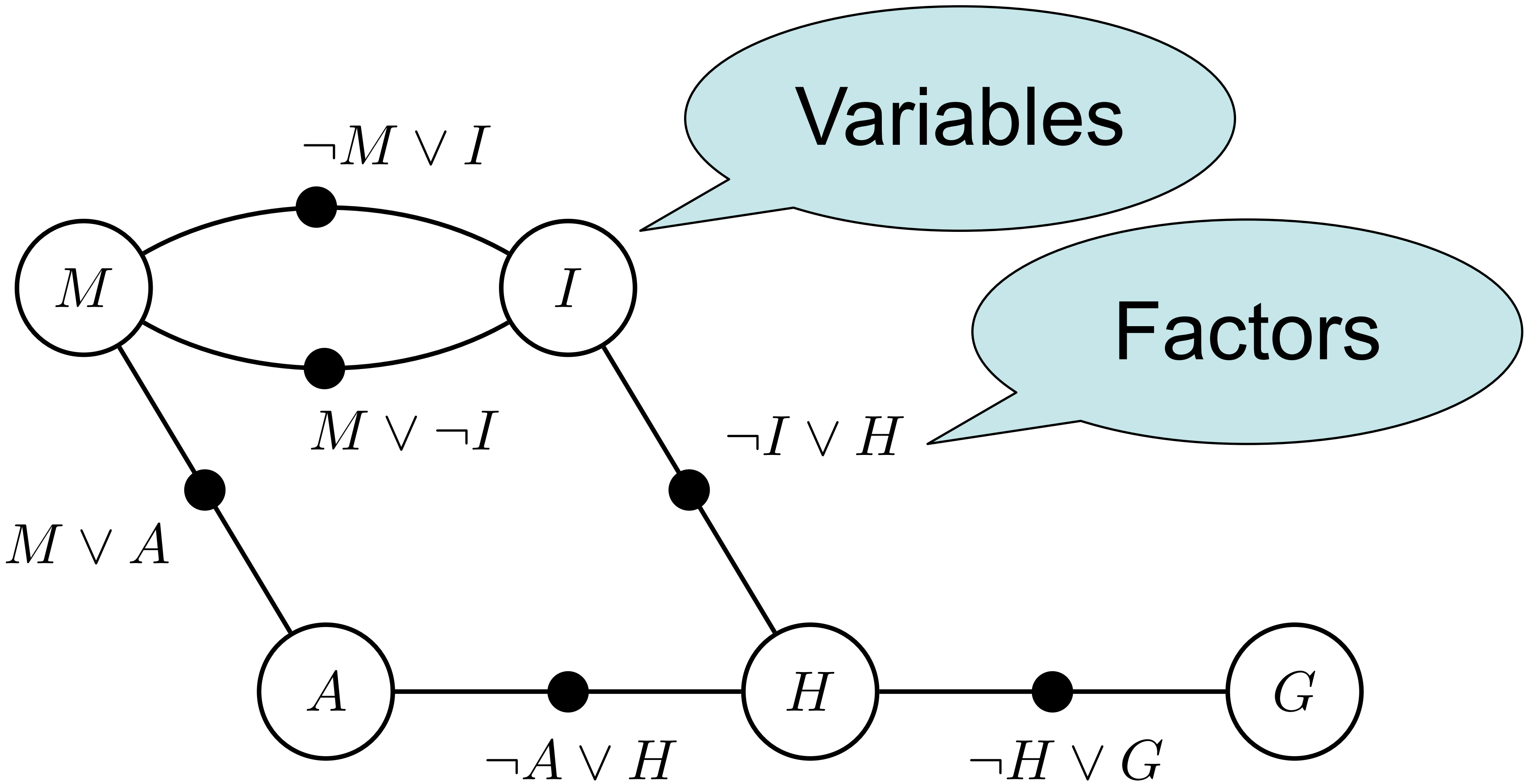
Boolean Satisfiability

$$(\neg M \vee I) \wedge (M \vee \neg I) \wedge (M \vee A) \wedge (\neg I \vee H) \wedge (\neg A \vee H) \wedge (\neg H \vee G)$$



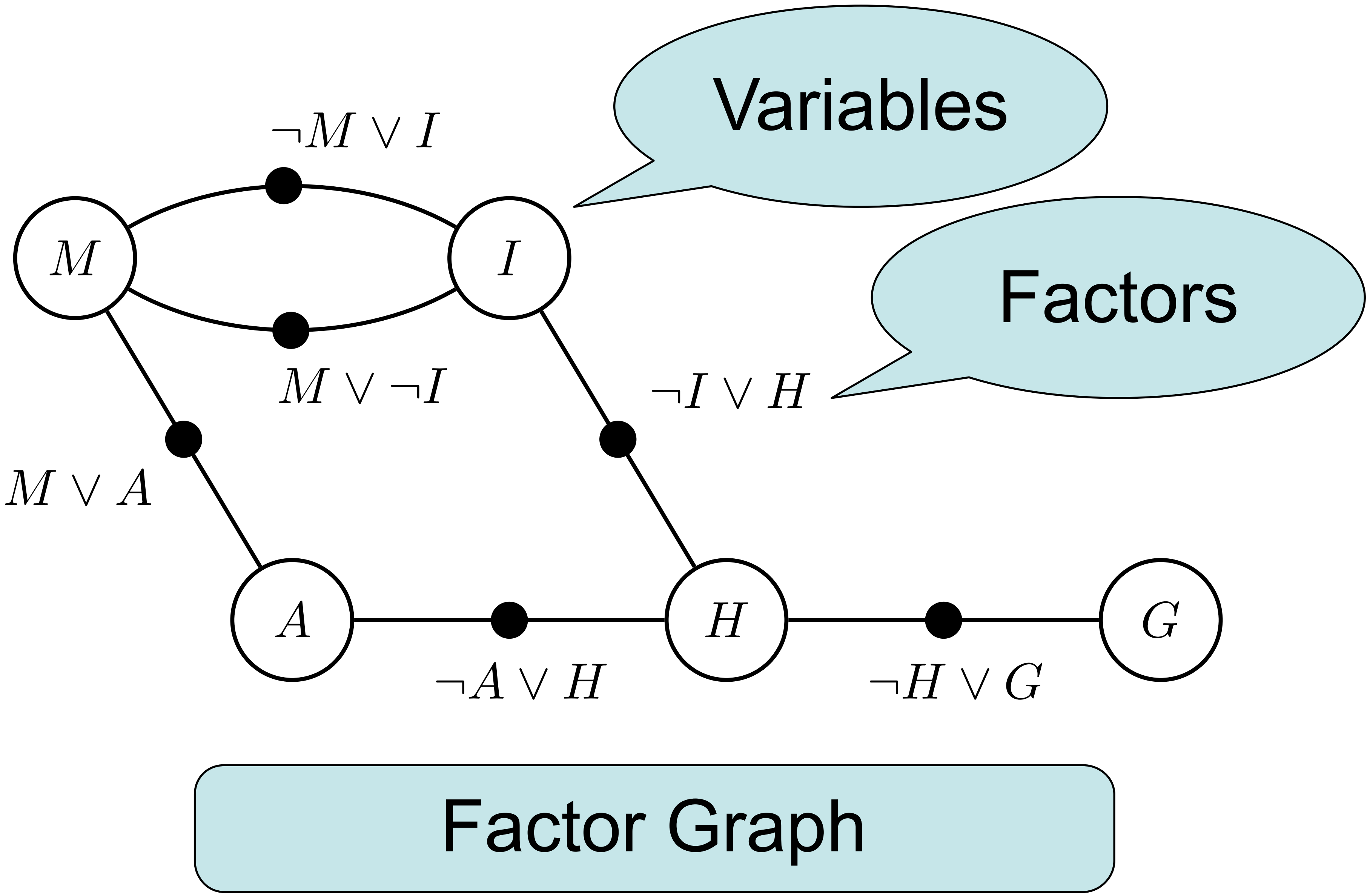
Boolean Satisfiability

$$(\neg M \vee I) \wedge (M \vee \neg I) \wedge (M \vee A) \wedge (\neg I \vee H) \wedge (\neg A \vee H) \wedge (\neg H \vee G)$$



Boolean Satisfiability

$$(\neg M \vee I) \wedge (M \vee \neg I) \wedge (M \vee A) \wedge (\neg I \vee H) \wedge (\neg A \vee H) \wedge (\neg H \vee G)$$

