Tracking Estimation and Beginner Data Association

Diane Theriault; ‘00 (BA), ‘15 (PhD)
March 25, 2021

Who am I

niversity Student Link

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RSITY CLASS SCHEDULE - REPORT

Spring 2014 **Search by:** Class Number

	Title /Instructor	Cr Hrs	Type	Open Seats	Bld	Room	Day	Start	Stop	Notes
Stdents registering for CAS CS585 must register for two sections: a Lec section, and a Lab section.										
CAS CS585 A1	Imagevideo COM Theriault	4.0	Lecture	40			Tue,Thu	12:30pm	2:00pm	
CAS CS585 A2	Imagevideo COM Theriault	0.0	Lab	20			Fri	9:00am	10:00am	
CAS CS585 A3	Imagevideo COM Theriault	0.0	Lab	20			Fri	11:00am	12:00pm	

https://www.linkedin.com/in/dhtheriault

Bats

Bats are super cute

Bats eat bugs (moths, not really mosquitos)

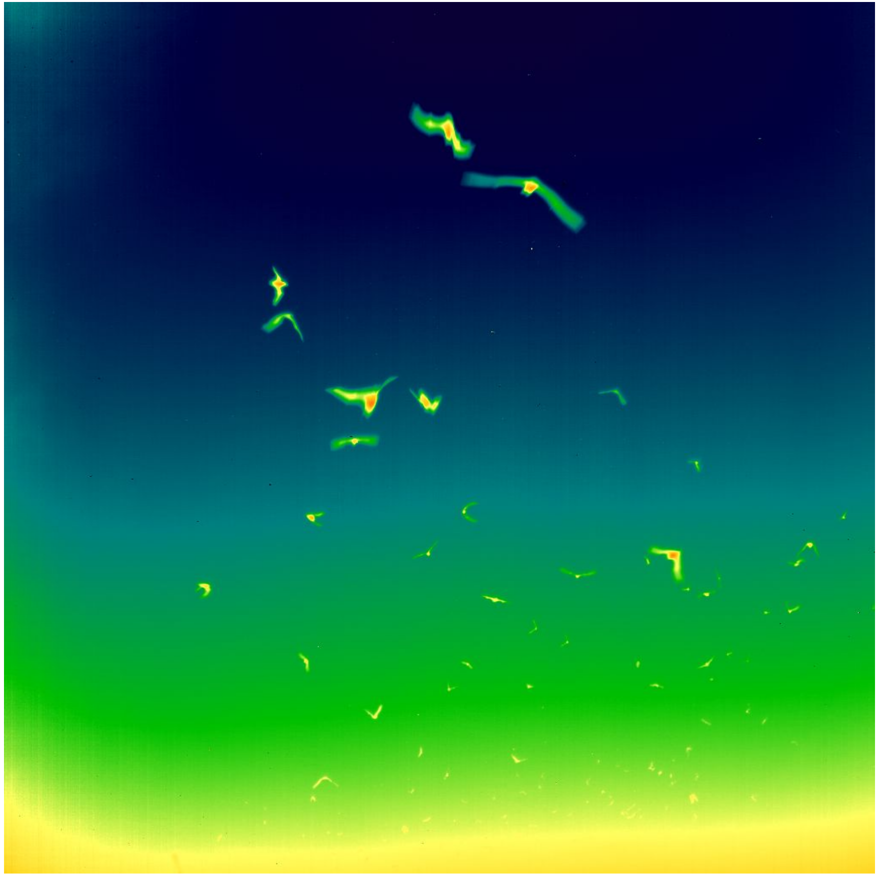
Bats

Bat colonies in TX
are very big

“How many are there?”

Bats

Infrared thermal video is cool



Bats

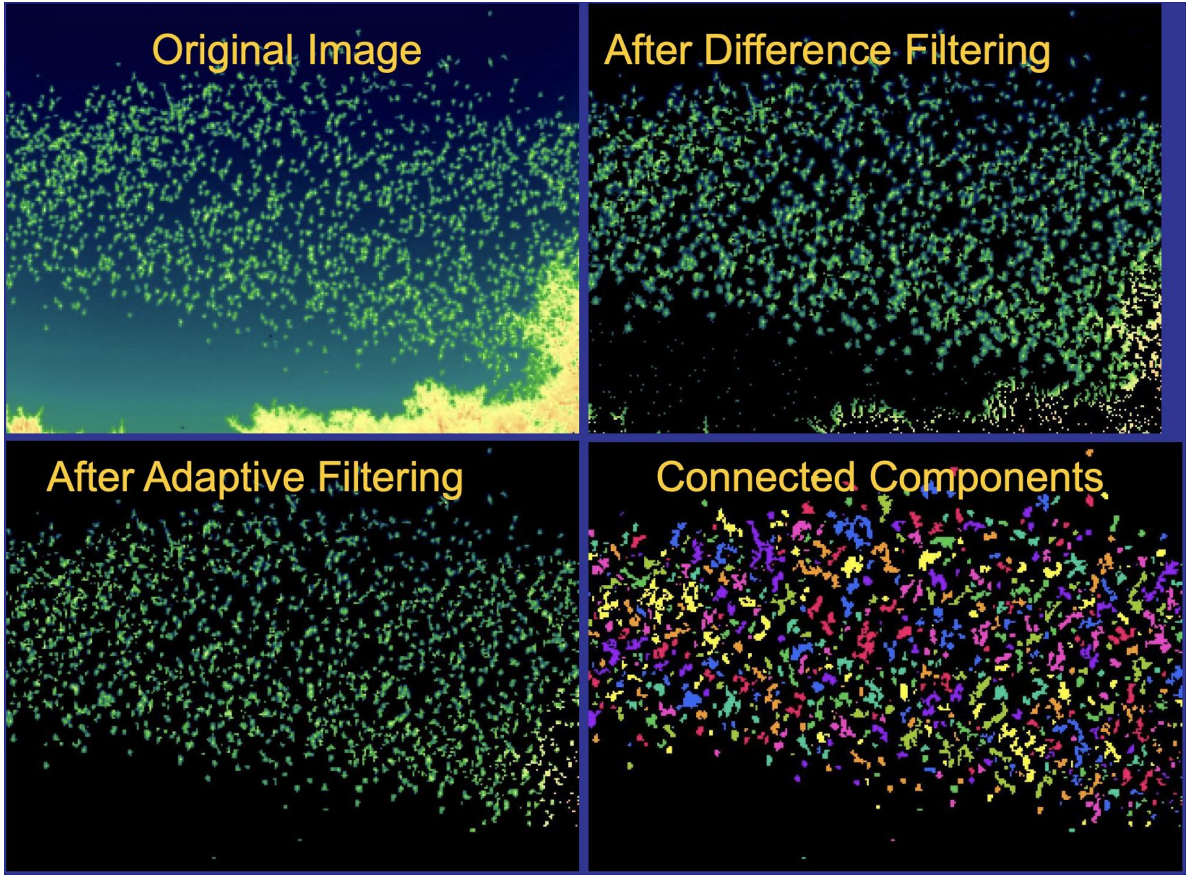
“How many are there?”

“How do they do that?”

[Alternate Link]

Assume: Detection

Given an image, find the regions that are interesting



Assume: Localization

Repeatably identify location of objects

Measurements vs State

Measurement: what you are able to observe

Example: Image position

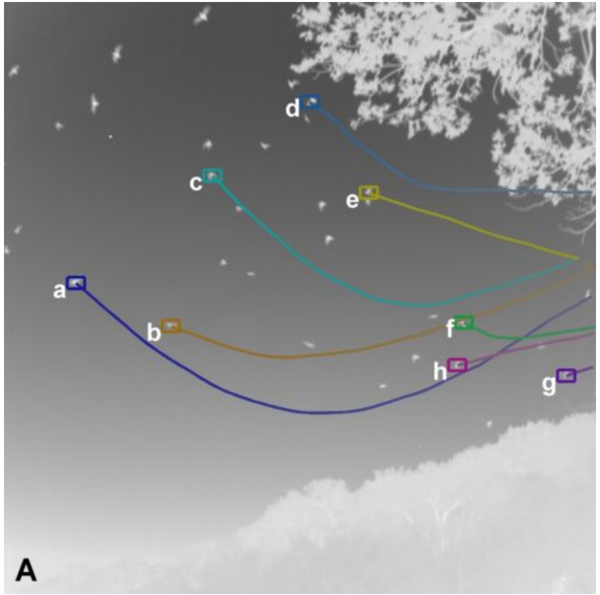
State: what you think is true

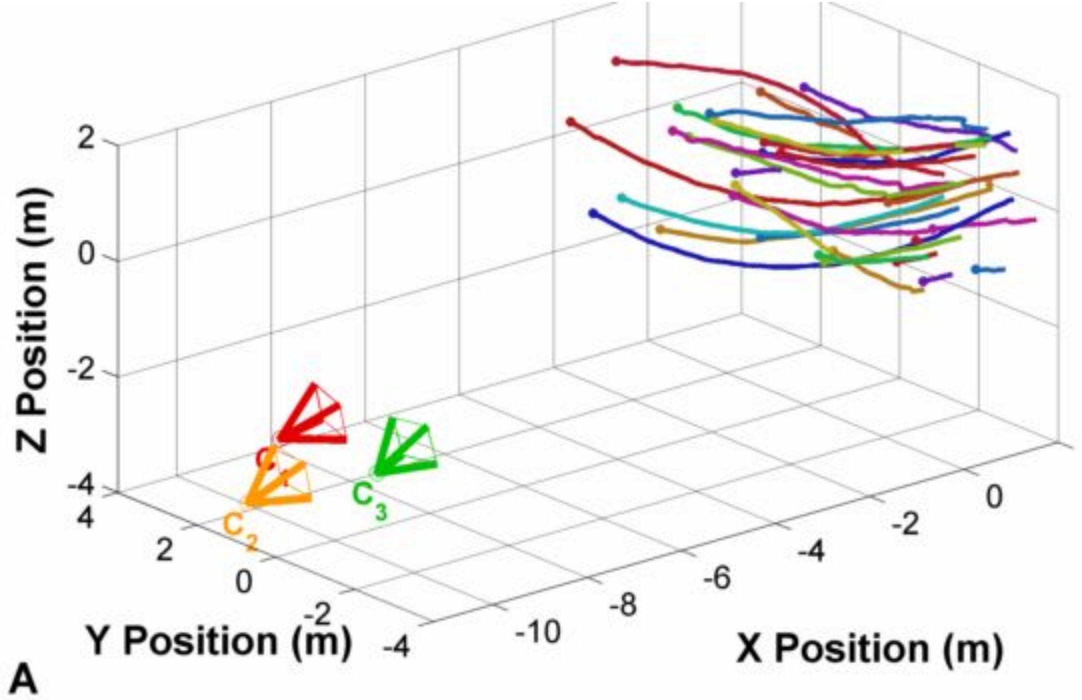
Example: Estimated Position

Example Derived Velocity (finite differences)