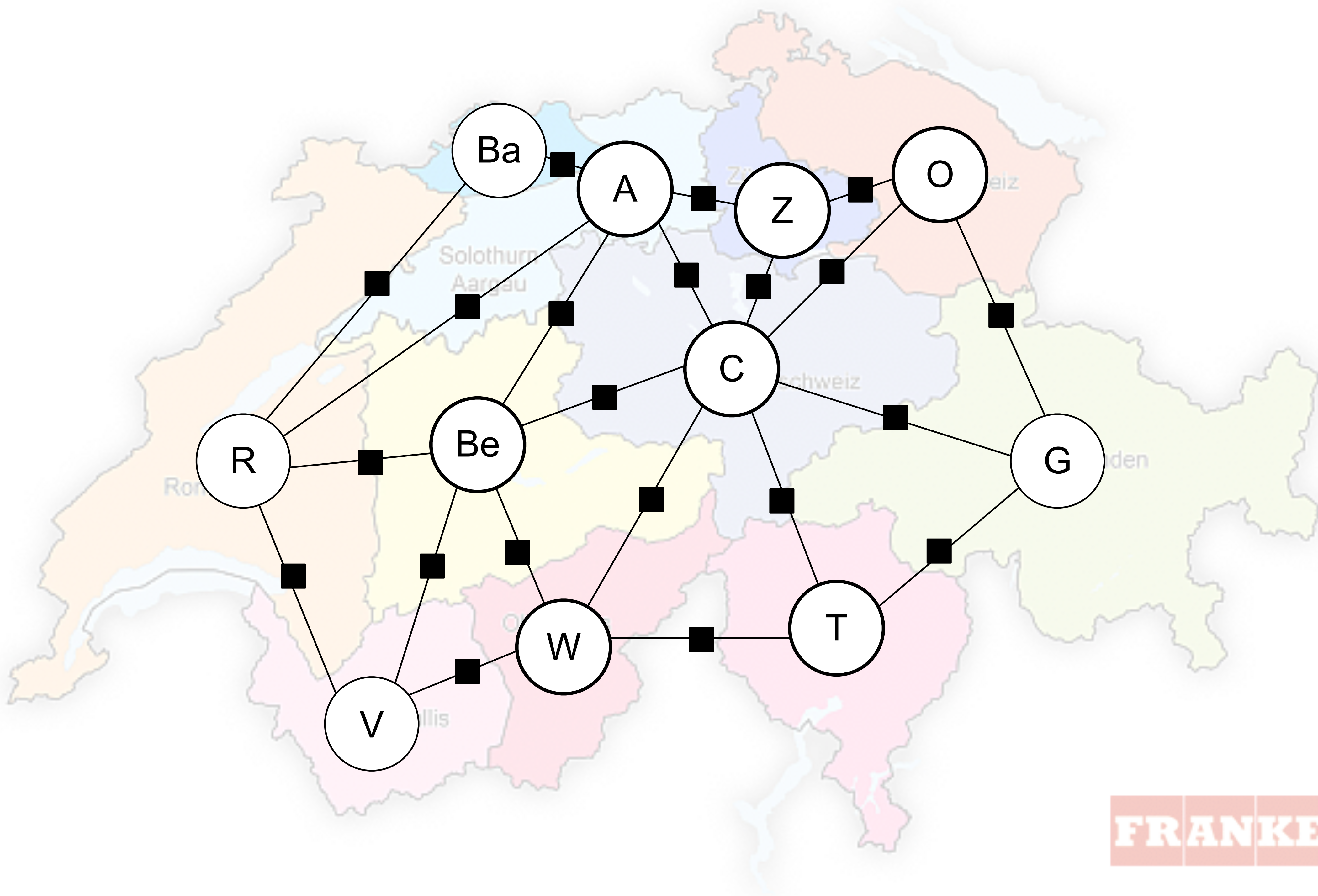


Constraint Satisfaction Problems

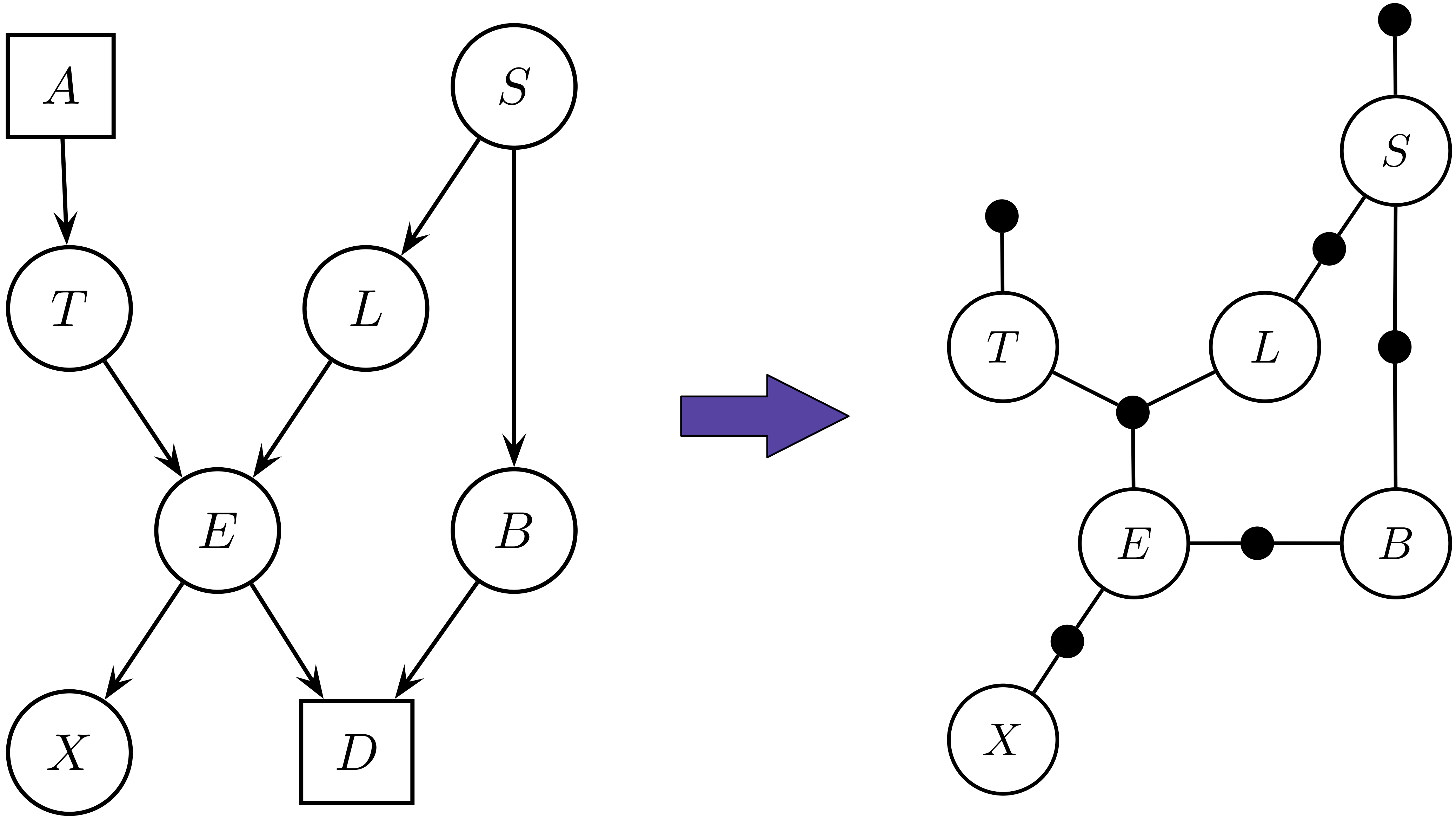
FRANK

Constraint Satisfaction Problems

Constraint Satisfaction Problems

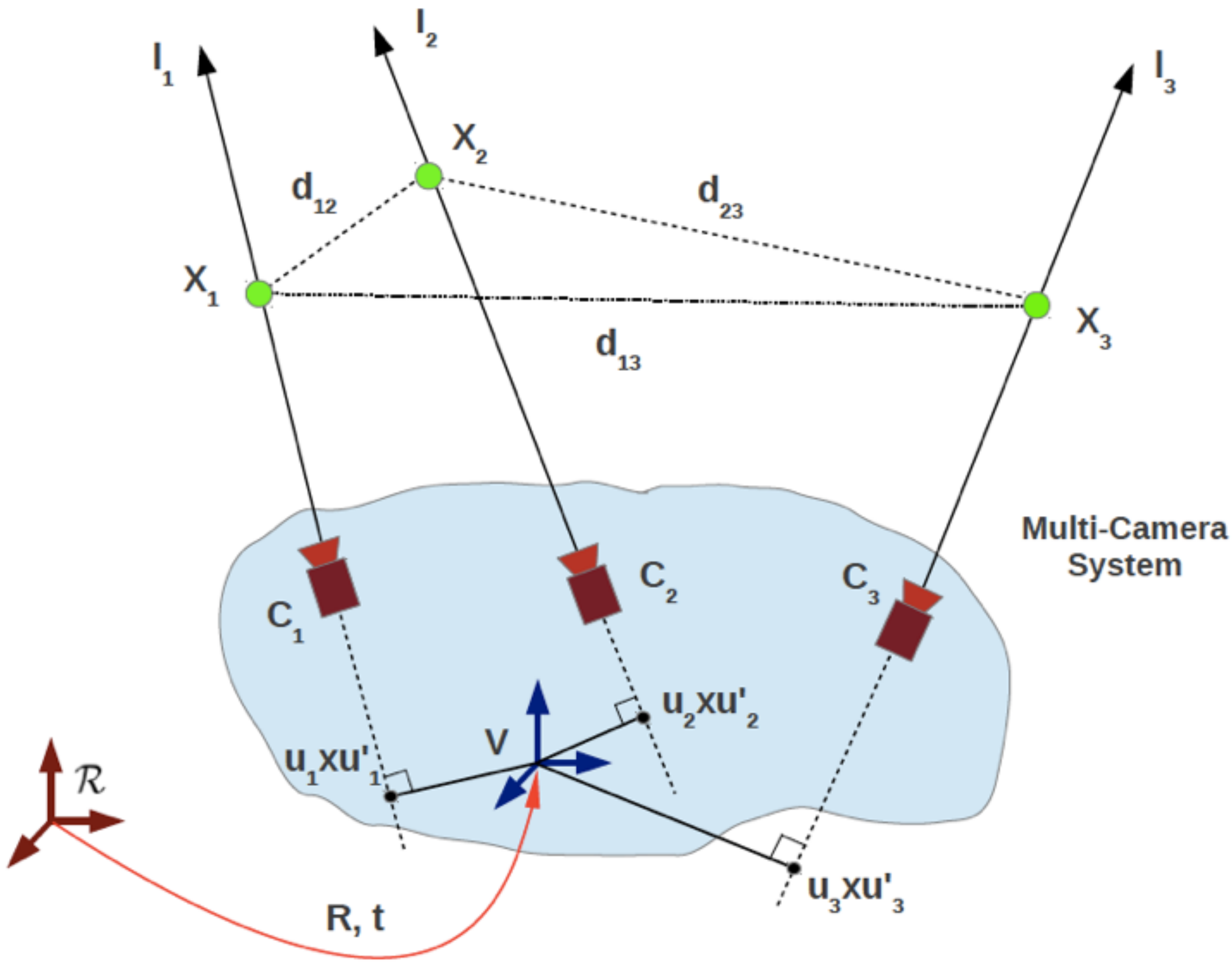


Graphical Models



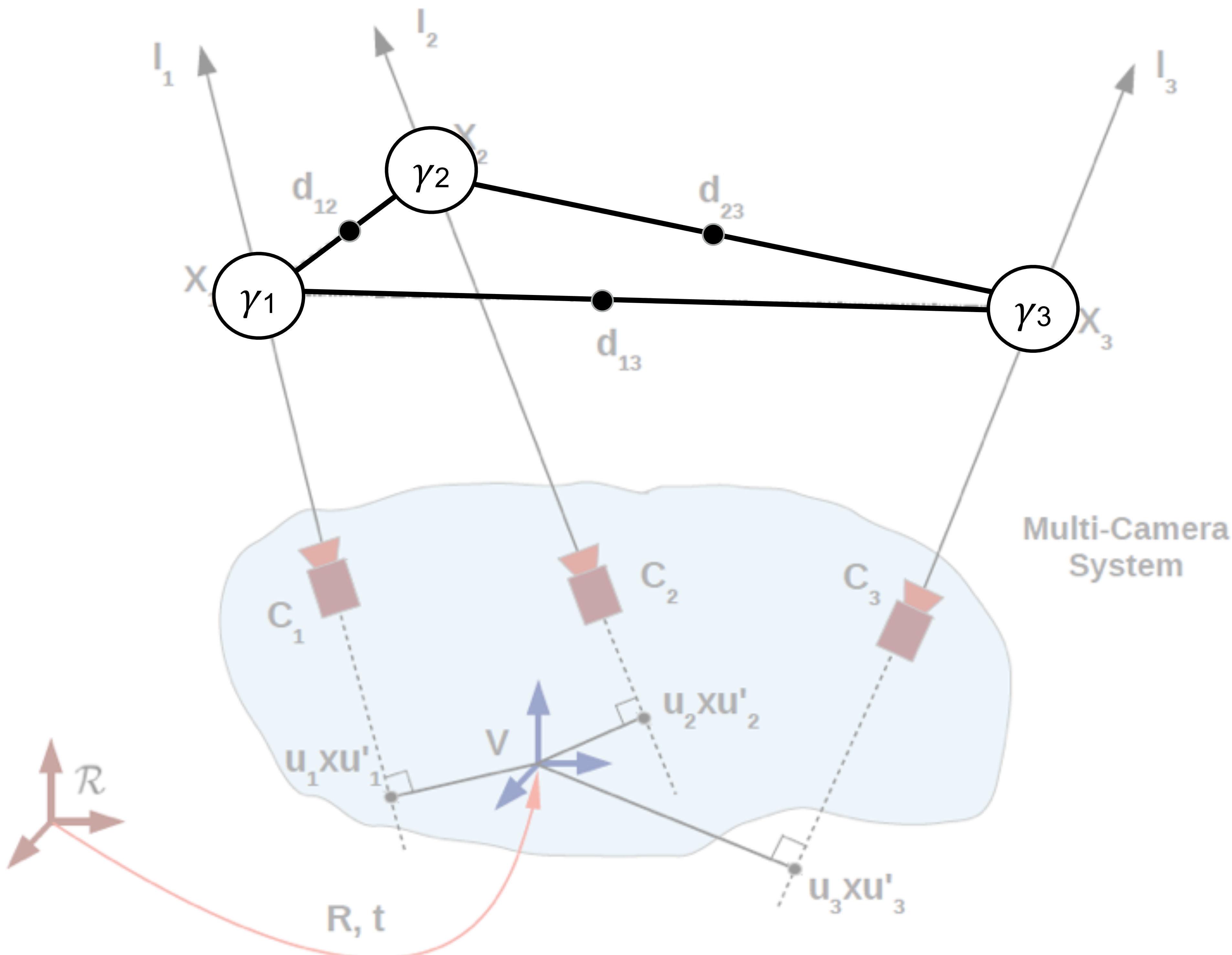
Polynomial Equations

Gim Hee Lee's thesis: multi-camera pose estimation

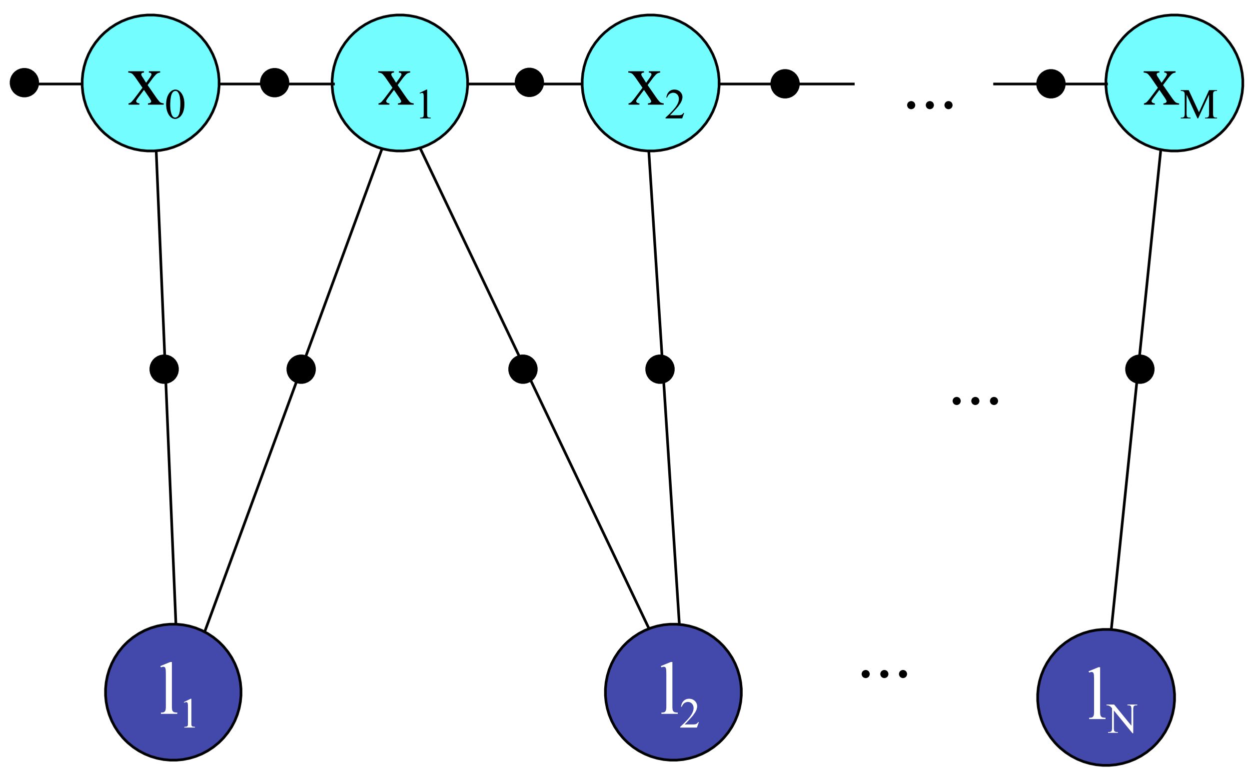


Polynomial Equations

Gim Hee Lee's thesis: multi-camera pose estimation



Continuous Probability Densities



- Trajectory of Robot

- Measurements

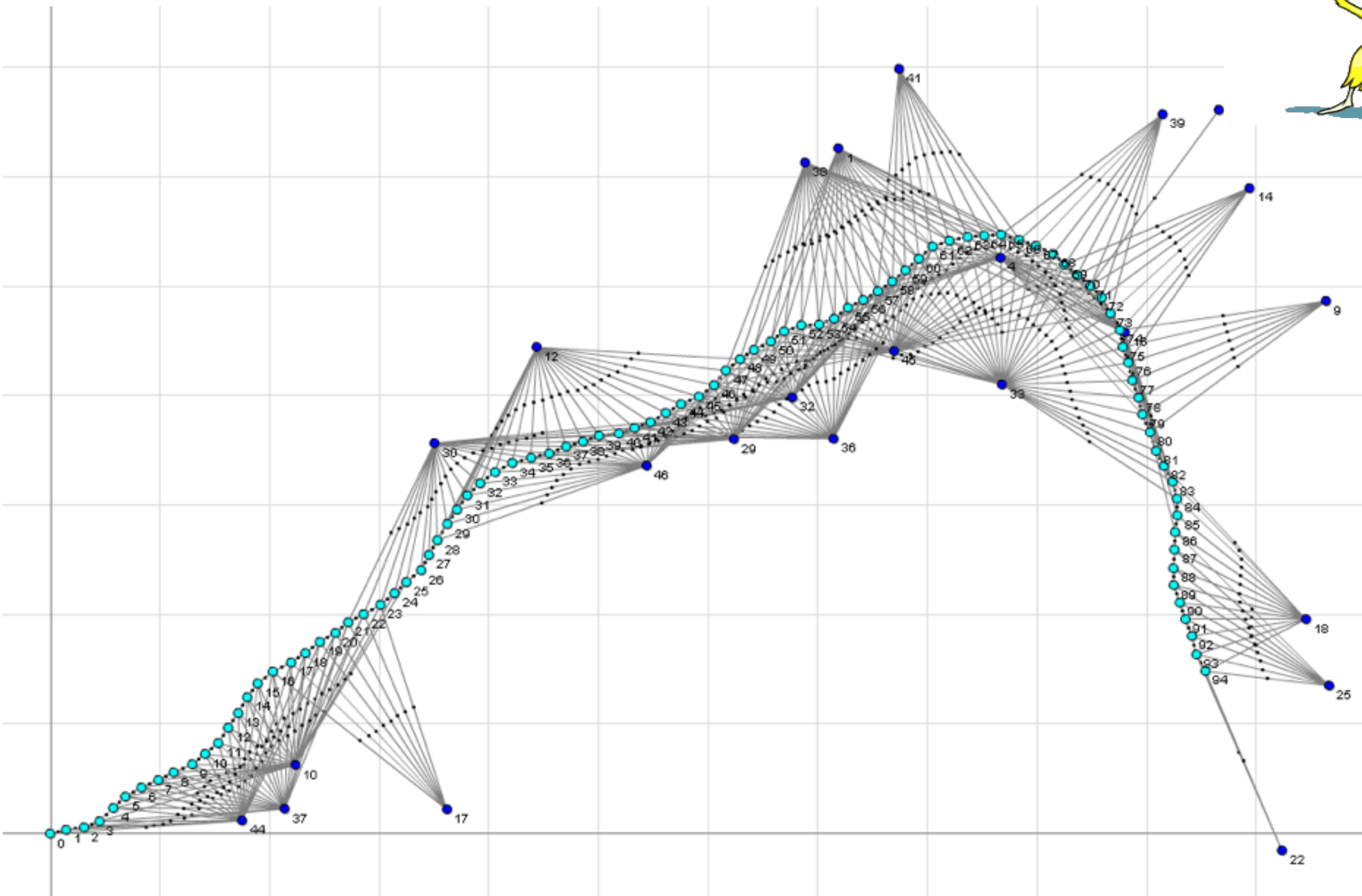
- Landmarks

$$P(X,M) = k * P(x_0) \prod_{i=1}^{M} P(x_i | x_{i-1}, u_i) \times \prod_{k=1}^{K} P(z_k | x_{i_k}, l_{j_k})$$

Simultaneous Localization and Mapping (SLAM)

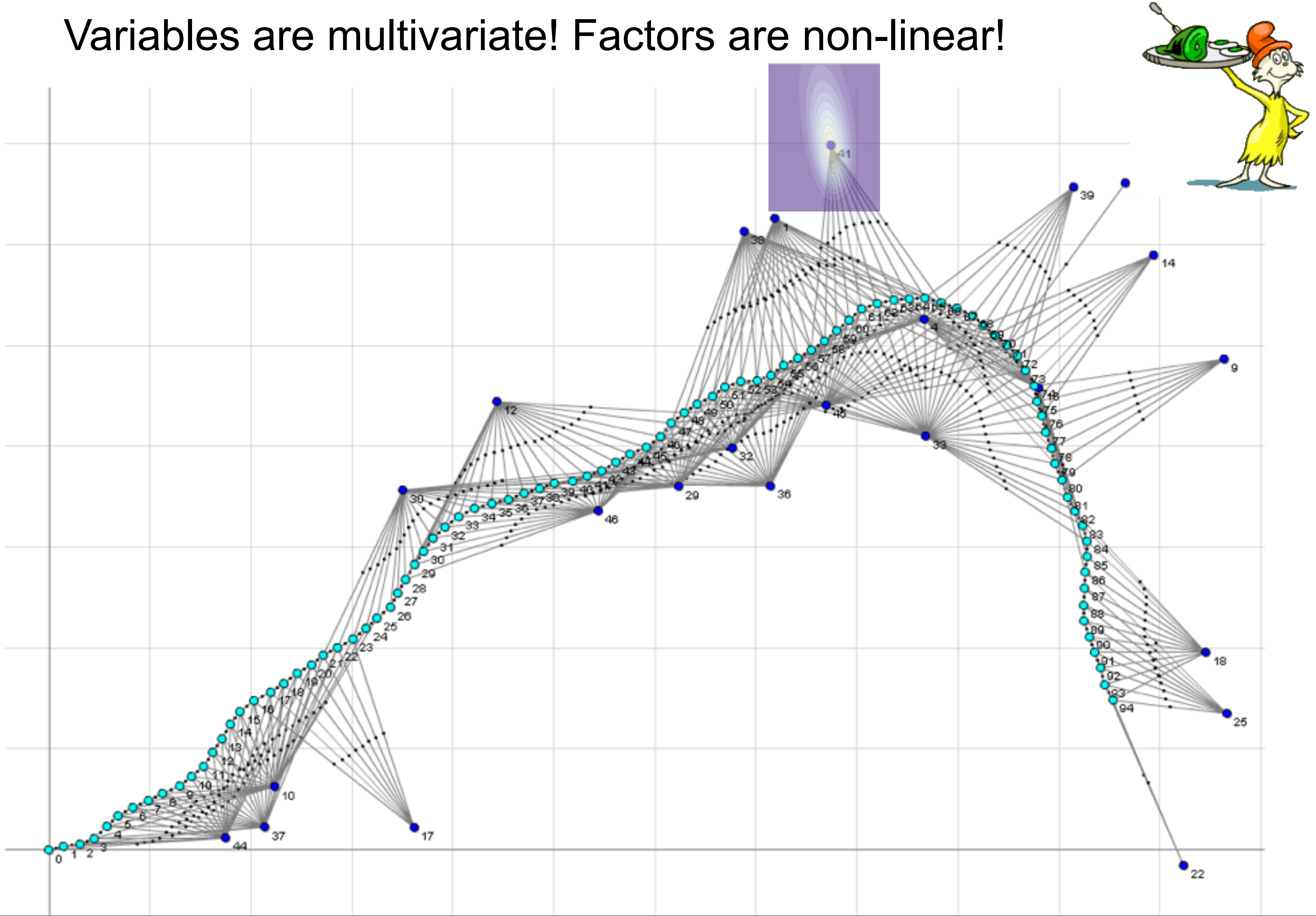
Simultaneous Localization and Mapping (SLAM)

Factor Graph -> Smoothing and Mapping (SAM) !



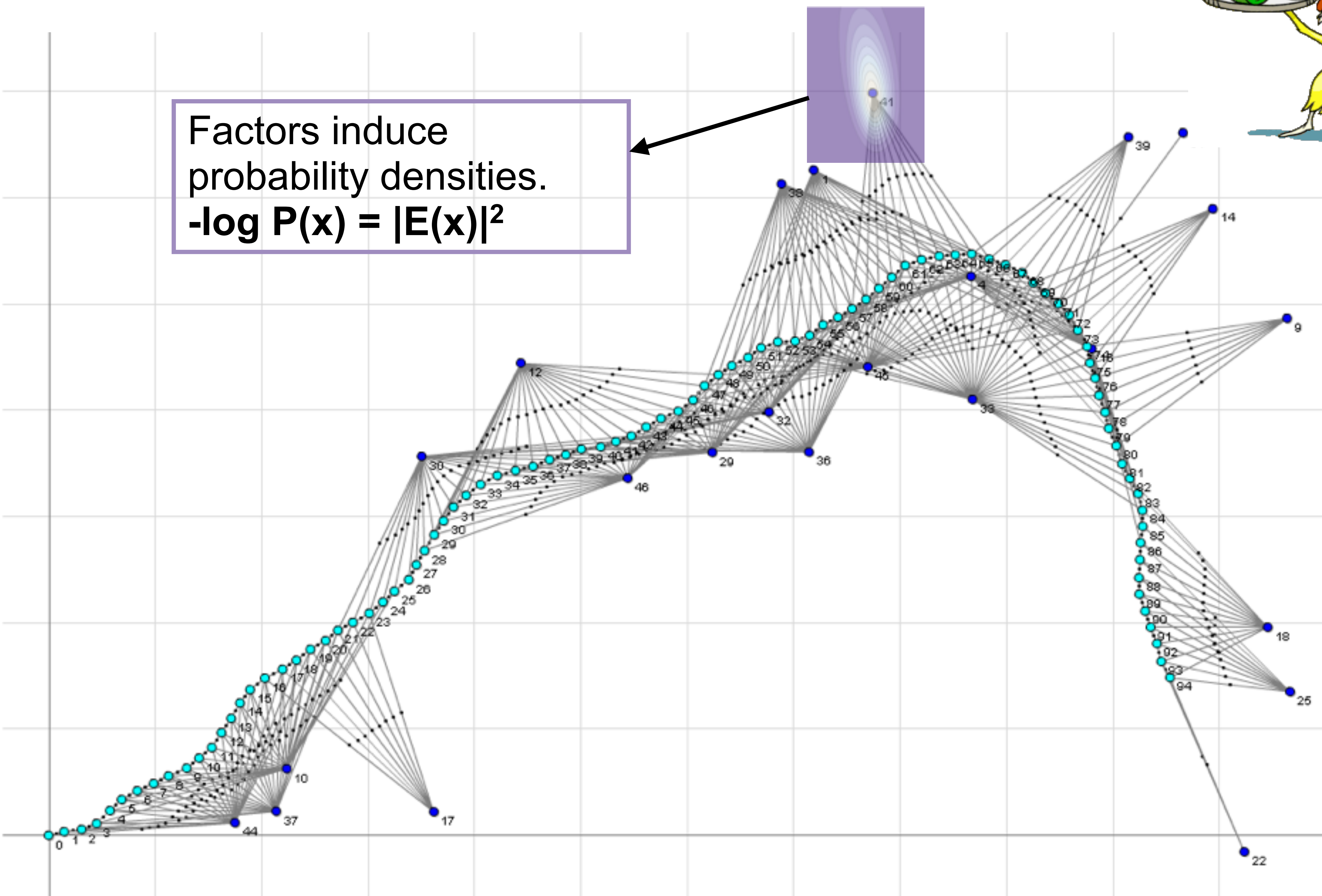
Factor Graph -> Smoothing and Mapping (SAM) !

Variables are multivariate! Factors are non-linear!



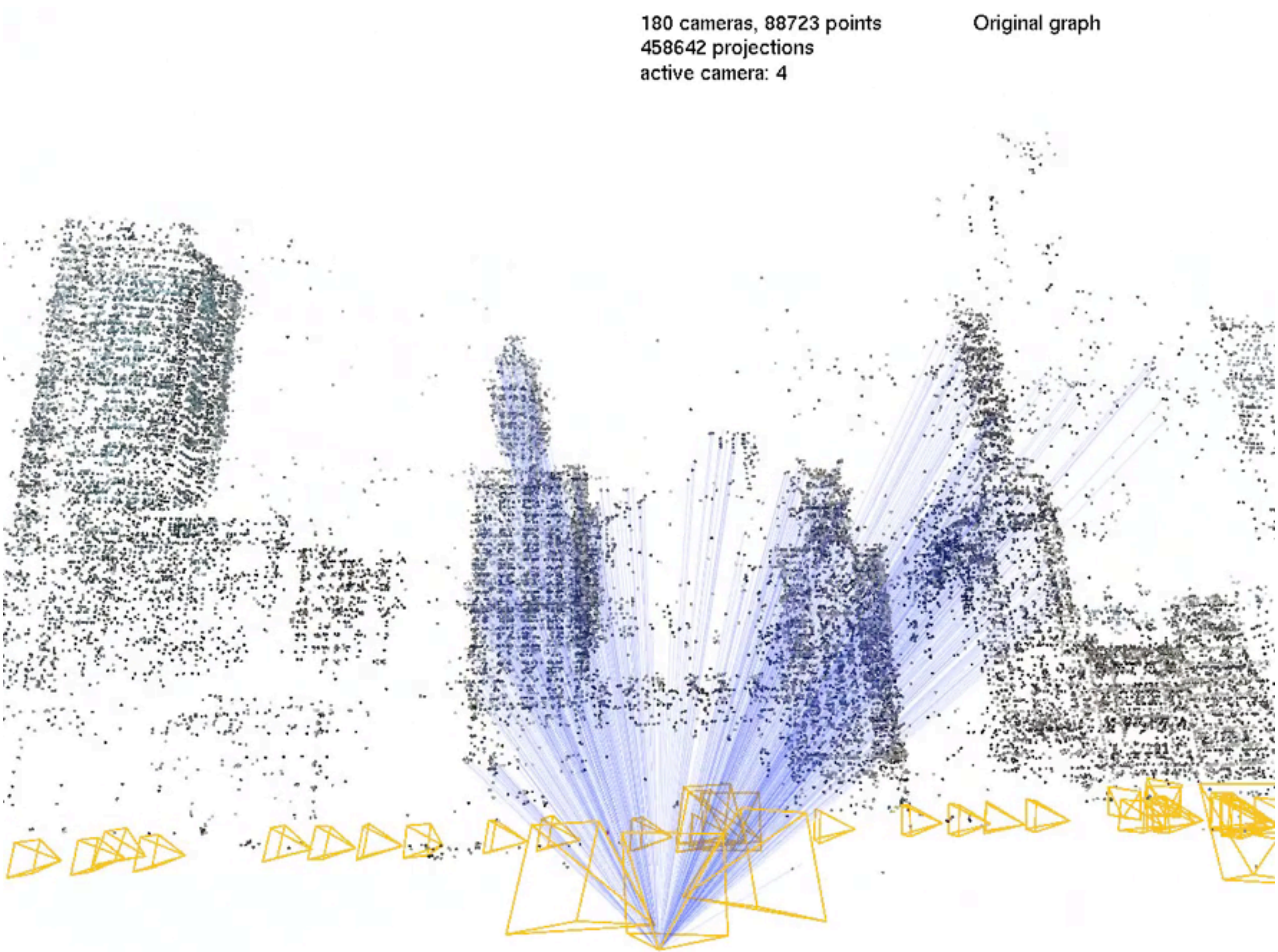
Factor Graph -> Smoothing and Mapping (SAM) !

Variables are multivariate! Factors are non-linear!

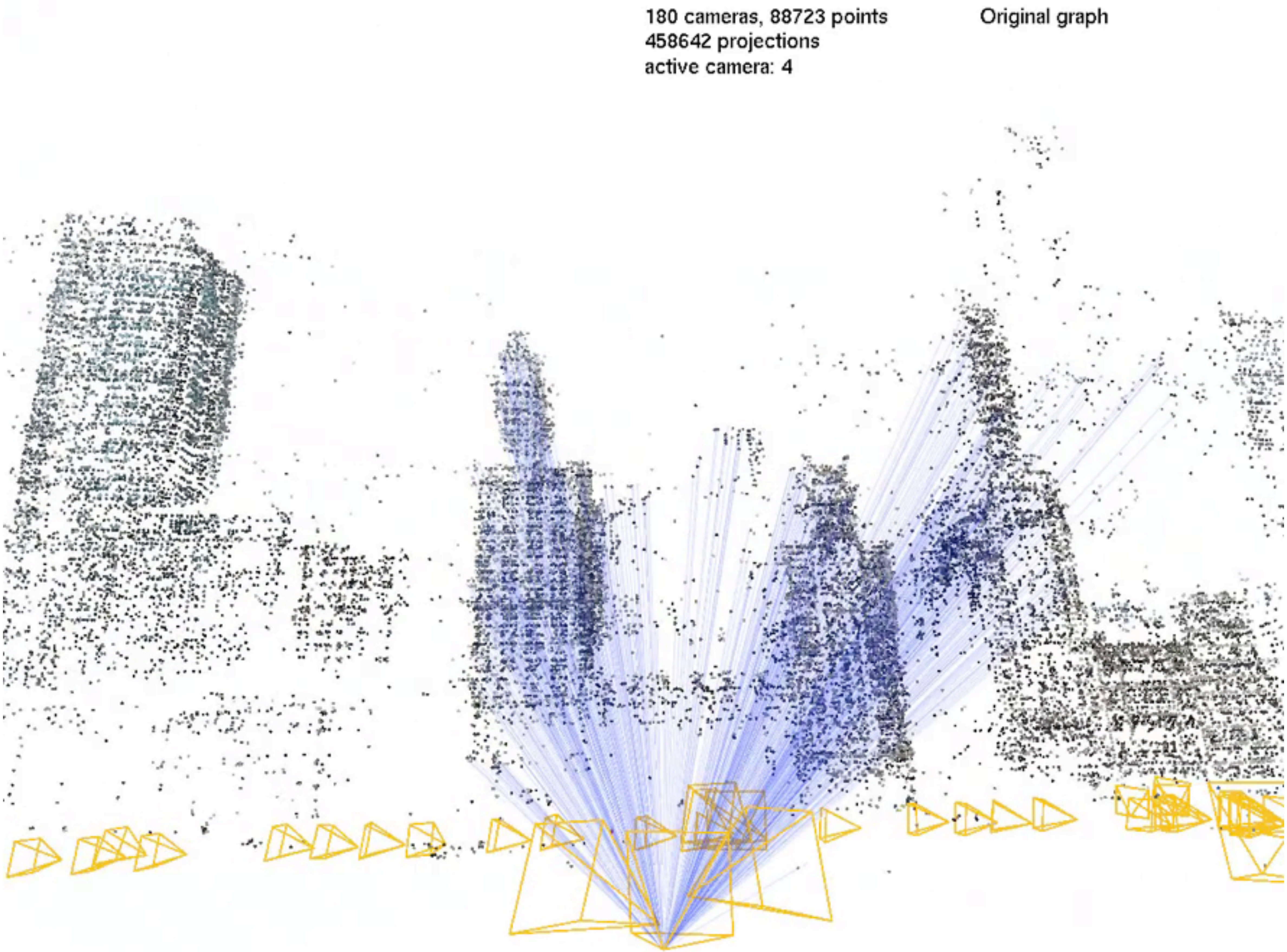


Factors induce probability densities.
-log P(x) = |E(x)|^2

Structure from Motion (Chicago, movie by Yong Dian Jian)