Measurements vs State

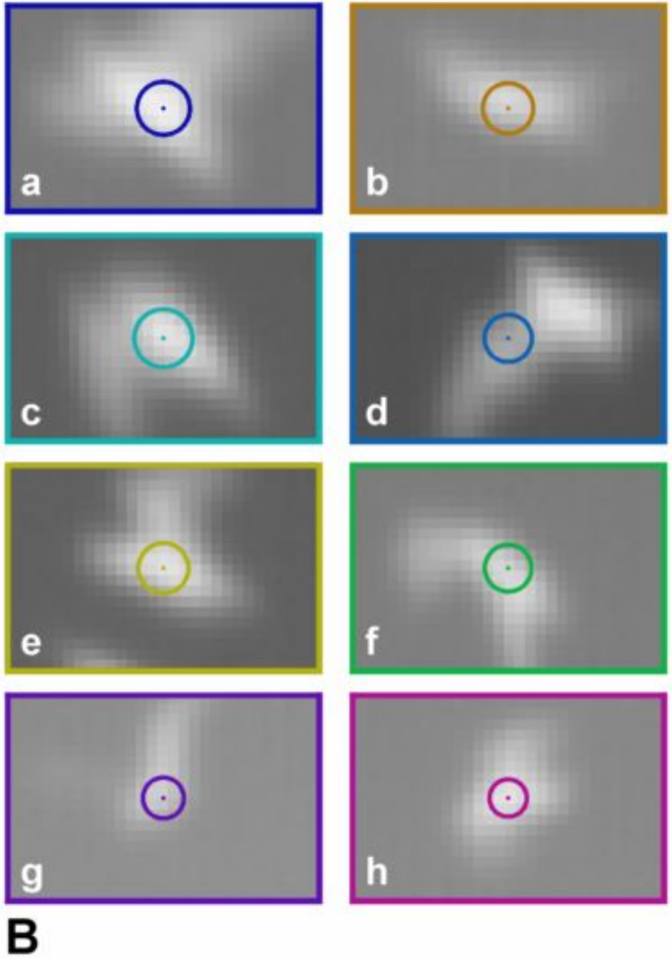
Measurement: Projected image position; State: 3D position





Why Estimation

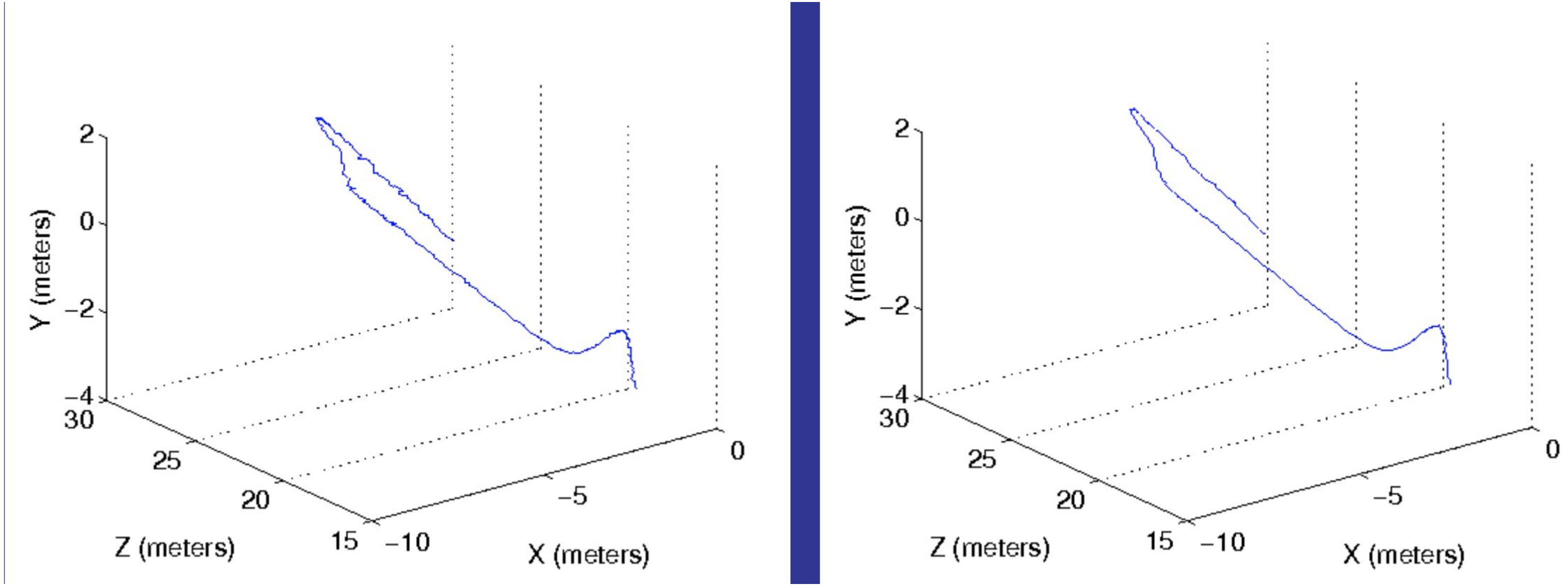
Measurements are noisy



Why Estimation

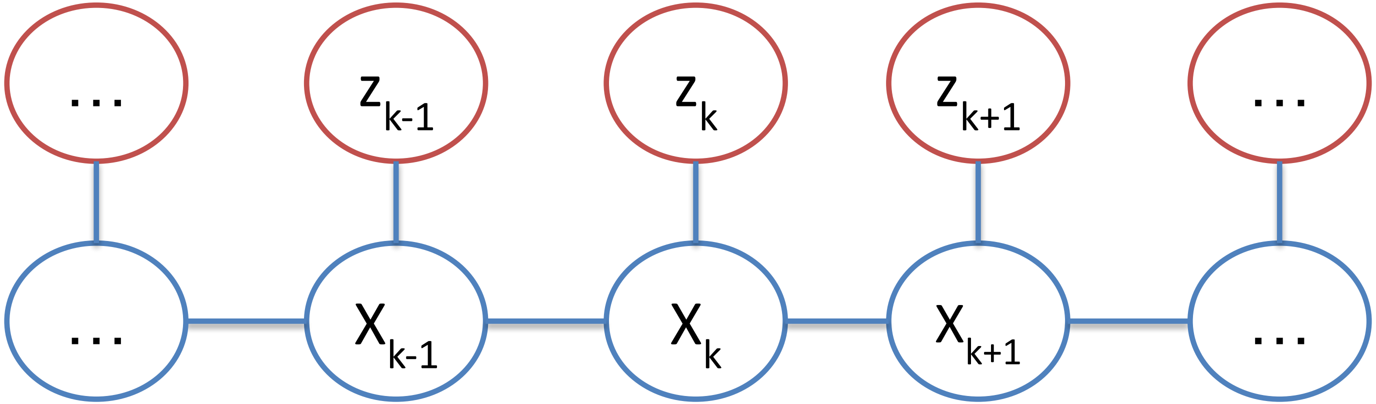
Measurements are noisy

Measurements may contain high frequency info that’s not interesting



What estimation

Goal: Infer state from measurements. State cannot be directly observed.



Components of Estimation

Measurement Model

Kinematic / State evolution Model

Math representation

Beliefs about the system, formatted for your math

Measurement Model

In: estimated state x_t

Out: estimated measurement $z_t = H(x_t)$

Example:

Position (p) + velocity (v) → collapse to position
$[p_{t1}\ p_{t2}\ v_{t1}\ v_{t2}] \rightarrow [z_{t1}\ z_{t2}]$

$$\begin{bmatrix} z_{t1} \\ z_{t2} \end{bmatrix} = \overbrace{\boxed{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}}^{H} \begin{bmatrix} p_{t1} \\ p_{t2} \\ v_{t1} \\ v_{t2} \end{bmatrix}$$

Kinematic Model (State Evolution Model)

In: previous state x_t

Out: estimated next state $x^-_{t+1} = A(x_t)$

"Prediction" or "evolution"

Example:

Constant velocity

$[p_{t+1,1}, p_{t+1,2}, v_{t+1,1}, v_{t+1,2}] = [p_{t1}+v_{t1}, p_{t2}+v_{t2}, v_{t1}, v_{t2}]$

$$\begin{bmatrix} p_{t+1,1} \\ p_{t+1,2} \\ v_{t+1,1} \\ v_{t+1,2} \end{bmatrix} = \overbrace{\boxed{\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}}^{A} \begin{bmatrix} p_{t1} \\ p_{t2} \\ v_{t1} \\ v_{t2} \end{bmatrix}$$

Other options: Constant position, acceleration

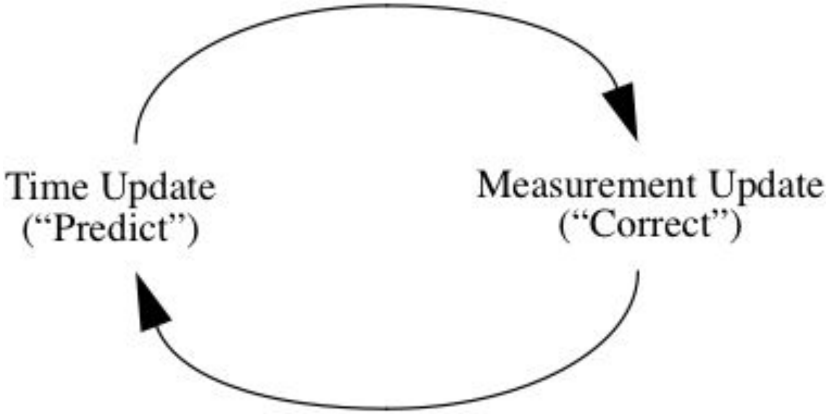
“Residual” or “Innovation”

Diff b/t actual measurement and prediction

$r_{k+1} = z_{k+1} - H(x^{-}_{t+1})$

$r_{k+1} = z_{k+1} - H(A(x_t))$

Update



Blend measurements and predictions

Tracking by detection: New state is the measurement

Recursive estimators: each estimate uses previous state as input

- Blend with hand-picked constants (alpha / beta filter)
- Blend with super fancy constants (Kalman filter)

How estimation: Alpha / Beta filter

Hand-picked constants

https://en.wikipedia.org/wiki/Alpha_beta_filter

State = [position (p), velocity (v)]

$p_{t+1} = p_t + \alpha \; r_{t+1}$

$v_{t+1} = v_t + \square \; / \; [\Delta T] \; r_{t+1}$

How estimation: Kalman Filter

Main extra piece: Uncertainty estimates for both state evolution and measurement

Other extra piece: Knowledge about how state *should* change (e.g. robot steering)