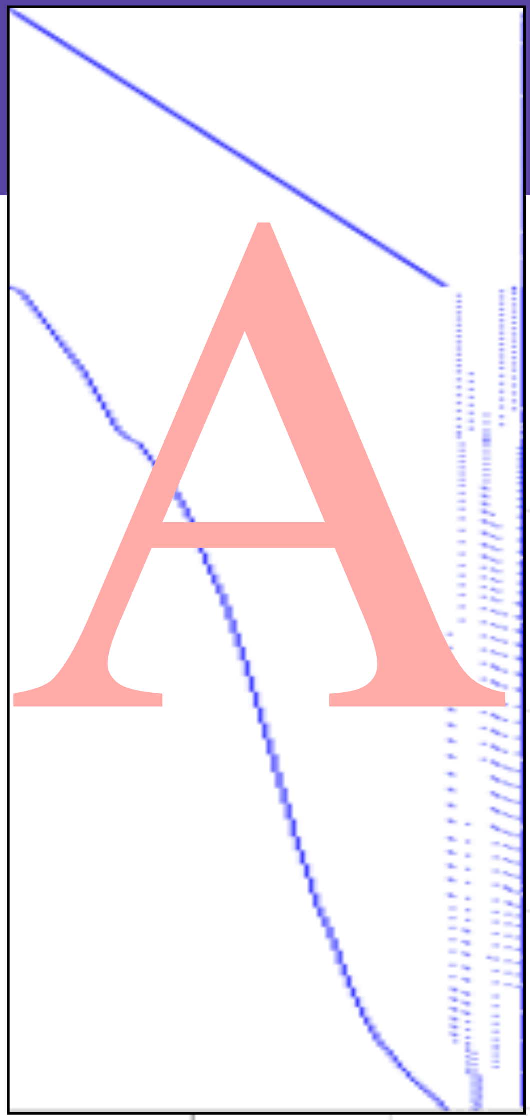
Structure from Motion (Chicago, movie by Yong Dian Jian)

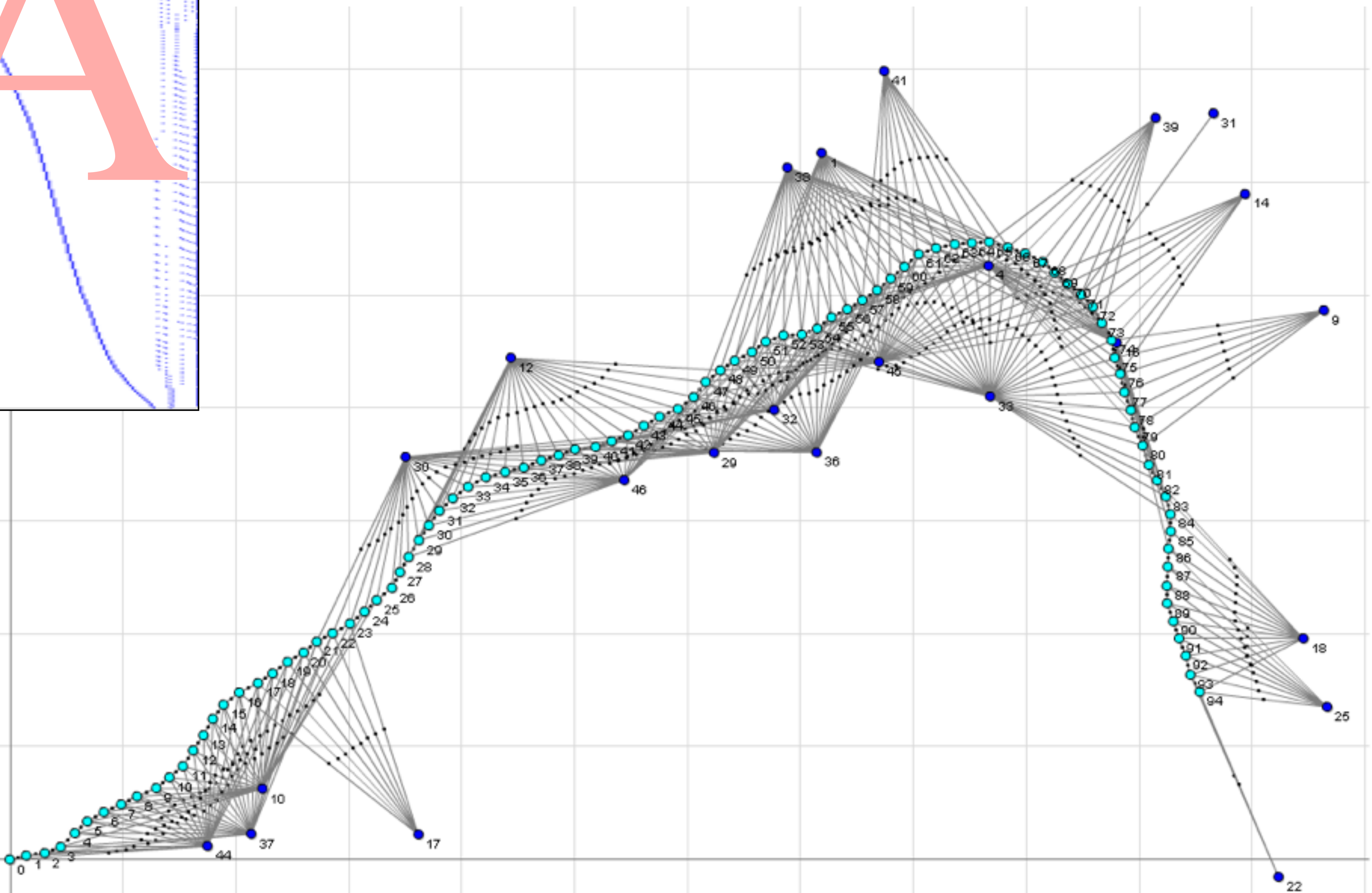


Outline

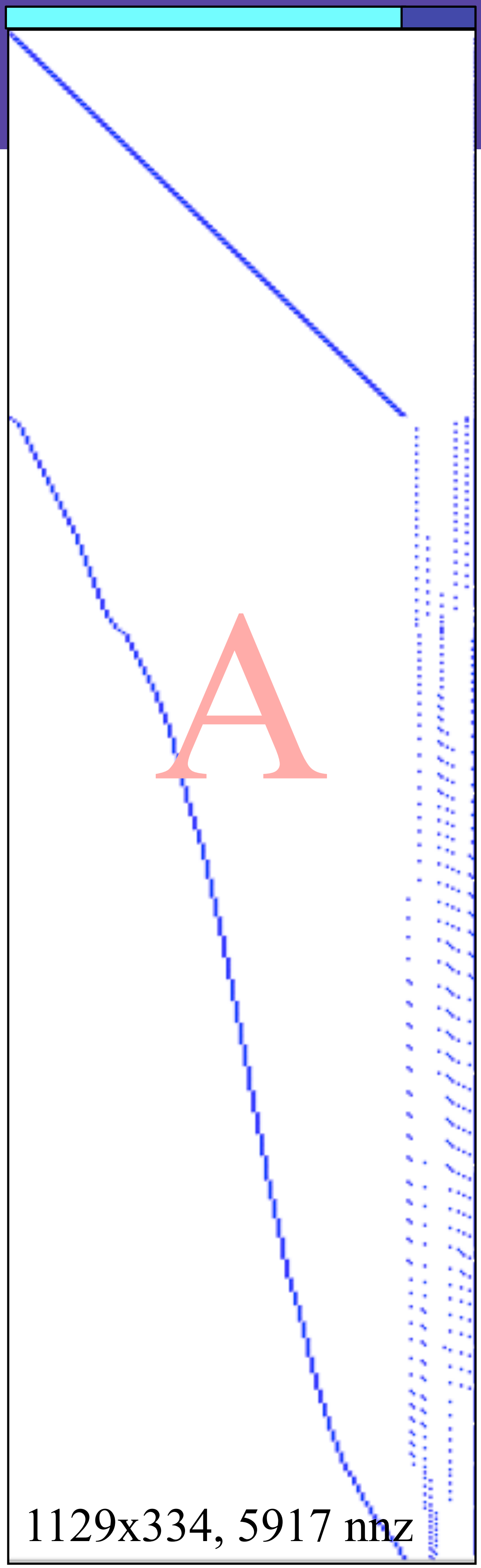
- Intro
- Factor Graphs
- On Graphs & Matrices
- Graph-Inspired Methods
- Support Subgraphs
- Future Directions
- End

Gaussian Factor Graph == mxn Matrix

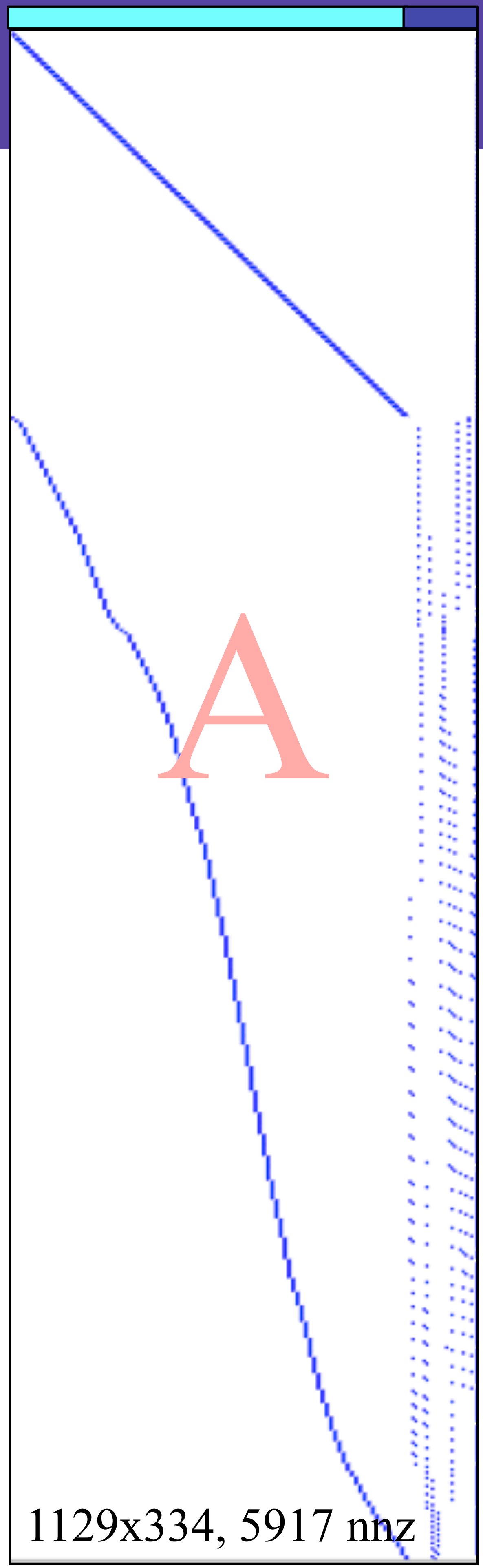




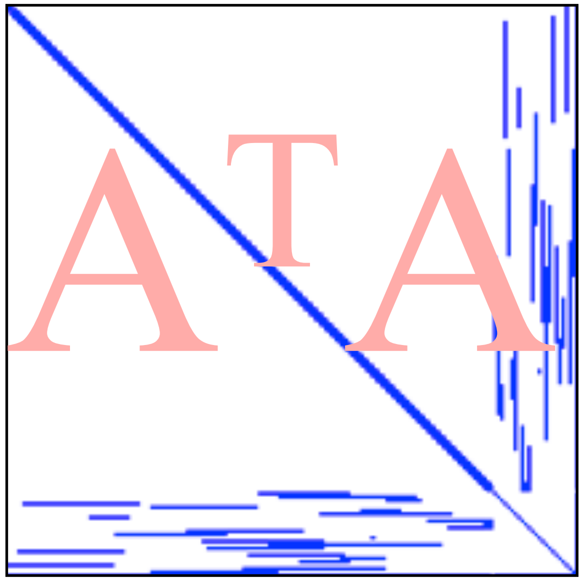
Linear Least Squares



Linear Least Squares

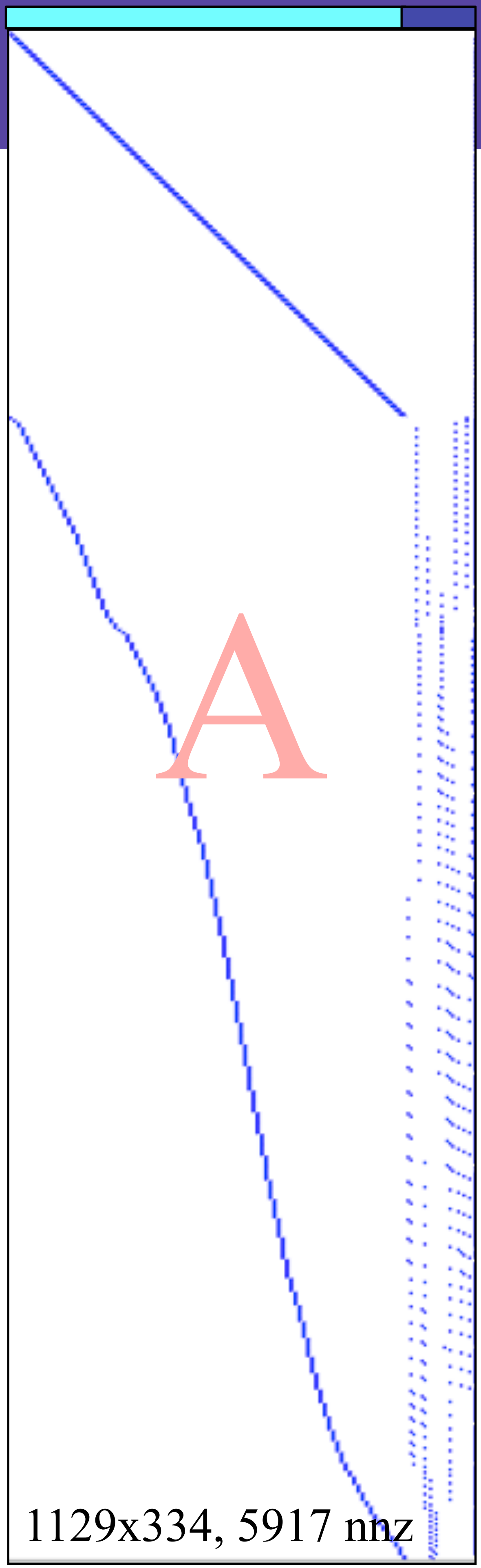


$$A^T A\theta^* = A^T b$$



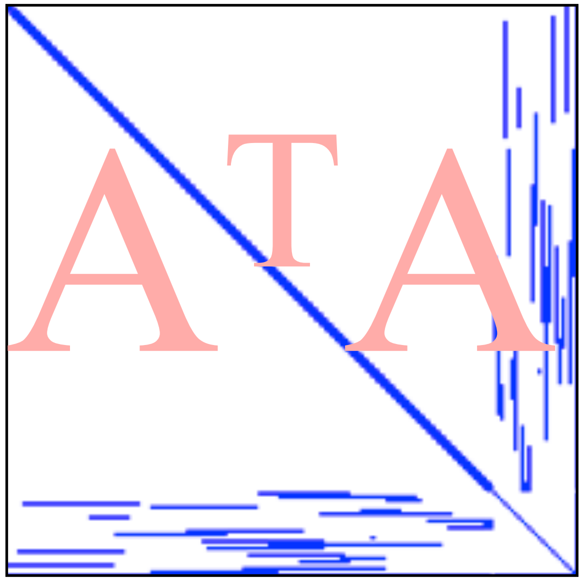
334x334, 7992 nnz

Linear Least Squares



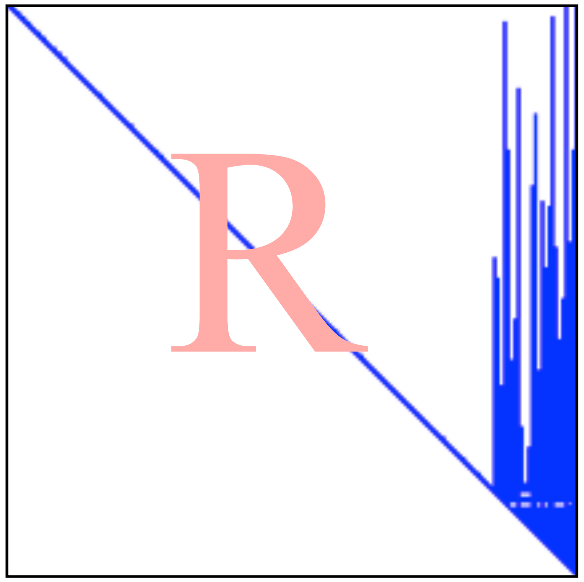
1129x334, 5917 nnz

$$A^T A \theta^* = A^T b$$



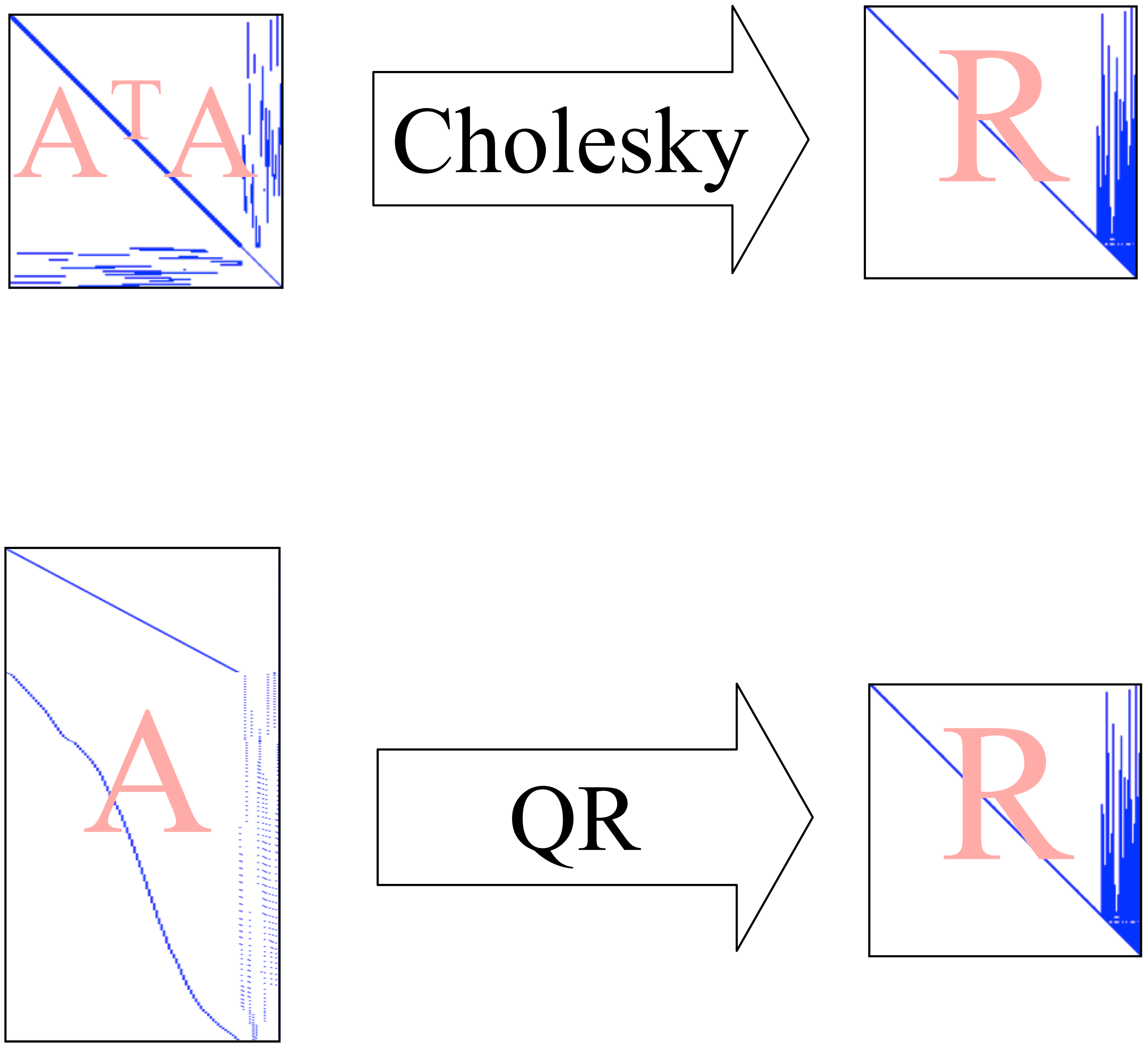
334x334, 7992 nnz

$$\mathcal{I} \triangleq A^T A = R^T R$$

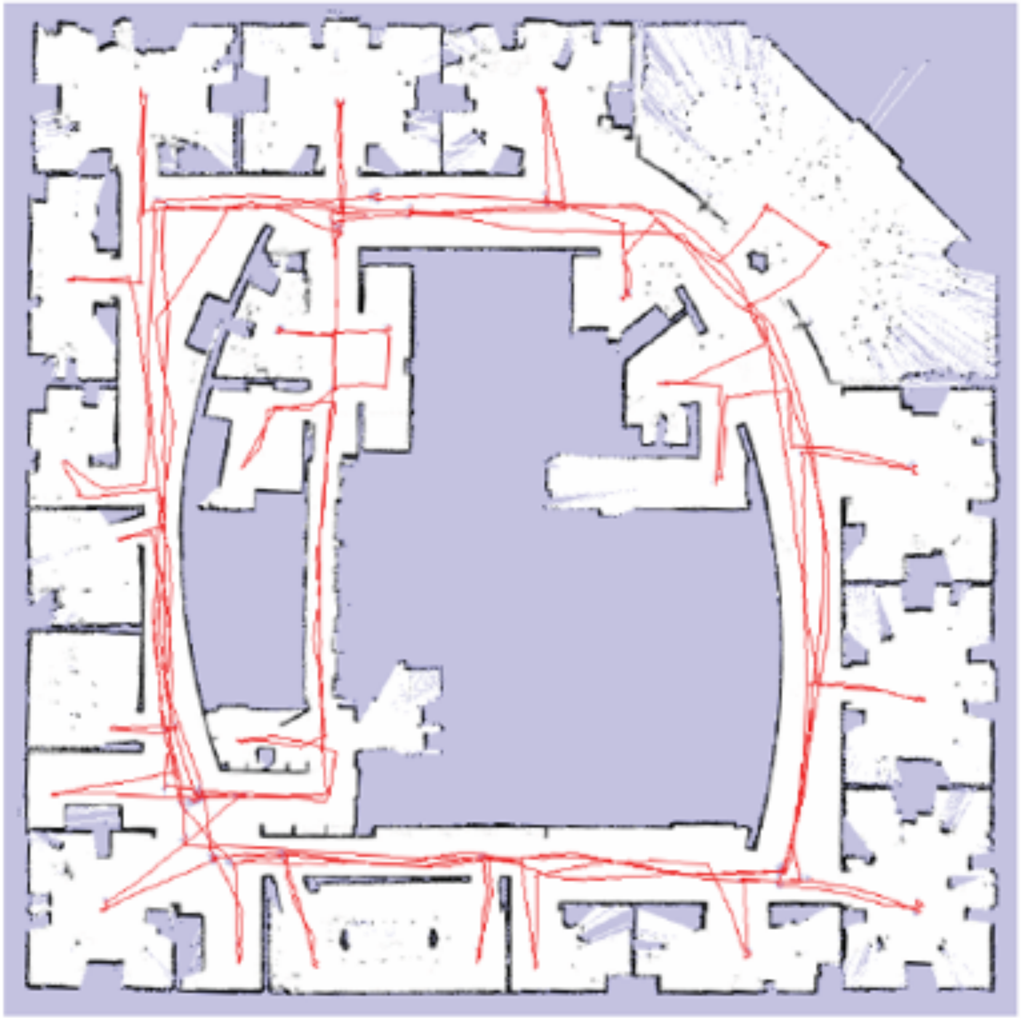


334x334, 9606 nnz

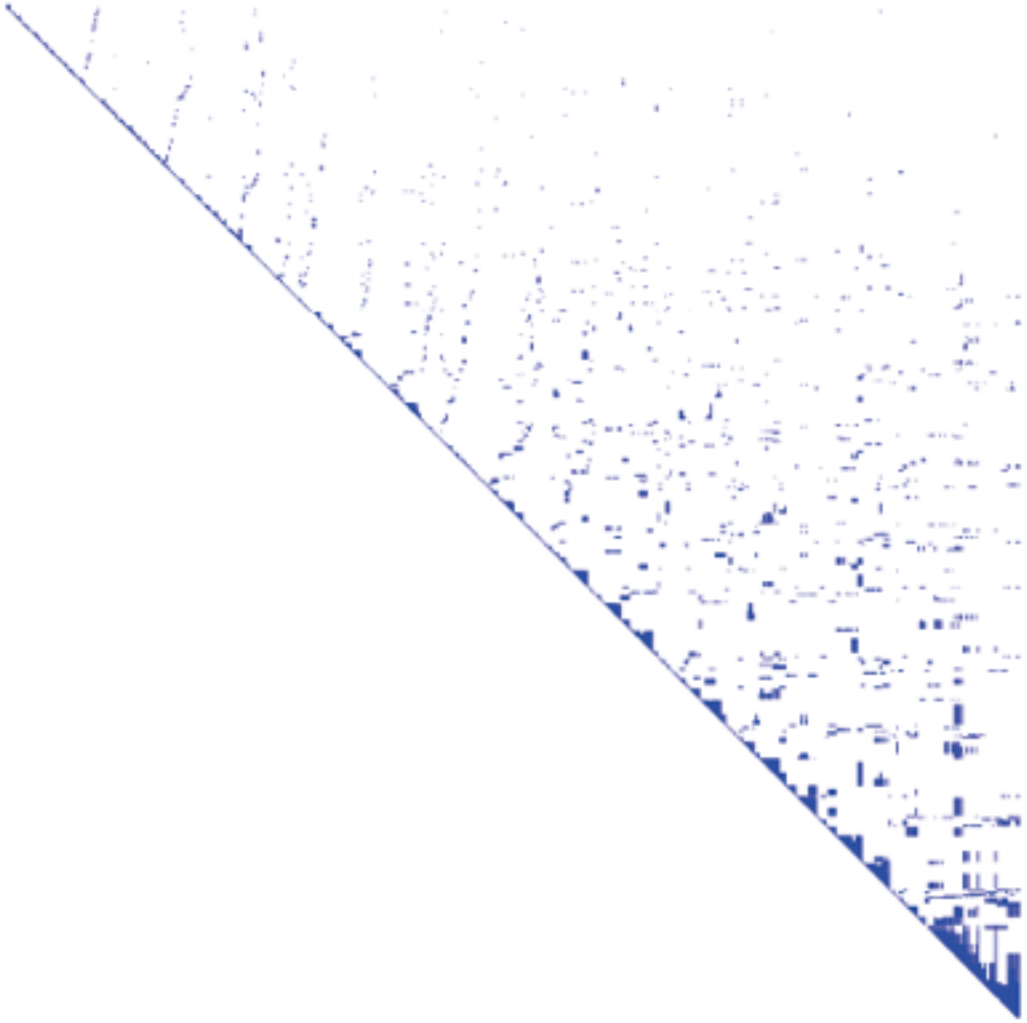
Square Root Factorization



Intel Dataset



(b) Final trajectory and evidence grid map.