$B_t u_t$ are the control model and control vector

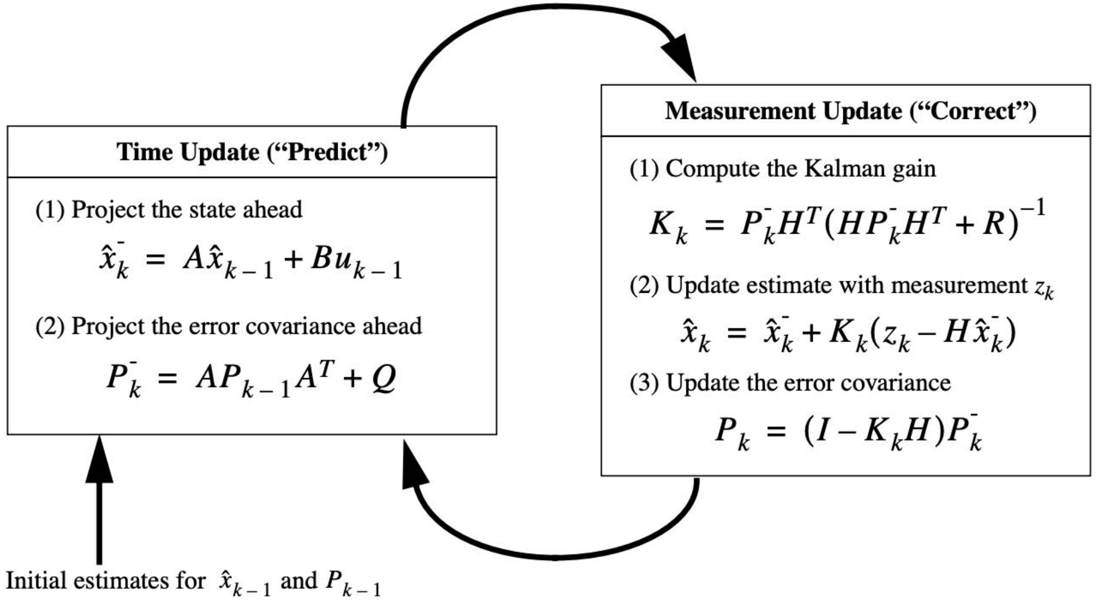
- $z_t = H(x_t) + v_t$ (v is noise term. ex: Gaussian with covariance R != Q)
- $x_{t+1} = A(x_t) + B_t u_t + w_t$ (w is noise term. ex: Gaussian with covariance Q)
- P_t Covariance matrix representing uncertainty

Update x_t and P_t by choosing weights based on uncertainty estimates

How estimation: Kalman Filter

Super fancy derivation formulated as **minimization of residuals**, but the result of the derivation is that you **can compute in terms of noise only**

http://www.cs.unc.edu/~welch/media/pdf/kalman_intro.pdf



How estimation: Kalman Filter

Accurate uncertainty covariances are actually really important

If your process noise is too large, your tracks won't follow maneuverable objects well
If your process noise is too small, your tracks will be very wobbly

- Process Noise (Q): how much uncertainty do you expect in your state evolution?
  - Ex: bats fly 10m/s. frame rate 131.5 fps : 7 cm per frame.

- Measurement Noise (R): how much uncertainty do you have in your measurements?
  - Ex: with three cameras, we can use camera geometry to estimate our expected uncertainty

How estimation: Kalman Filter

How to produce a smoothed / filtered track:

That’s easy: For every time step, use the state estimate instead of the state backed out from the measurement

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$$

Questions about estimation

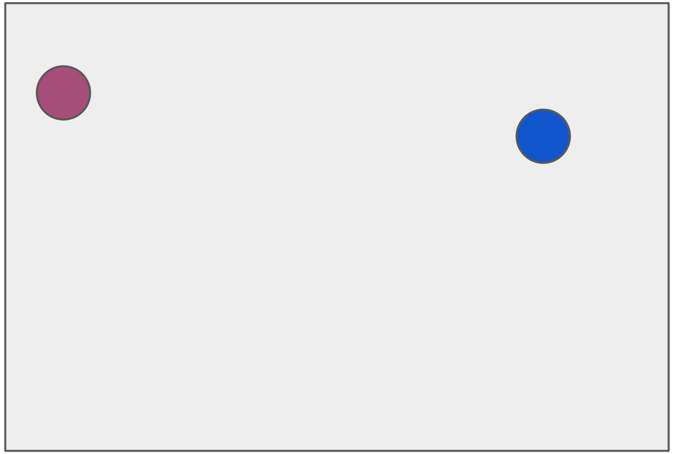
We are about to shift to a new topic

Beginner Data Association

Track two objects far apart

Decide which dots go together

Track by detection if velocities are small



Beginner Data Association

Track many objects

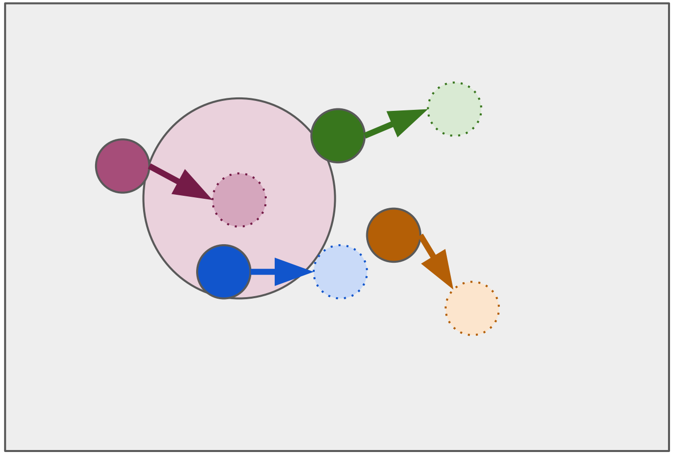
Decide which dots go together

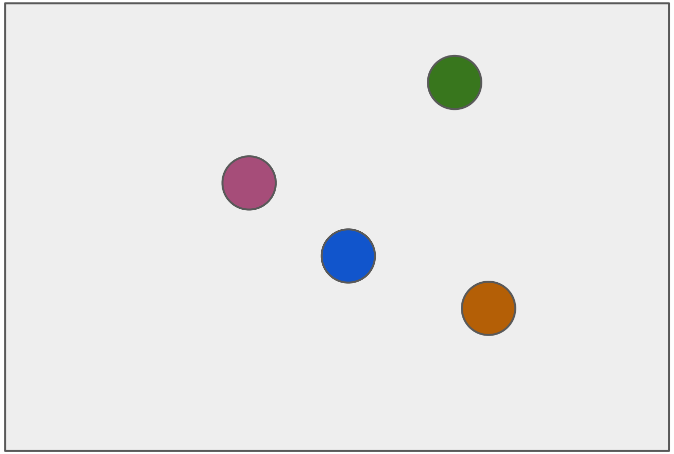
Using predictions

Gates

Lots of potential algorithms / data structures

The harder your problem is, the more important it is to be able to formulate it in math to use general solvers



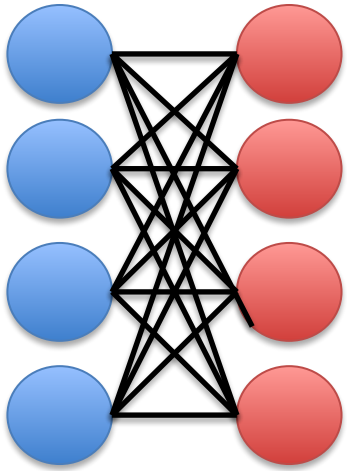


Beginner Data Association

"Global Nearest Neighbor Standard Filter" (GNNSF)

Bipartite matching

- Hungarian / Kuhn-Munkres assignment algorithm
- POLYNOMIAL (don't let anyone tell you otherwise)
- http://en.wikipedia.org/wiki/Hungarian_algorithm



Beginner Data Association

"Global Nearest Neighbor Standard Filter" (GNNSF)

Matrix formulation (check rows and columns with your library docs!)

$$\underbrace{\begin{array}{cc} & \text{measurements} \\ \text{tracks} & \begin{bmatrix} 0.8 & 0.3 & 0.9 & 0.7 \\ 0.2 & 0.9 & 0.8 & 0.7 \\ 0.9 & 0.3 & 0.8 & 0.2 \\ 0.8 & 0.9 & 0.4 & 0.9 \end{bmatrix} \end{array}}_{\text{Cost matrix (c)}} \qquad \underbrace{\begin{array}{cc} & \text{measurements} \\ \text{tracks} & \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}}_{\text{Assignment matrix (x)}}$$

$$\min_{x_{i,j}} \sum c_{i,j} x_{i,j}$$

$$s.t. \sum_{i:i>0} x_{i,j} = 1$$

$$\sum_{j:j>0} x_{i,j} = 1$$

$$x_{i,j} \in \{0,1\}$$

Multi-target Tracking - Put it all together

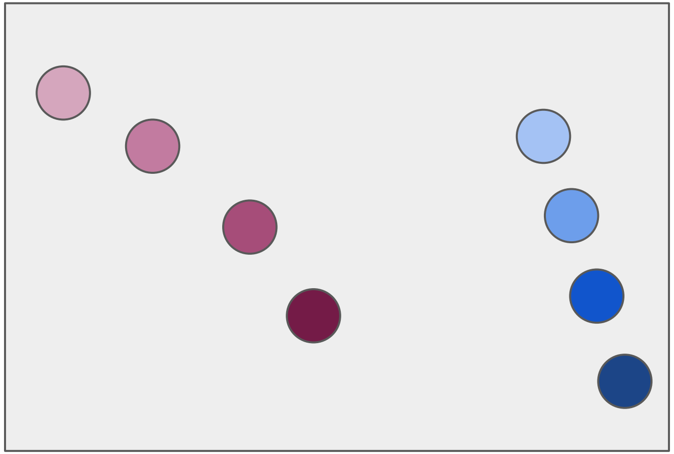
You need to do this in your assignment

- Run detection / localization to find things in your first image

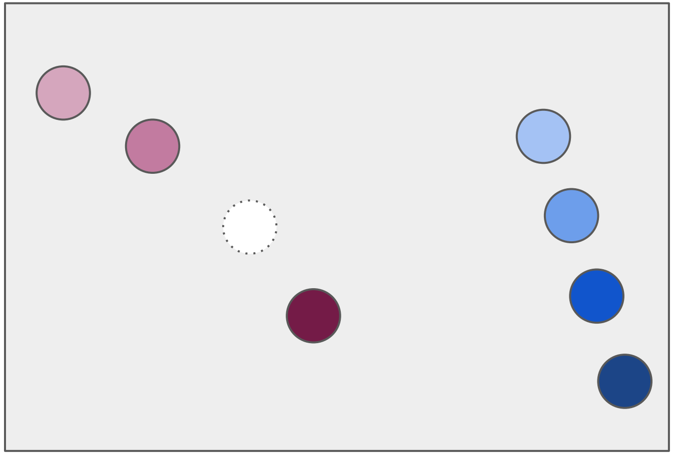
- for v in video frames:
    - Predict state of known objects
    - Run detection / localization to get measurements from your image
    - Do data association to decide which measurements should go with which state
    - Update state of known objects