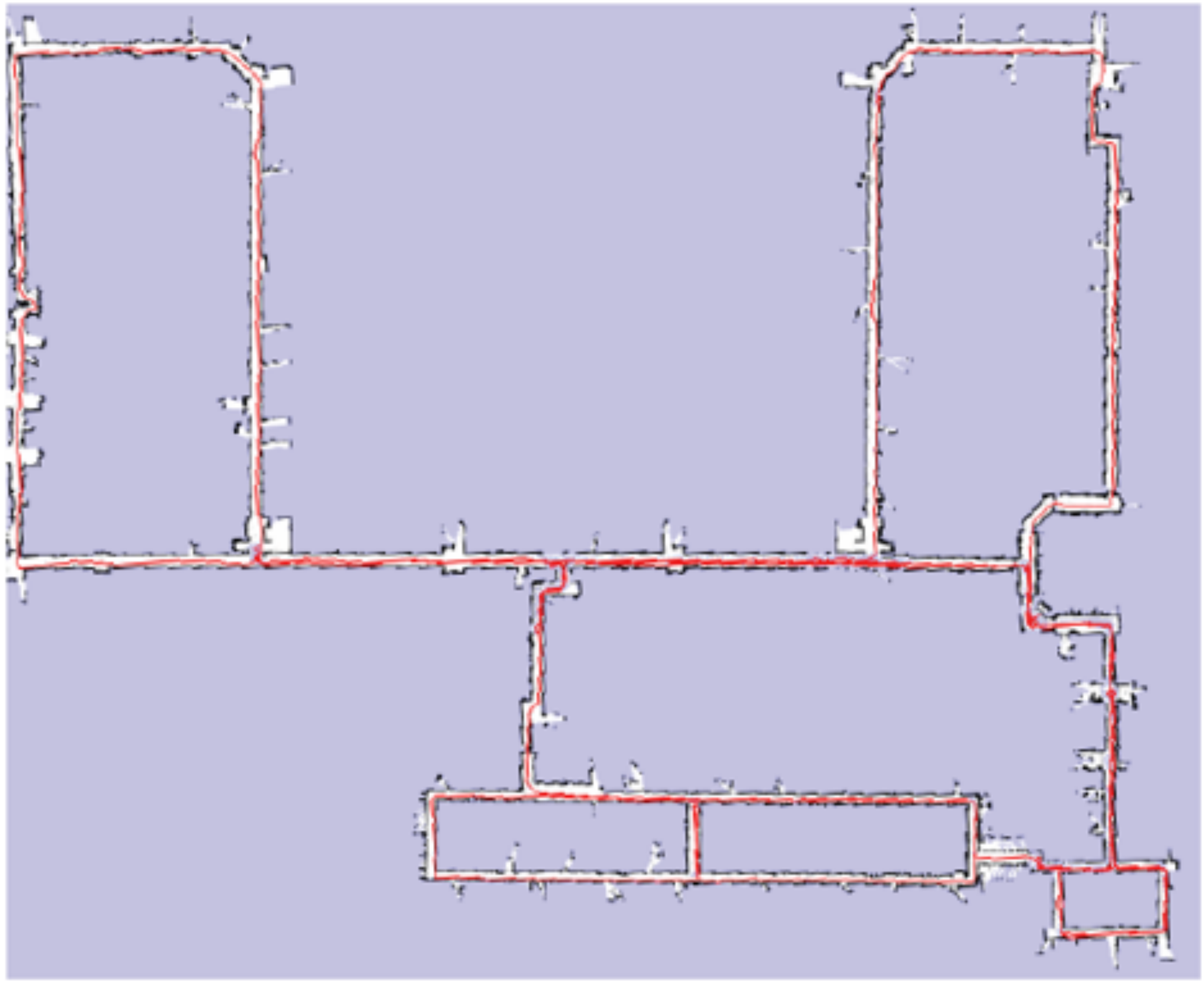


(c) Final R factor with side length 2730.

910 poses, 4453 constraints, 45s or 49ms/step

(Olson, RSS 07: iterative equation solver, same ballpark)

MIT Killian Court Dataset

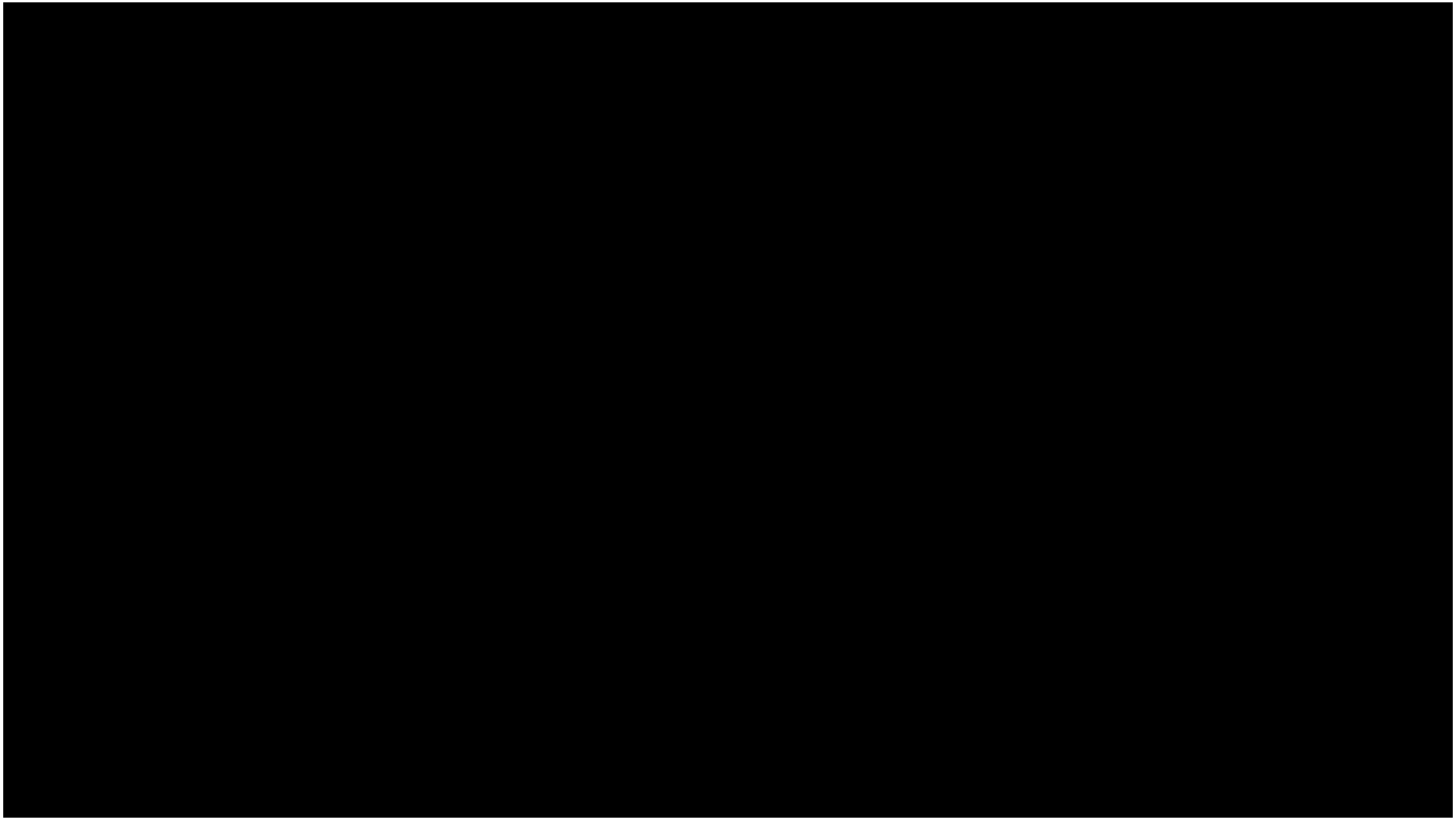


(b) Final trajectory and evidence grid map.

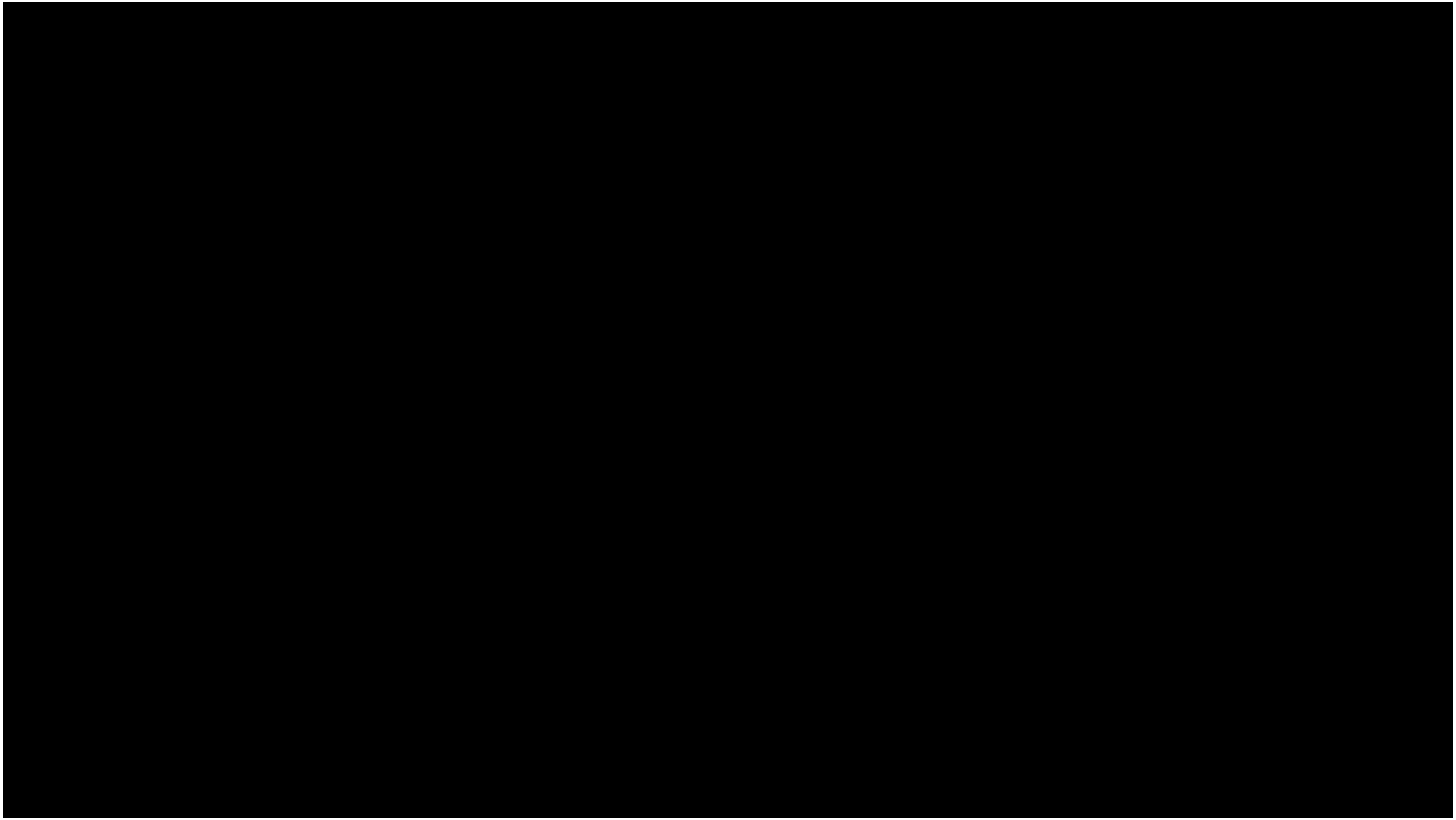
(c) Final R factor with side length 5823.

1941 poses, 2190 constraints, 14.2s or 7.3ms/step

- On Vesta and Ceres

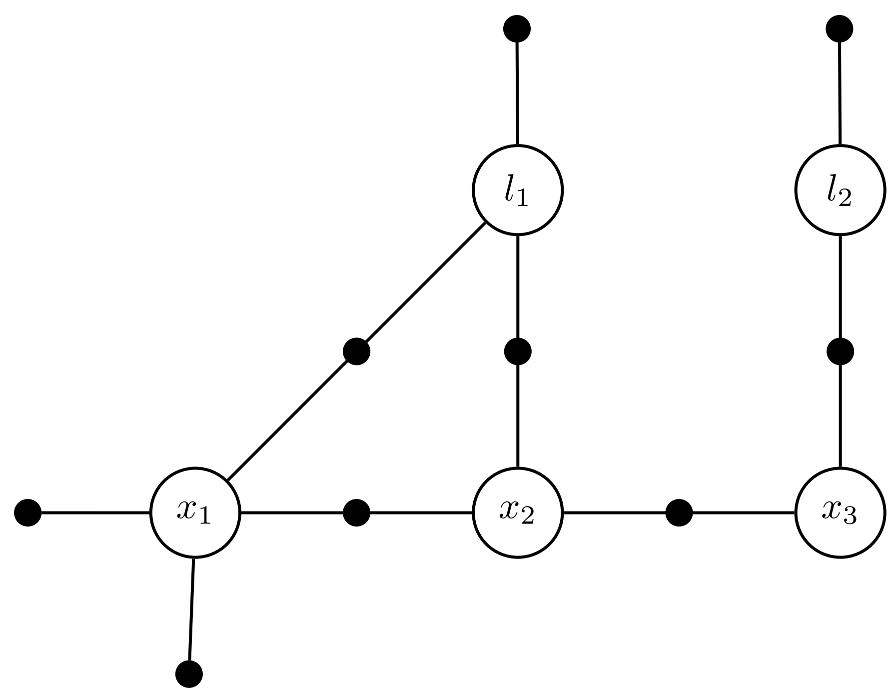


- On Vesta and Ceres



Variable Elimination

- Choose Ordering
- Eliminate one node at a time

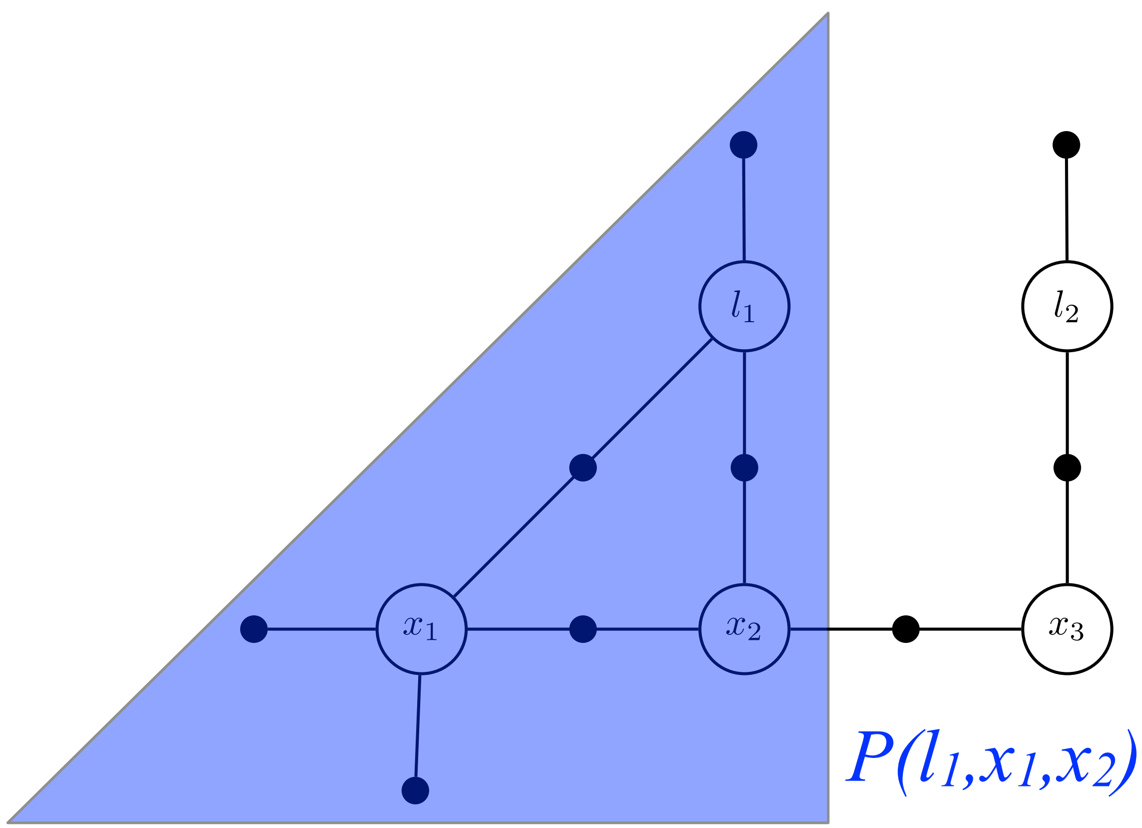


l_1	l_2	x_1	x_2	x_3
x				
x		x		
x			x	
	x			
	x			x
		x		
		x		
		x	x	
			x	x

- Express node as function of adjacent nodes

Variable Elimination

- Choose Ordering
- Eliminate one node at a time



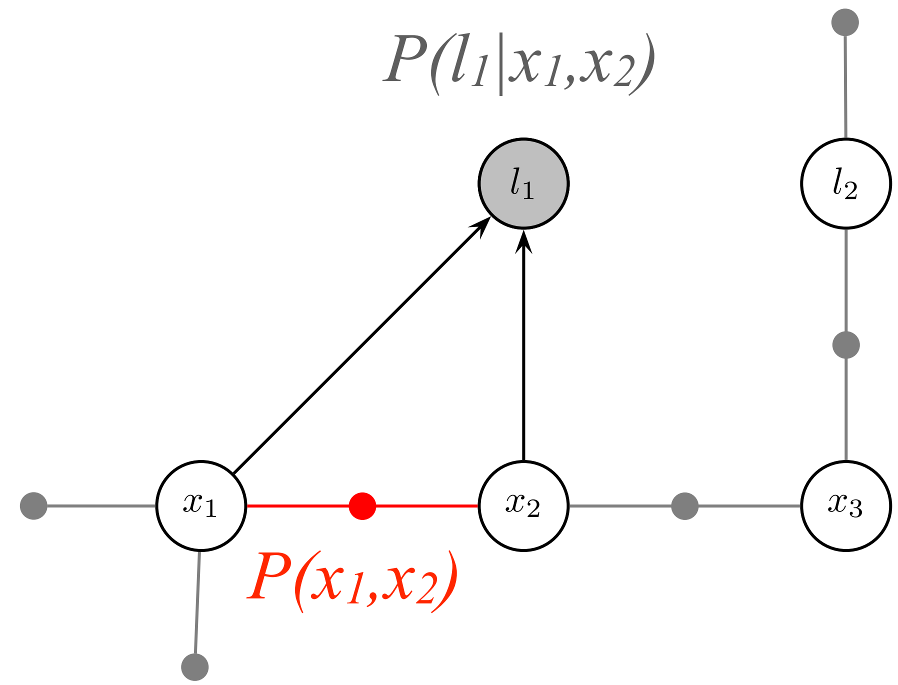
l_1	l_2	x_1	x_2	x_3
x				
x		x		
x			x	
	x			
	x			x
		x		
		x		
		x	x	
			x	x

- Express node as function of adjacent nodes

Basis = Chain Rule ! e.g. $P(l_1,x_1,x_2)=P(l_1|x_1,x_2)P(x_1,x_2)$

Small Example

- Choose Ordering
- Eliminate one node at a time



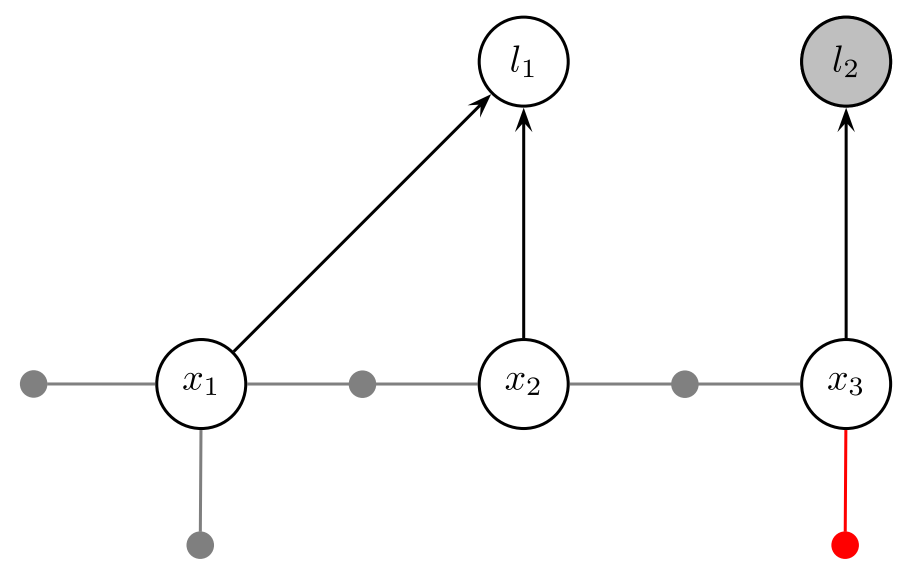
l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			
	x			x
		x	x	
		x		
		x		
		x	x	
			x	x

- Express node as function of adjacent nodes

Basis = Chain Rule ! e.g. $P(l_1,x_1,x_2)=P(l_1|x_1,x_2)P(x_1,x_2)$

Small Example

- Choose Ordering
- Eliminate one node at a time



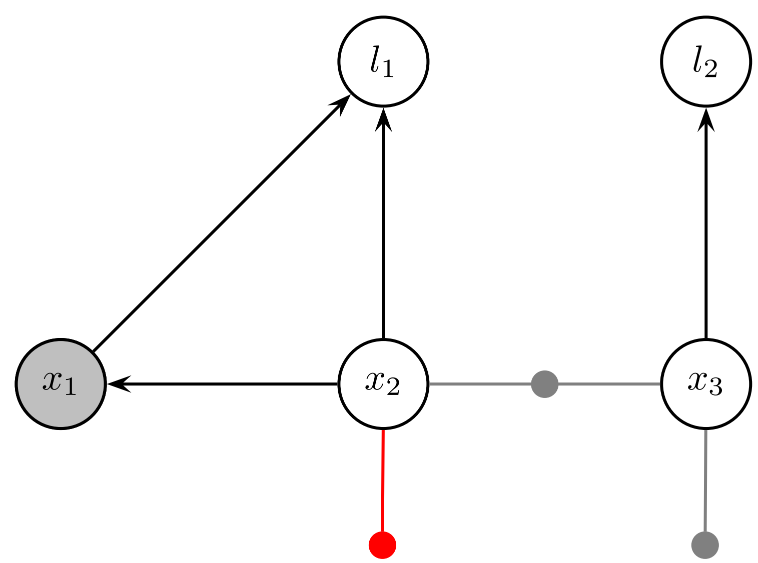
l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			x
		x	x	
		x		
		x		
		x	x	
			x	x
				x

- Express node as function of adjacent nodes

Small Example

- Choose Ordering
- Eliminate one node at a time

l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			x
		x	x	
			x	
			x	x
				x

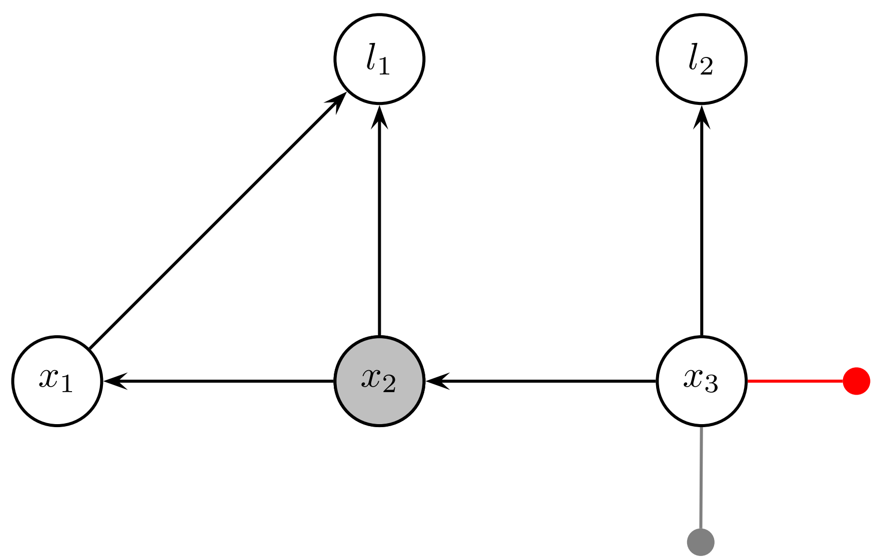


- Express node as function of adjacent nodes

Small Example

- Choose Ordering
- Eliminate one node at a time

l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			x
		x	x	
			x	x
				x
				x

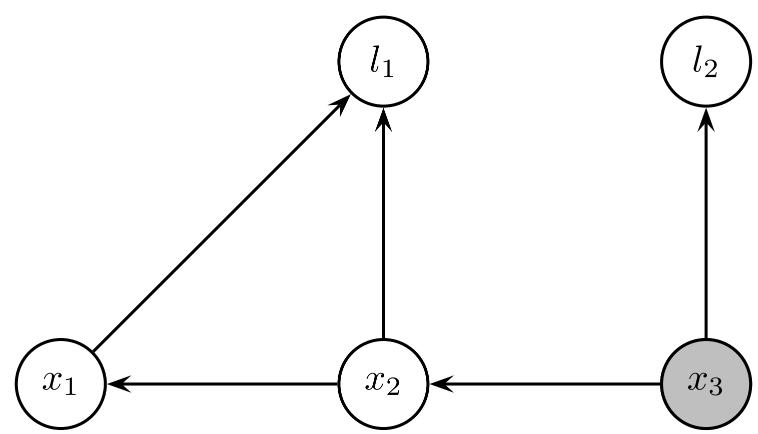


- Express node as function of adjacent nodes

Small Example

- Choose Ordering
- Eliminate one node at a time

l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			x
		x	x	
			x	x
				x

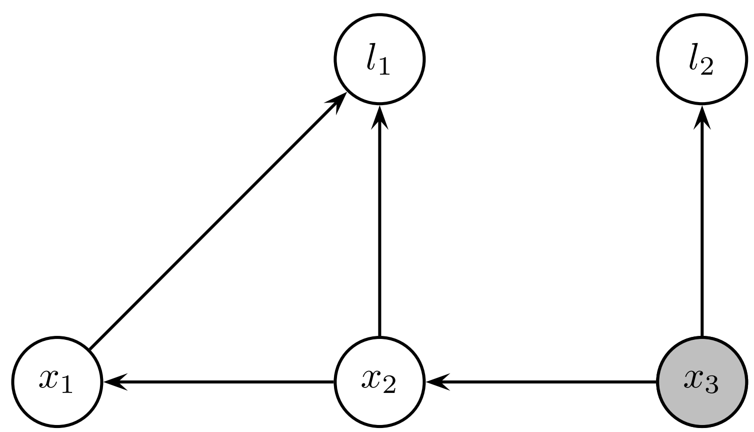


- Express node as function of adjacent nodes

Small Example

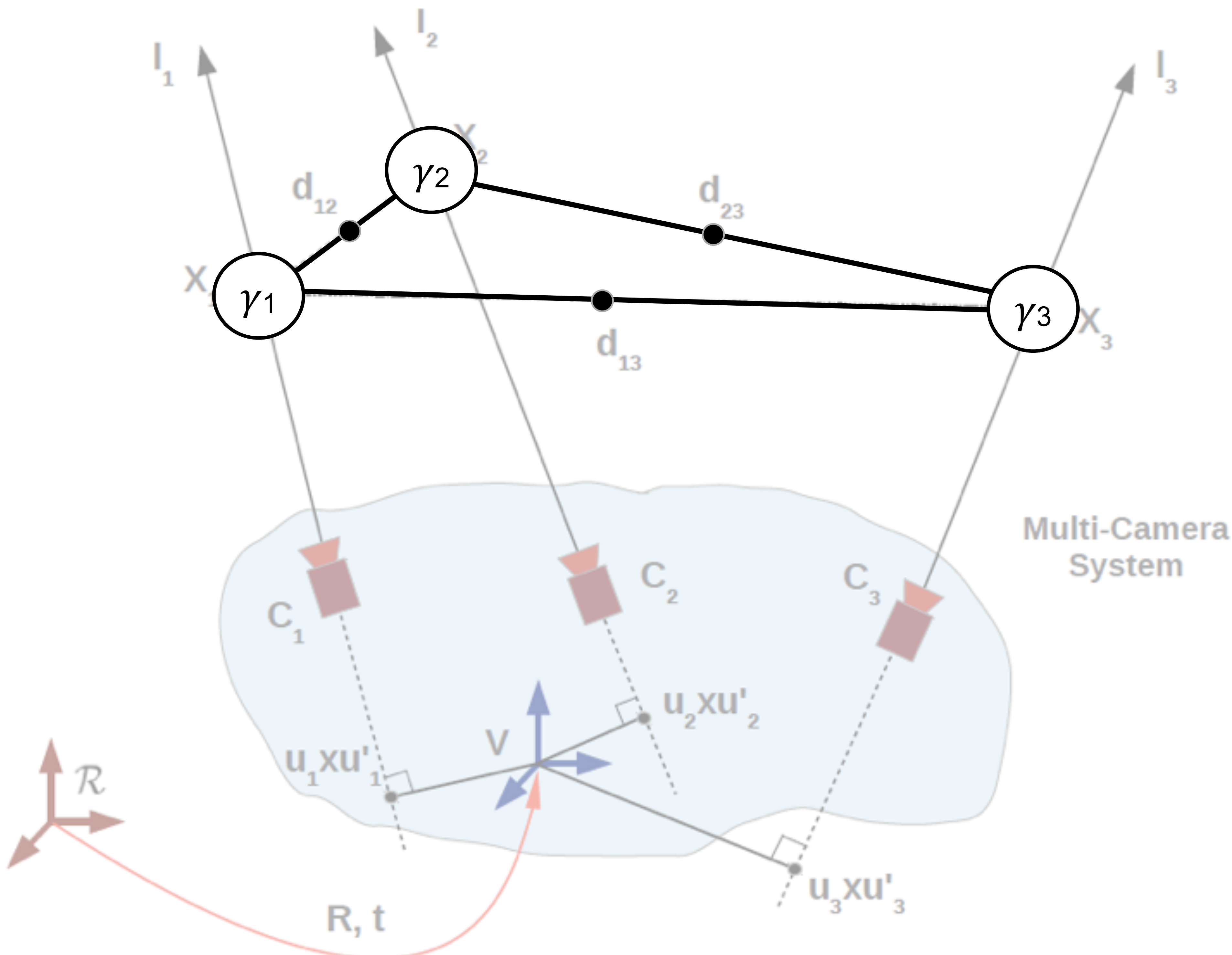
- End-Result = Bayes Net !