Data association fails - Missing data

Answer: Coasting / dummy variables



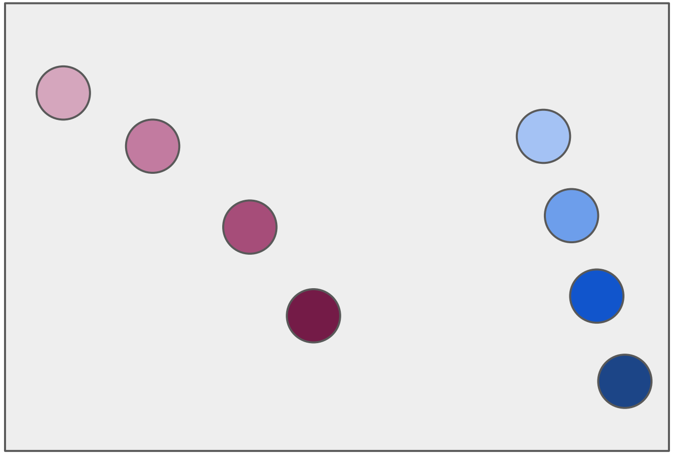
Aspirational



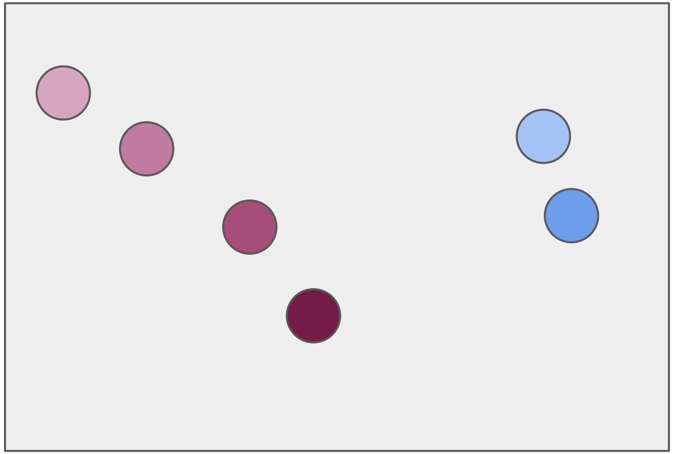
Actual

Data association fails - Lost tracks

Answer: “dummy” nodes, cost for lost track



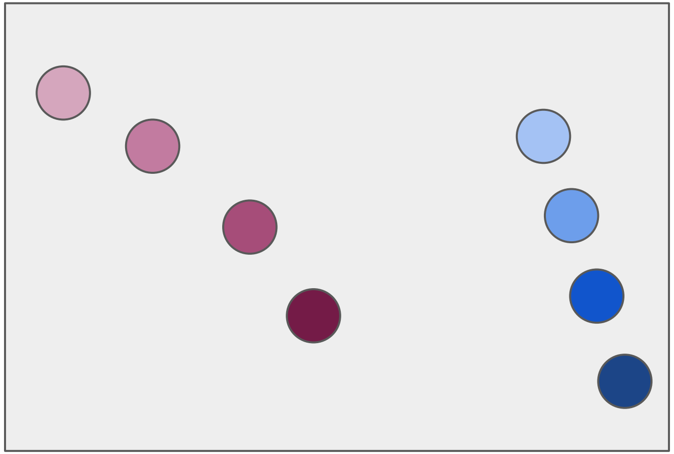
Aspirational



Actual

Data association fails - Spurious measurements

Answer: “dummy” nodes, gating



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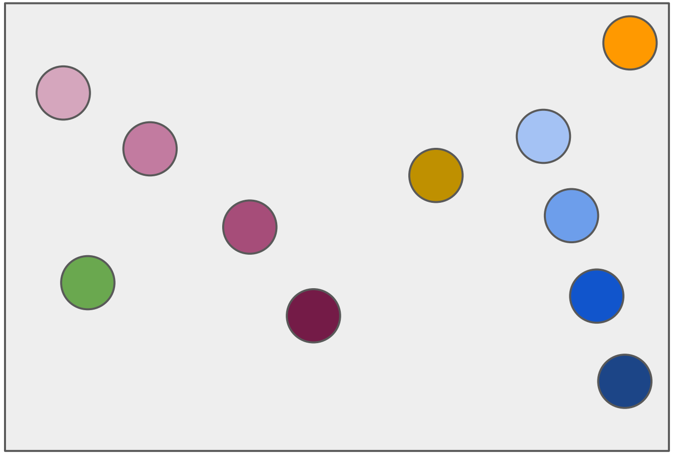
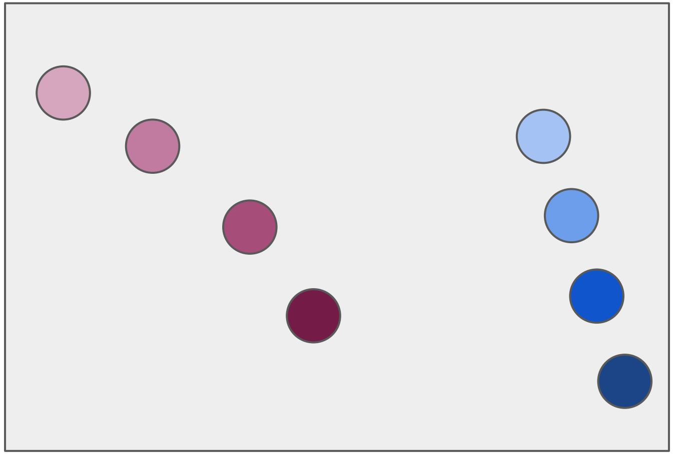


Aspirational

Data association fails - New tracks

Answer: “dummy” nodes, cost for new tracks (how do you know it’s not spurious?)



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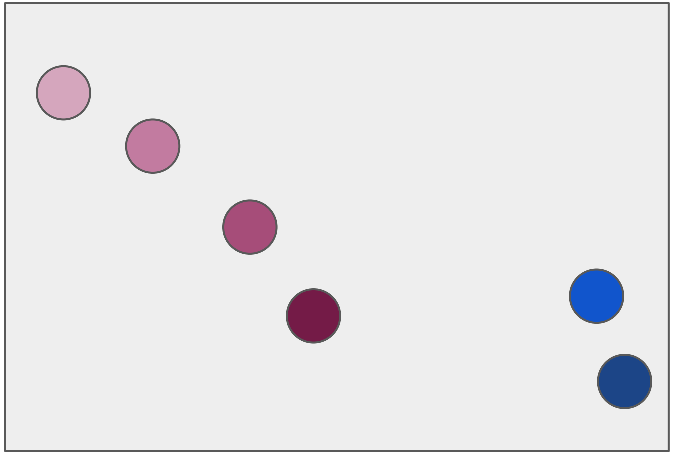
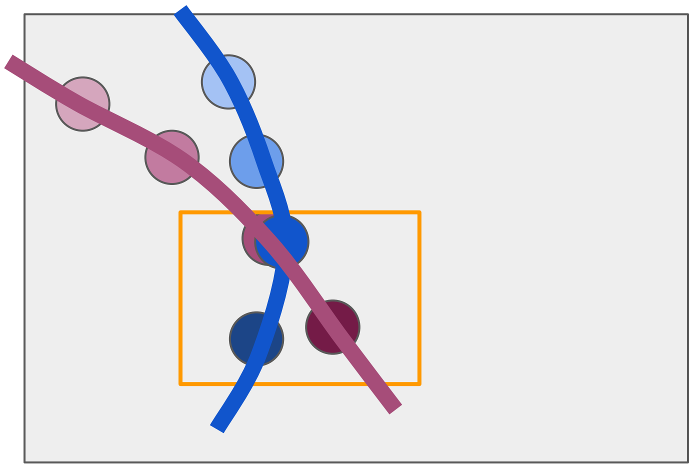


Actual

Data association fails - ambiguous motion / track switching

Answer: MHT



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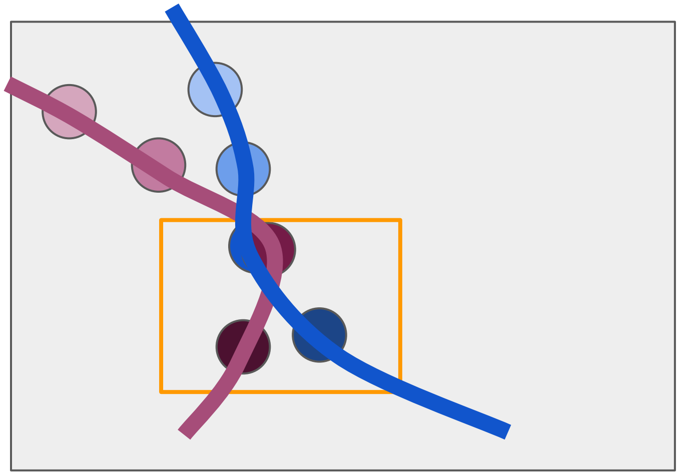

Janky Track Switch

Questions

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Tracking
Estimation and
Beginner Data Association

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March 25, 2021

Tracking
Advanced Data Association and The Importance of Data Collection

Diane Theriault; ‘00 (BA), ‘15 (PhD)
March 30, 2021

Last time

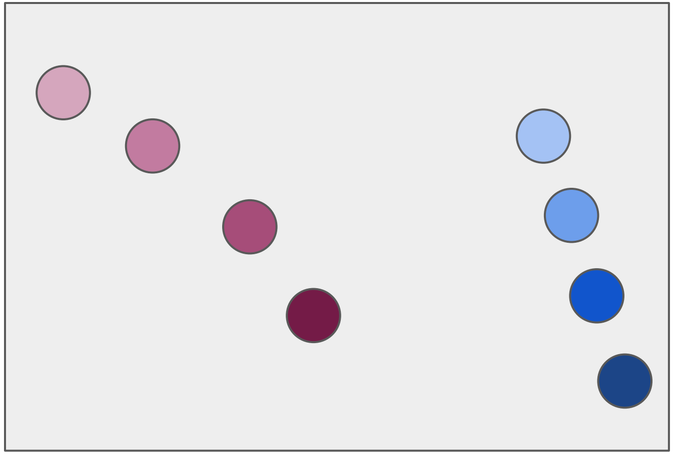
- State != Measurements

- Estimation means “how to use measurements to infer state”
    - Kinematic model uses current state to **predict** future state
    - Measurement model uses state to predict measurement
    - The “innovation” or “residual” is the
      difference between the prediction and measurement

- Kalman filter is a popular tool for doing estimation
    - Key feature: uncertainty estimate along with state estimate

Last time

- Data Association = “put the dots together”
- Data Association != Estimation
- **The harder your problem is, the more important it is to be able to formulate it in math to use general solvers**

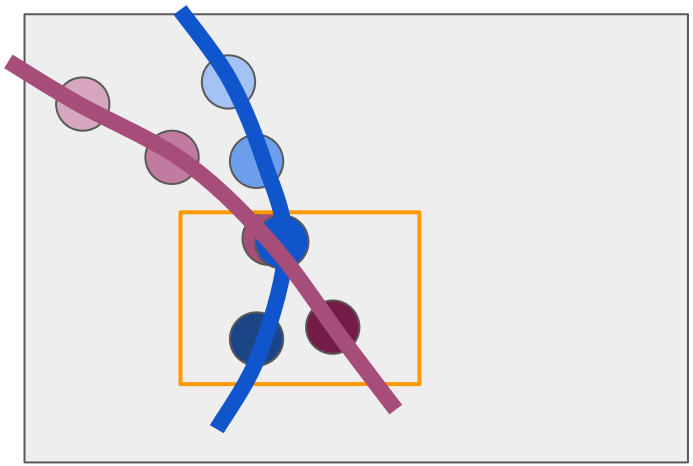


- Bi-partite matching is polynomial

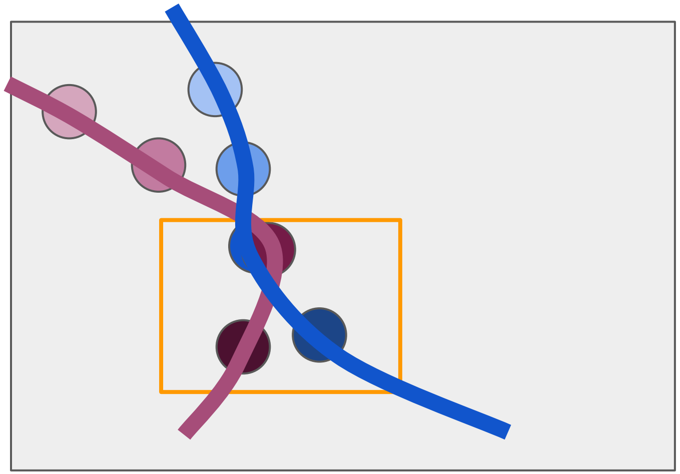
- Cost Matrix is real-valued
- Constraint Matrix is integer (boolean) valued

Data association fails - ambiguous motion / track switching

Answer: MHT (Multiple Hypothesis Tracking)



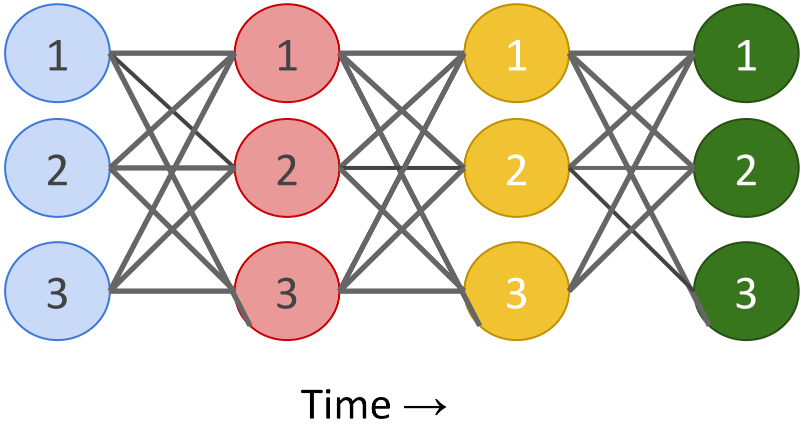
Aspirational



Janky Track Switch

Advanced Data Association: Multidimensional Assignment

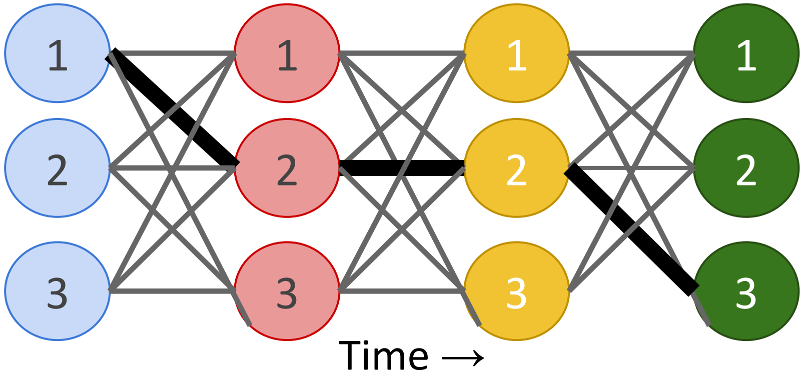
- Tri-partite (or higher) matching
- Ex: measurements from 3 or more frames of video.



- This actually is NP Complete (but we won't let that stop us)
- https://www.optimization101.org/ Chapters 12 and 13

Advanced Data Association: Multidimensional Assignment

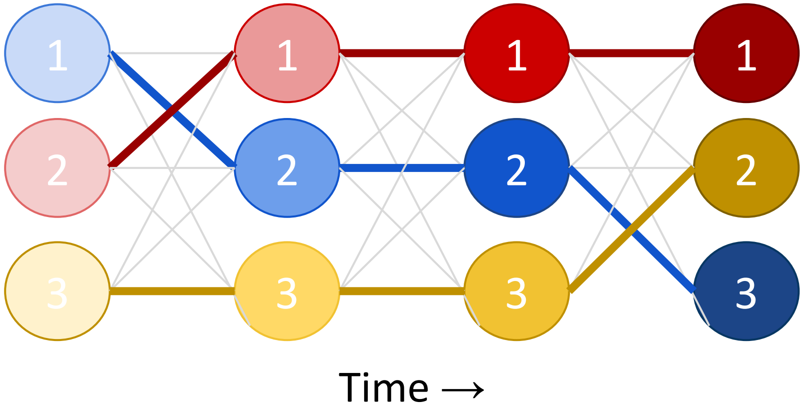
- Nodes are measurements
- Links are (potential) associations



- Path through the graph from left to right is a track

Tracking as Multi-dimensional Assignment

- Restate Multi-target tracking as multi-dimensional assignment:
- “Choose the best possible set of tracks so that each measurement is used only once”

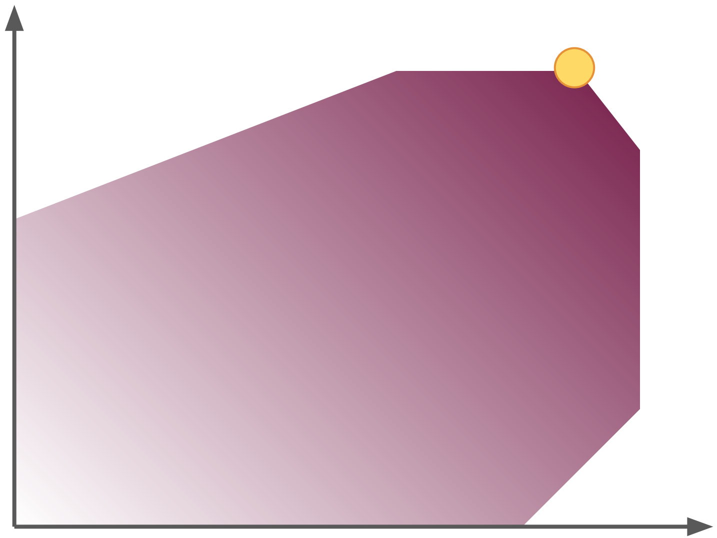


- How to formulate data association task mathematically?

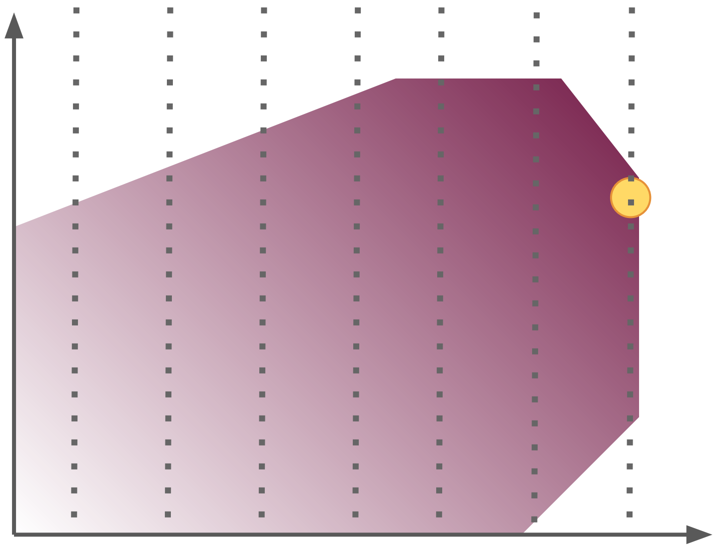
Questions

Linear and integer programming

https://en.wikipedia.org/wiki/Linear_programming

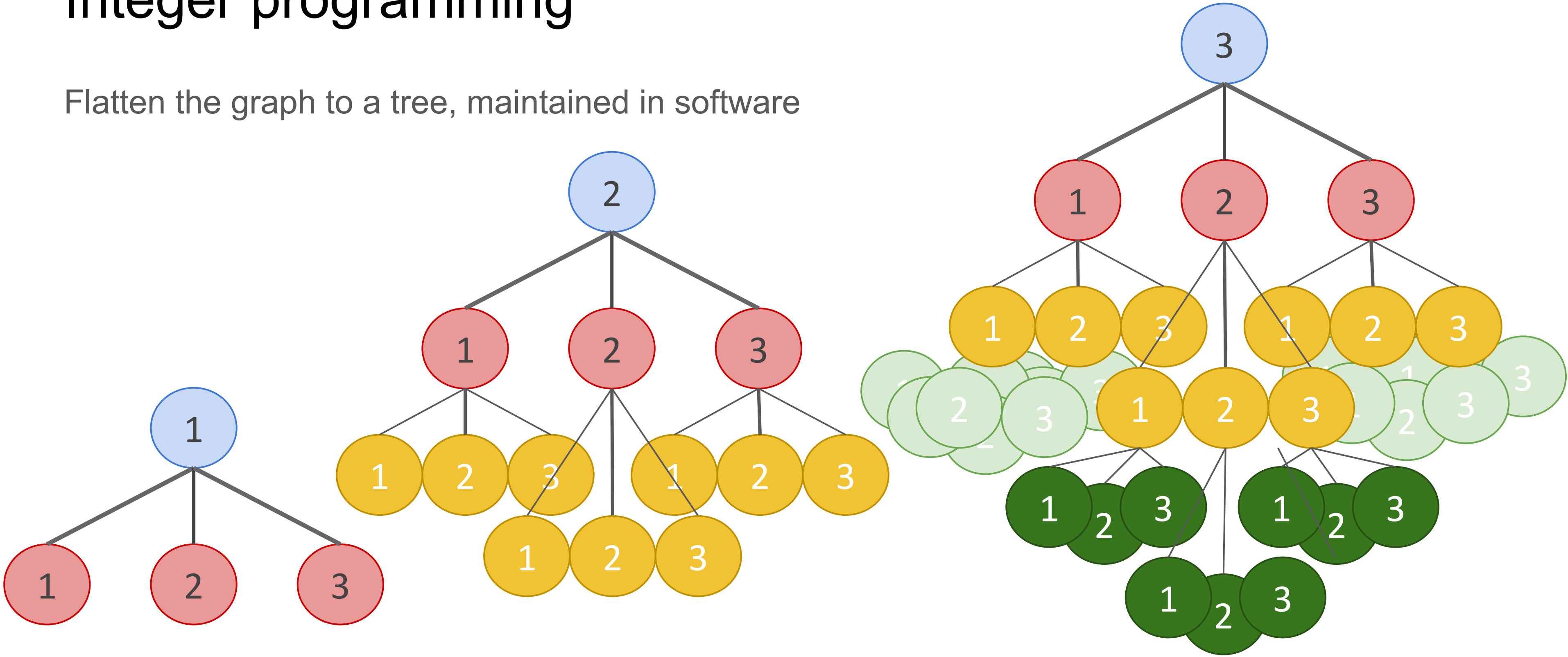


https://en.wikipedia.org/wiki/Integer_programming



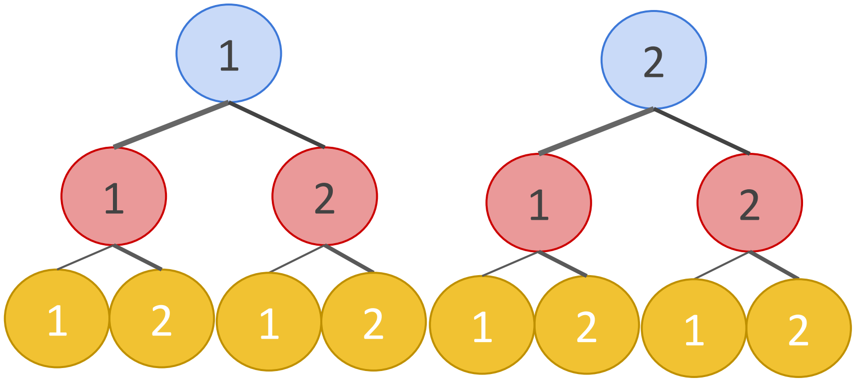
Solving Multi-dimensional Assignment with Integer programming