l_1	l_2	x_1	x_2	x_3
x		x	x	
	x			x
		x	x	
			x	x
				x



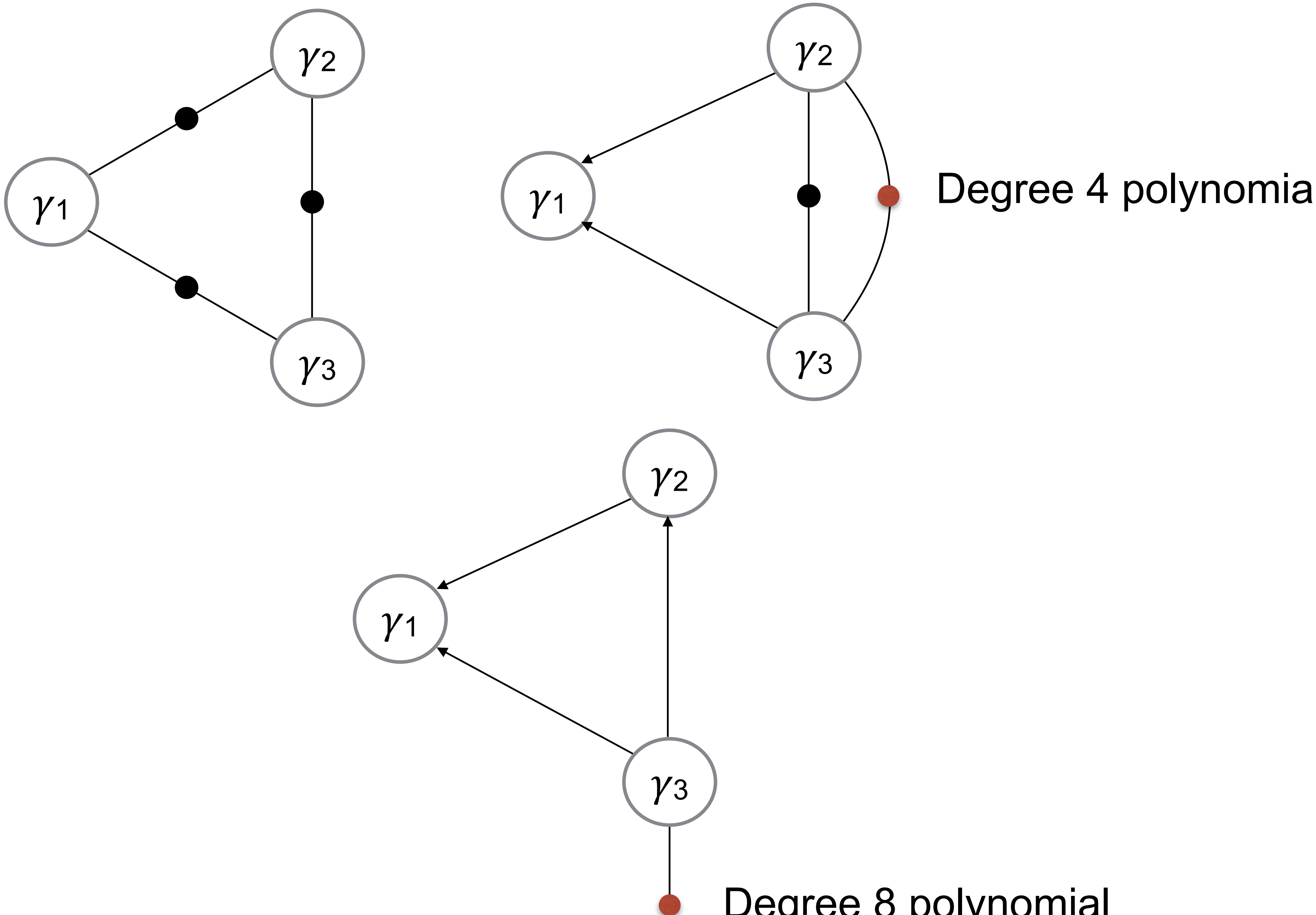
Polynomial Equations

Gim Hee Lee's thesis: multi-camera pose estimation

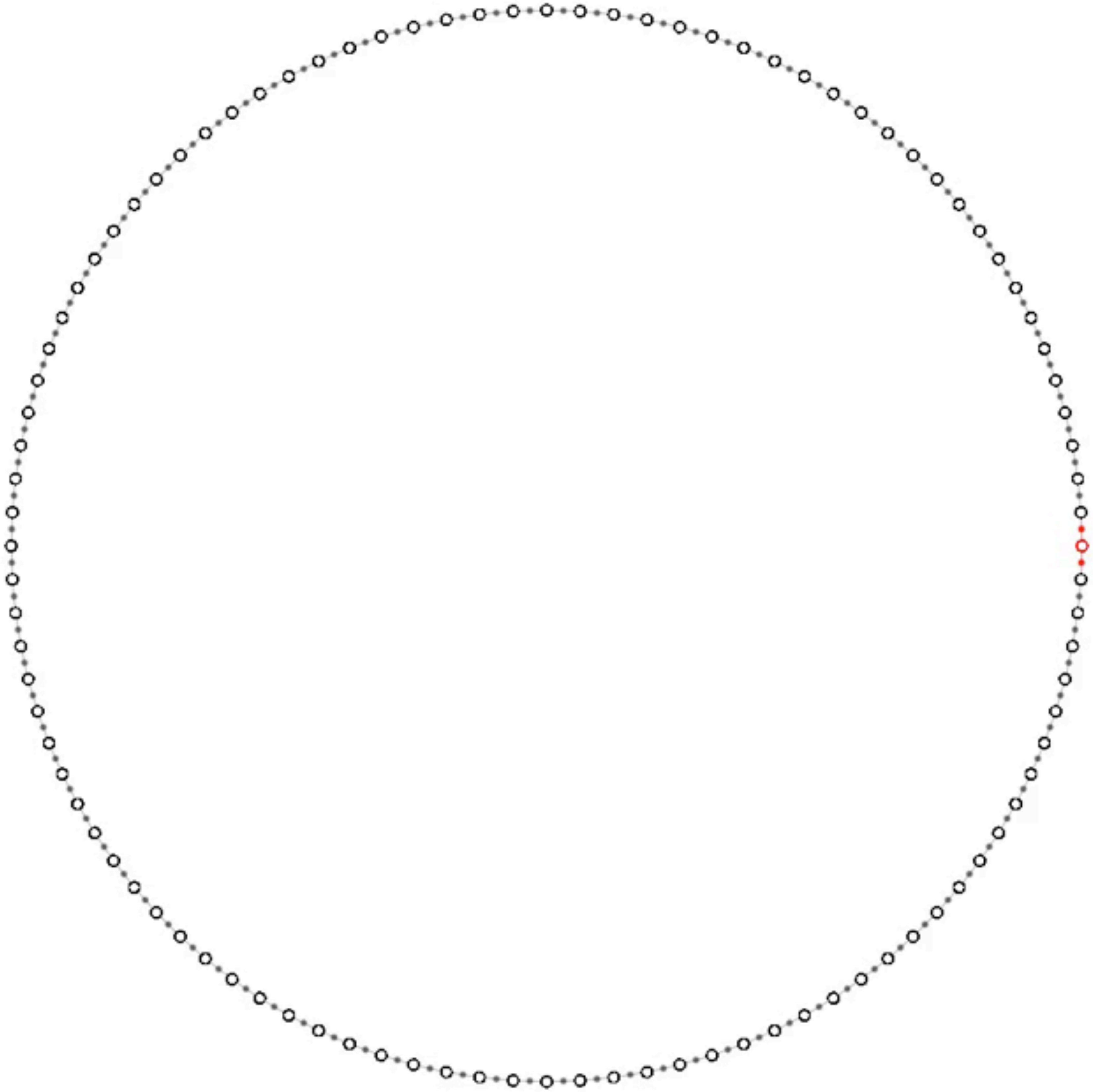


Polynomial Equations

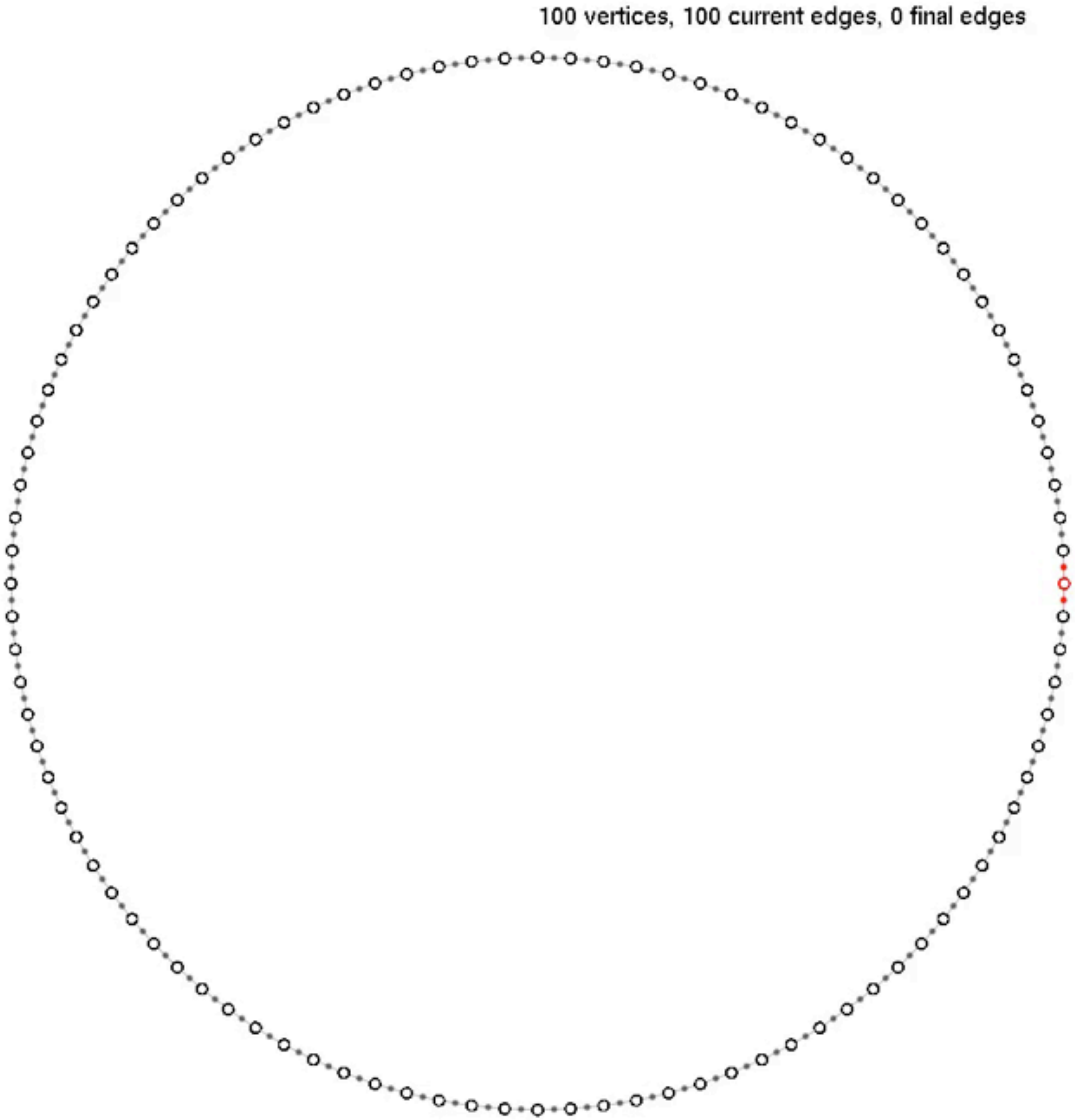
Three degree 2 polynomials, each in only 2 variables



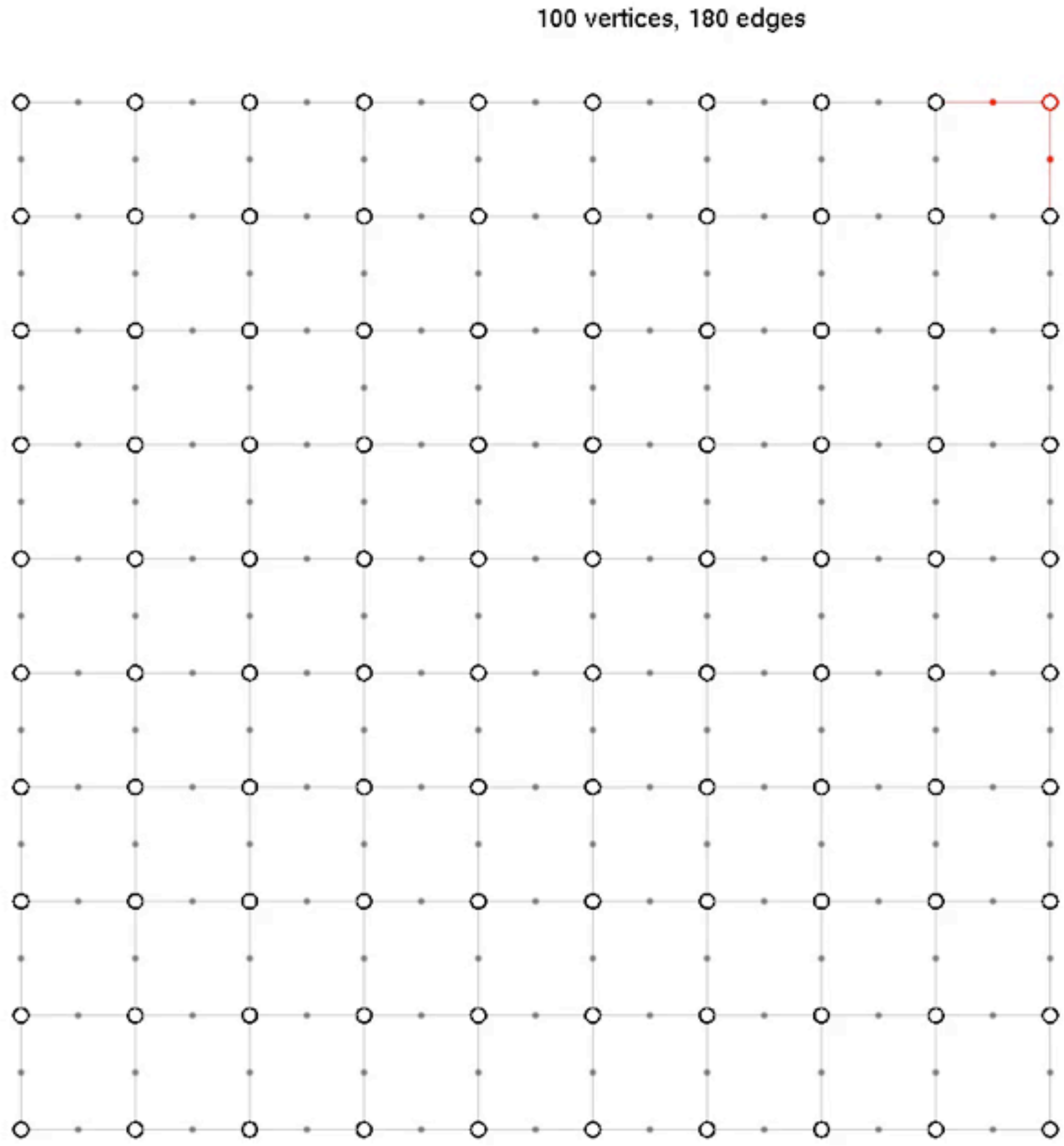
Elimination at work



Elimination at work



Elimination at work



Elimination at work