Flatten the graph to a tree, maintained in software



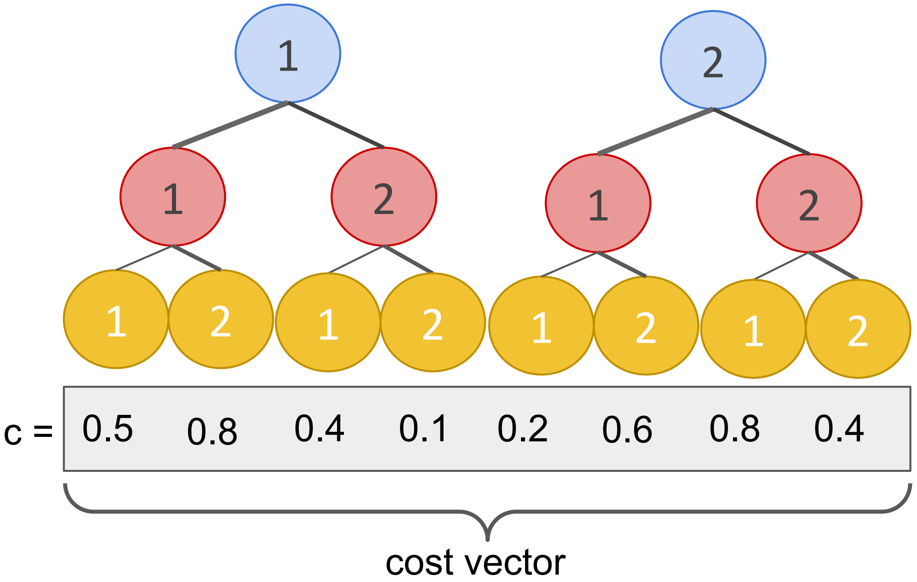
Solving Multi-dimensional Assignment with Integer programming

(Visualization pruned)



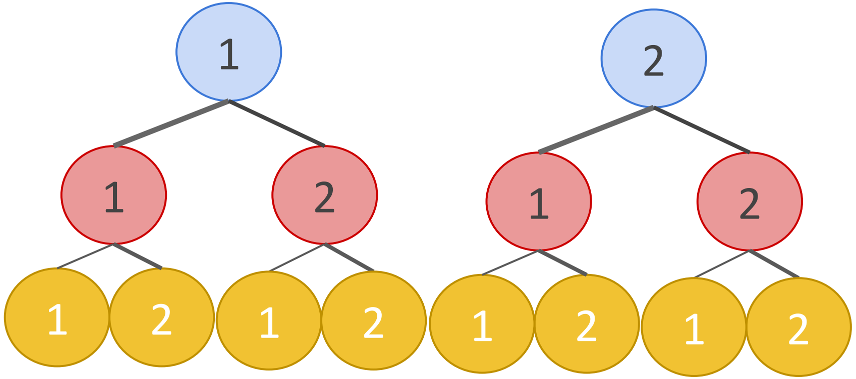
Solving Multi-dimensional Assignment with Integer programming

Score the leaves; e.g. average **magnitude of residuals, or probabilistic formulation from Kalman uncertainties**



Solving Multi-dimensional Assignment with Integer programming

Construct constraint matrix. Columns are tracks, Rows are measurements



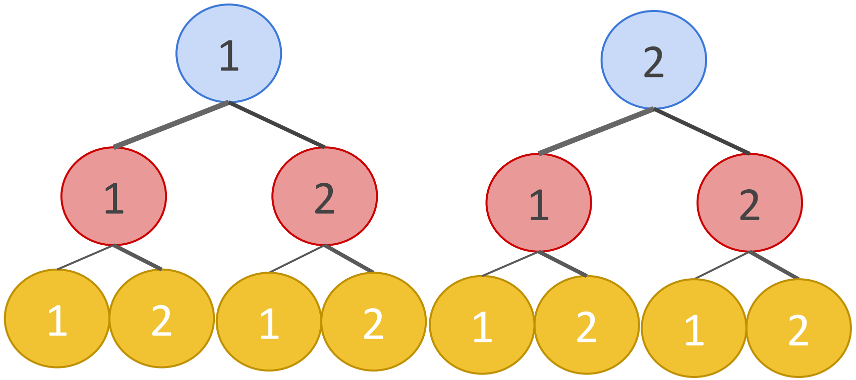
$$\underbrace{c = \begin{bmatrix} 0.5 & 0.8 & 0.4 & 0.1 & 0.2 & 0.6 & 0.8 & 0.4 \end{bmatrix}}_{\text{cost vector}}$$

tracks / leaves

$$\underbrace{\begin{array}{c} \text{measurements} \end{array} \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}_{\text{Constraint matrix (Z)}}$$

Solving Multi-dimensional Assignment with Integer programming

$$\boxed{\min_{x} c^T x \quad \text{s.t. } Zx = [1]}$$ *(column vector)*



$$c = \underbrace{\begin{bmatrix} 0.5 & 0.8 & 0.4 & 0.1 & 0.2 & 0.6 & 0.8 & 0.4 \end{bmatrix}}_{\text{cost vector}}$$

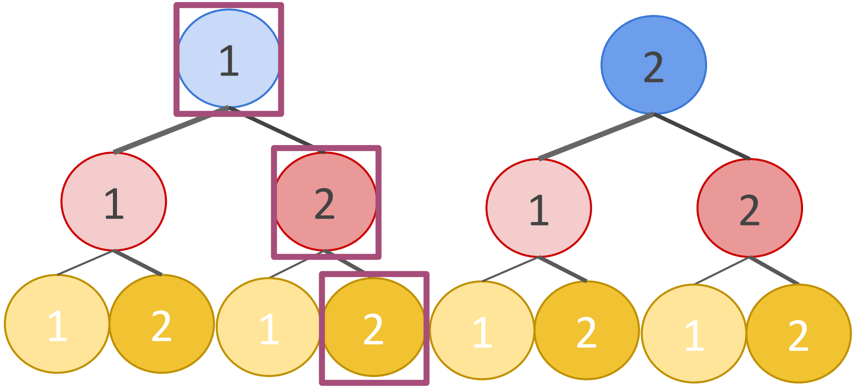
$$x = \overbrace{\begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}}^{\text{Assignment / selection vector (x)}}$$

tracks / leaves

$$\text{measurements} \quad \underbrace{\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}_{\text{Constraint matrix (Z)}}$$

Solving Multi-dimensional Assignment with Integer programming

$$\min_{x} c^T x \quad \text{s.t. } Zx = [1]$$



$$\underbrace{c = \begin{bmatrix} 0.5 & 0.8 & 0.4 & 0.1 & 0.2 & 0.6 & 0.8 & 0.4 \end{bmatrix}}_{\text{cost vector}}$$

$$\overbrace{x = \begin{bmatrix} 0 & 0 & 0 & \boxed{1} & 1 & 0 & 0 & 0 \end{bmatrix}}^{\text{Assignment / selection vector (x)}}$$

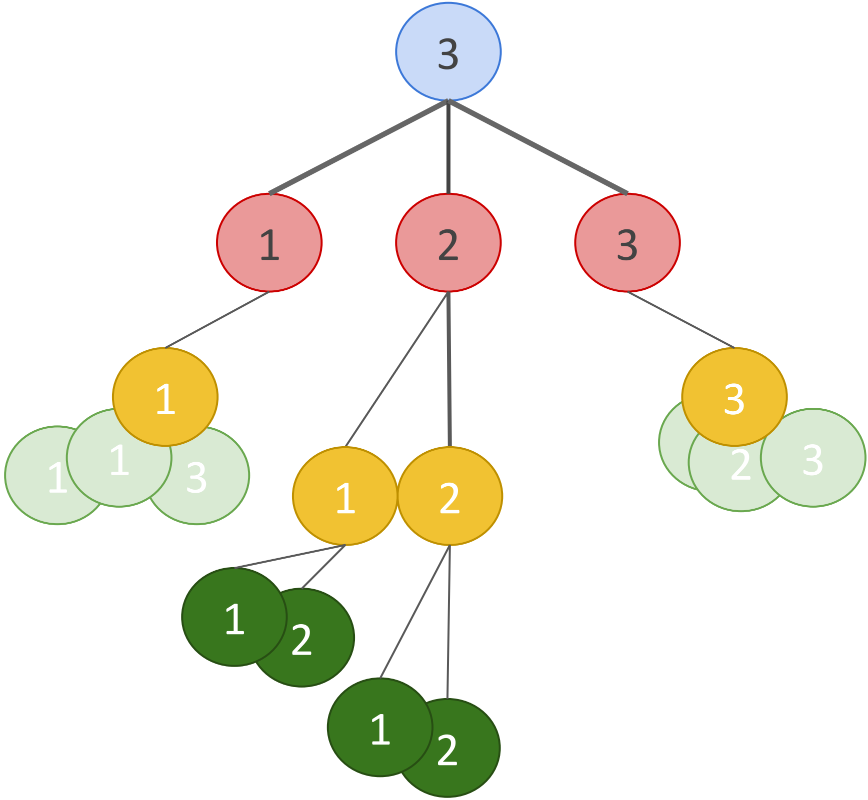
tracks / leaves

measurements

$$\underbrace{\begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}}_{\text{Constraint matrix (Z)}}$$

Solving Multi-dimensional Assignment with Integer programming

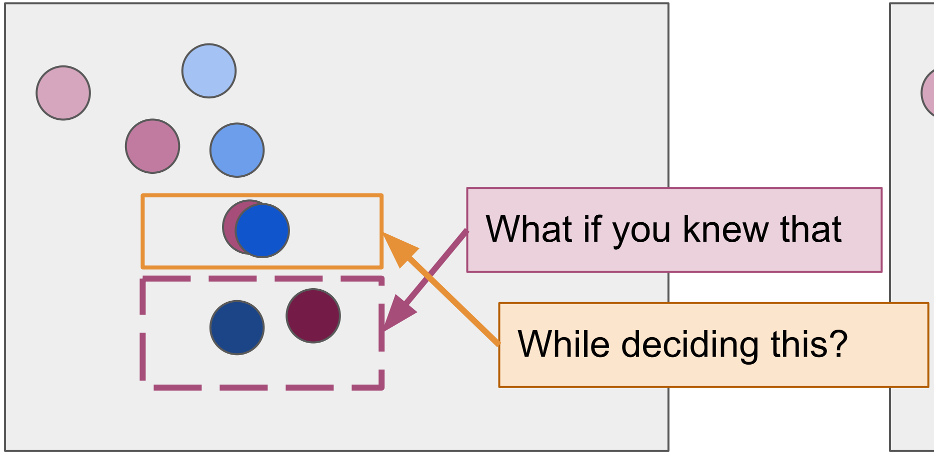
No need to maintain obviously bad associations in software



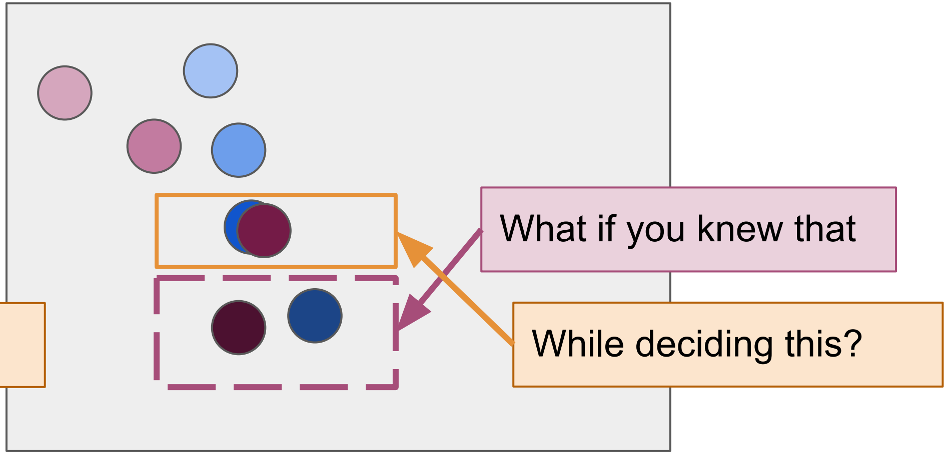
Questions

Multiple Hypothesis Tracking

Look ahead tracking



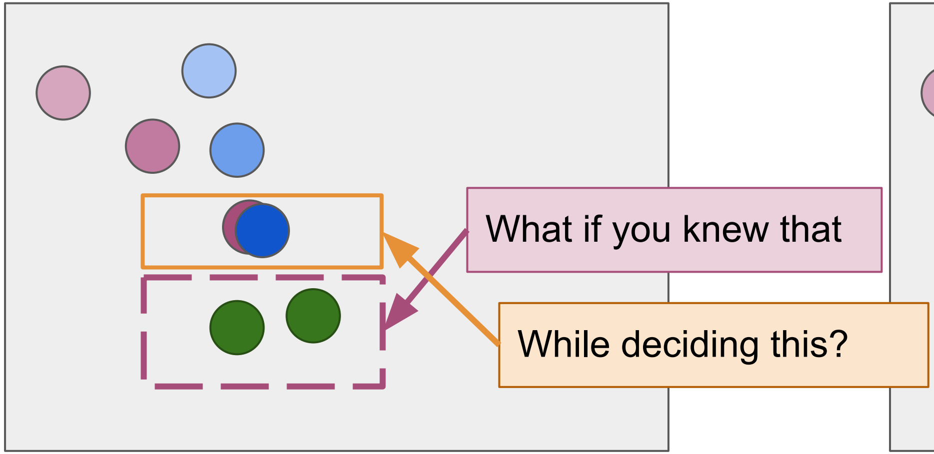
Aspirational



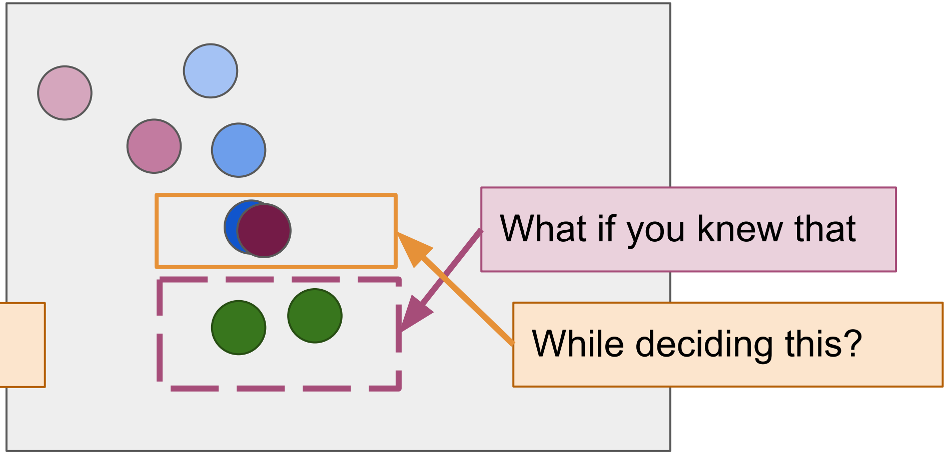
Janky Track Switch

Multiple Hypothesis Tracking

Answer: MHT (Multiple Hypothesis Tracking)



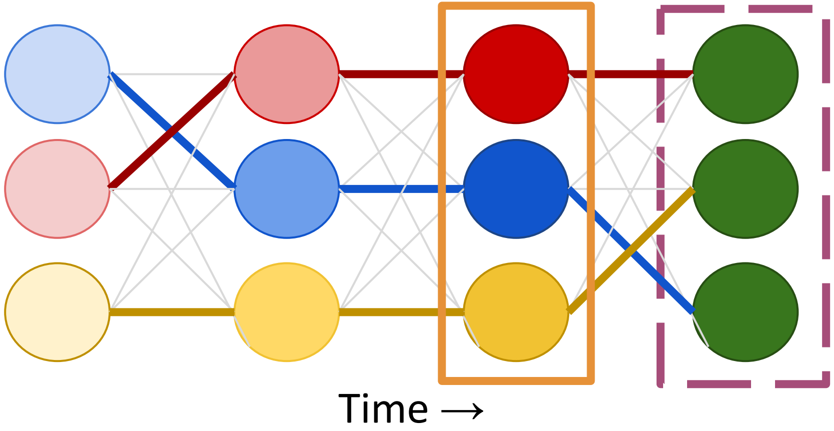
Aspirational



Janky Track Switch

Multiple Hypothesis Tracking

- In software, don't construct full trees. Treat early nodes as fixed, designate a resolution layer of fixed depth



Questions

We are about to move to a new topic

The importance of data collection

The one thing I use every day during my day job

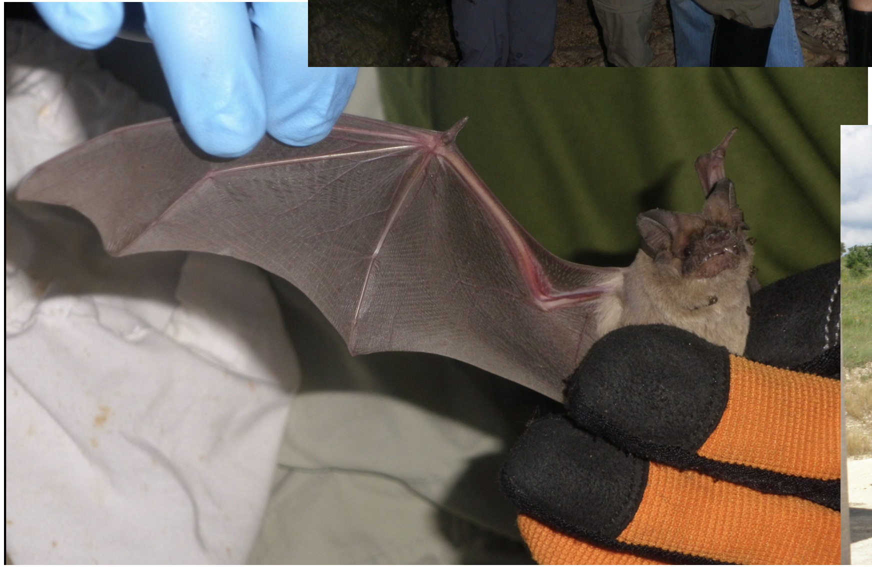
Story Time

The one thing I use every day during my day job

Trigger Warning: personal loss

Spoiler:

- Two problems that appear superficially similar may actually be very different
- You must design your data collection to match your problem

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Group Behavior with Multi-view Stereo Multi-target Tracking

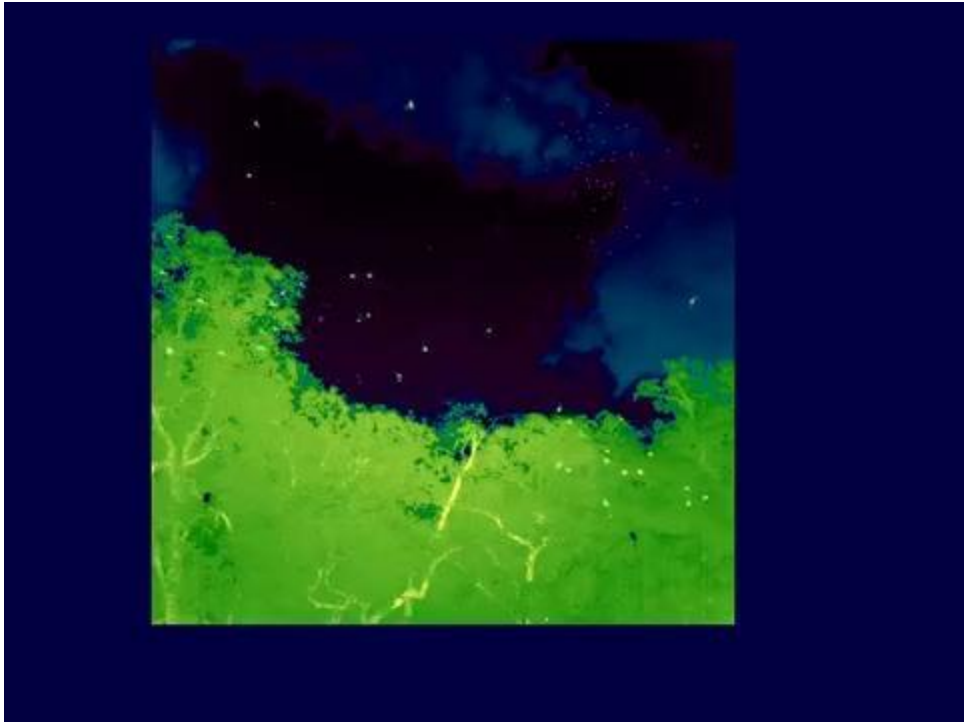
2010: Where should we put the cameras?

Unprepared, I needed to come up with something fast.

To do depth maps on robots, image planes parallel; cameras in a line

Horizontal search for corresponding points is efficient

What could possibly go wrong?



3D Multi-target tracking:

TWO data association problems

1.) 3D matching and reconstruction (epipolar geometry)

2.) Multi-target tracking

What could possibly go wrong?

Reprojected 3D points nowhere near bats in the image

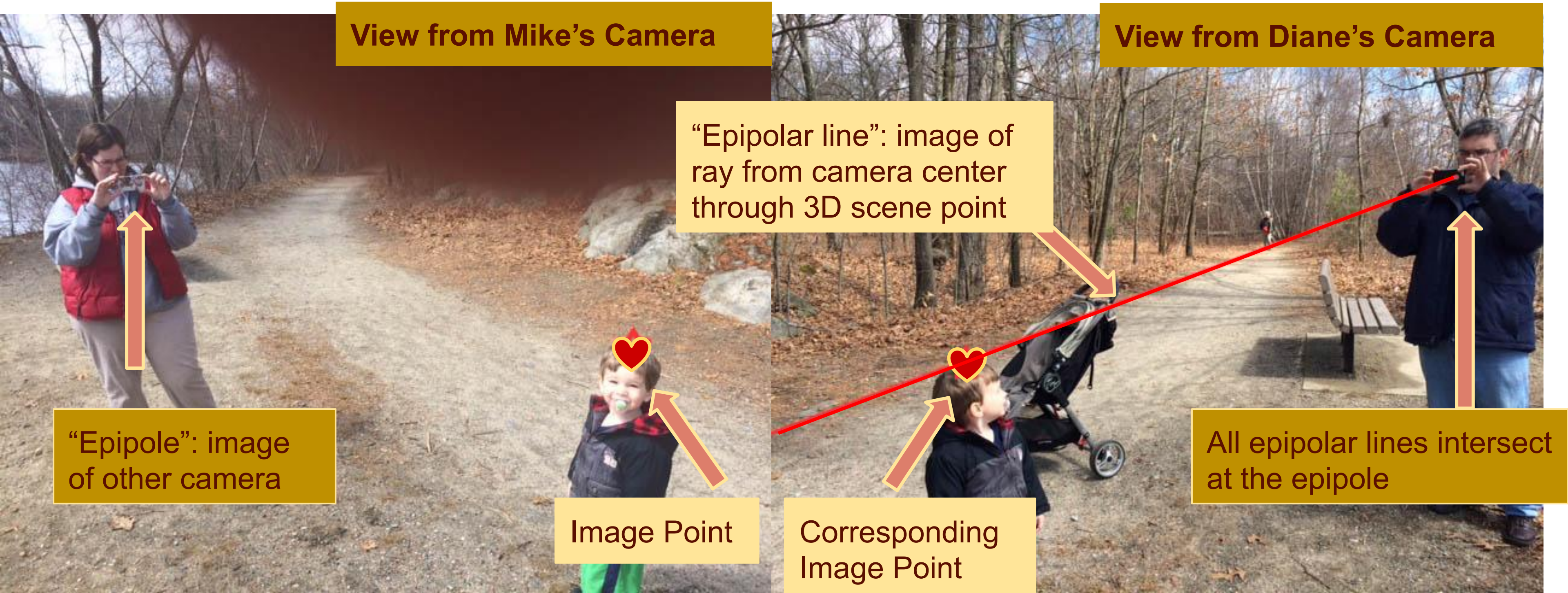
3D points behind the camera

Tracking switching and chaos with more than 50 bats

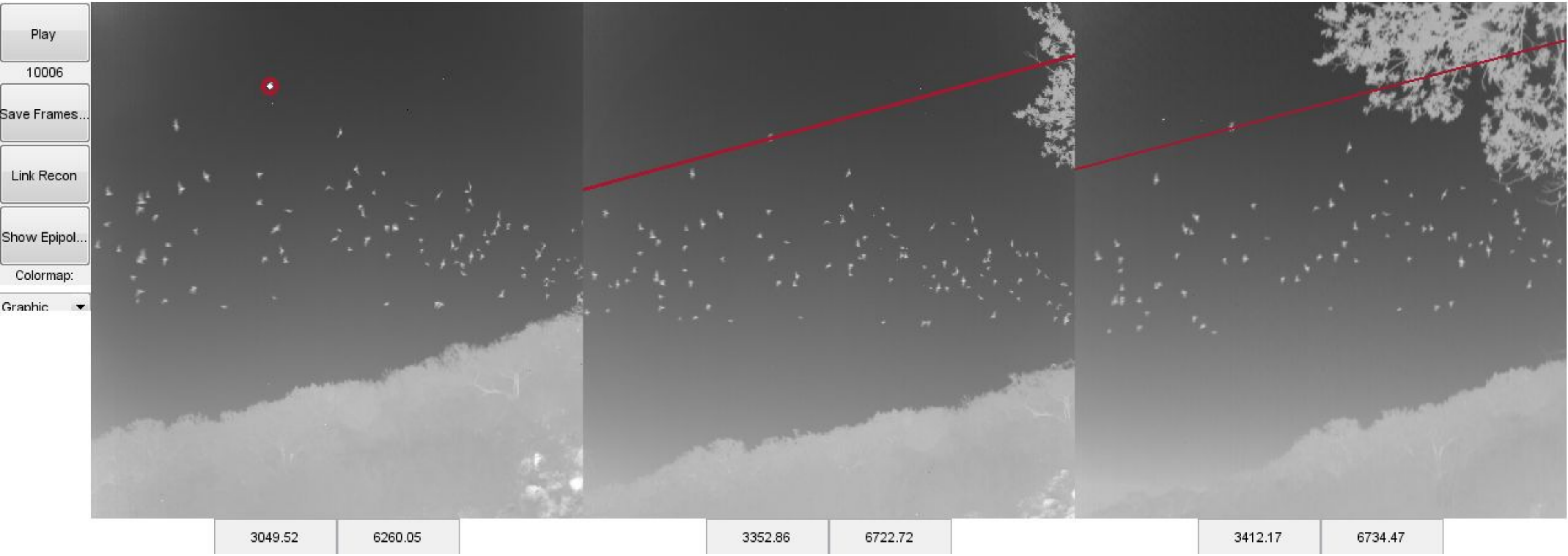
>> Epipolar constraints not enough to disambiguate image detections

Epipolar Geometry in 30 seconds

Spatial relationship between two cameras constrains the relationship between image locations corresponding to the same object



Epipolar line constraints, applied to bats



2011: Try again!

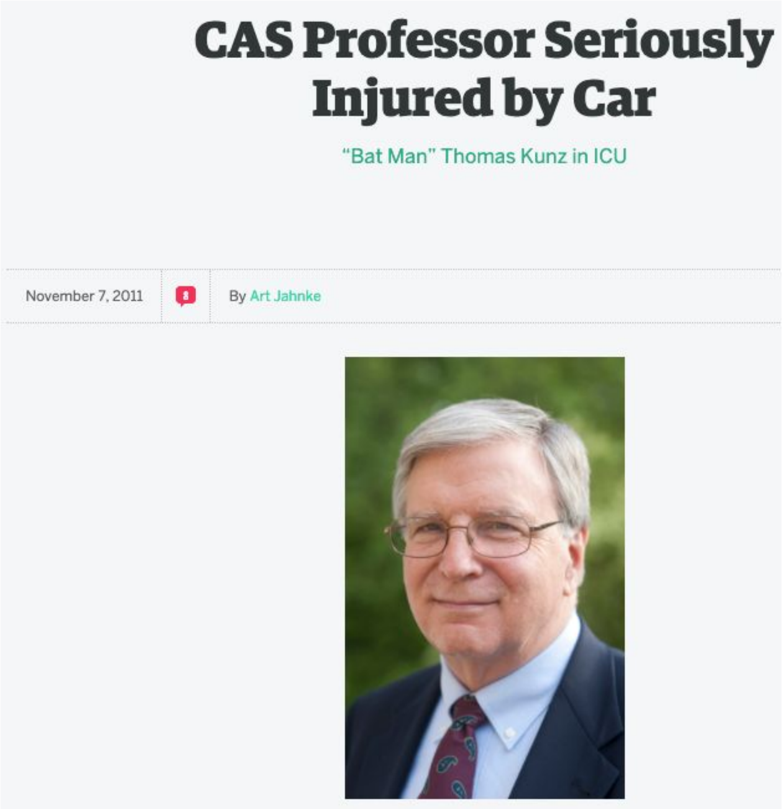
Tried stacking cameras vertically

Tried aiming at the sky

Tried all kinds of things

Garbage.

2011 - 2012: And then the stakes went up



CAS Professor Seriously Injured by Car

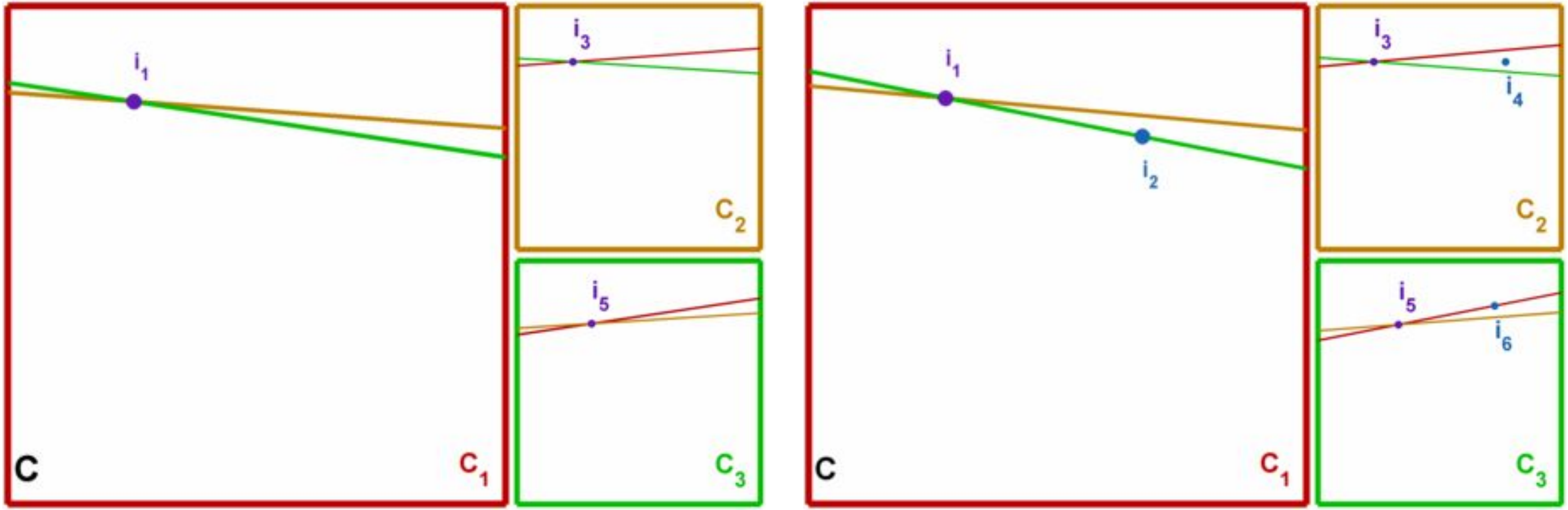
"Bat Man" Thomas Kunz in ICU

November 7, 2011 | 8 | By Art Jahnke

2013: “We need to go back to Texas one more time.”

“I’ll go. But you need to prove to me that we are going to nail it this time. This is our last shot.”

Why are there zeros in the denominator?

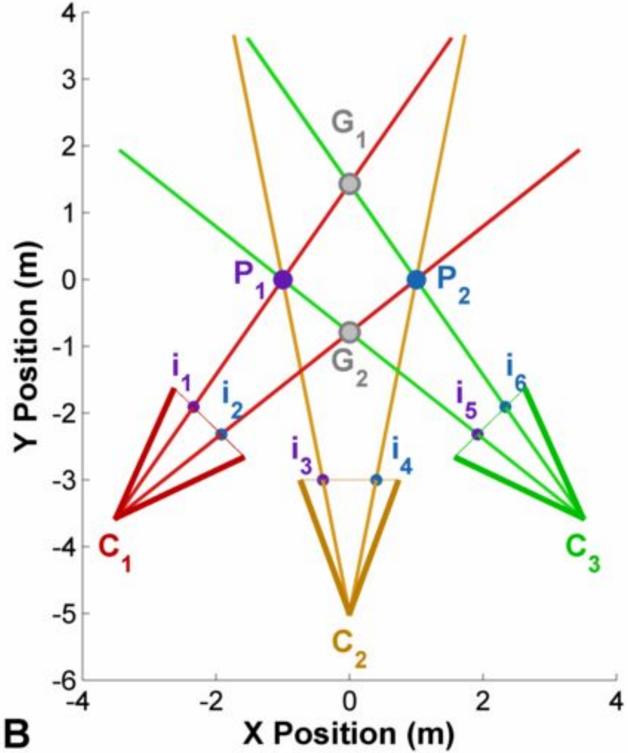


Parallel epipolar lines were wrong.

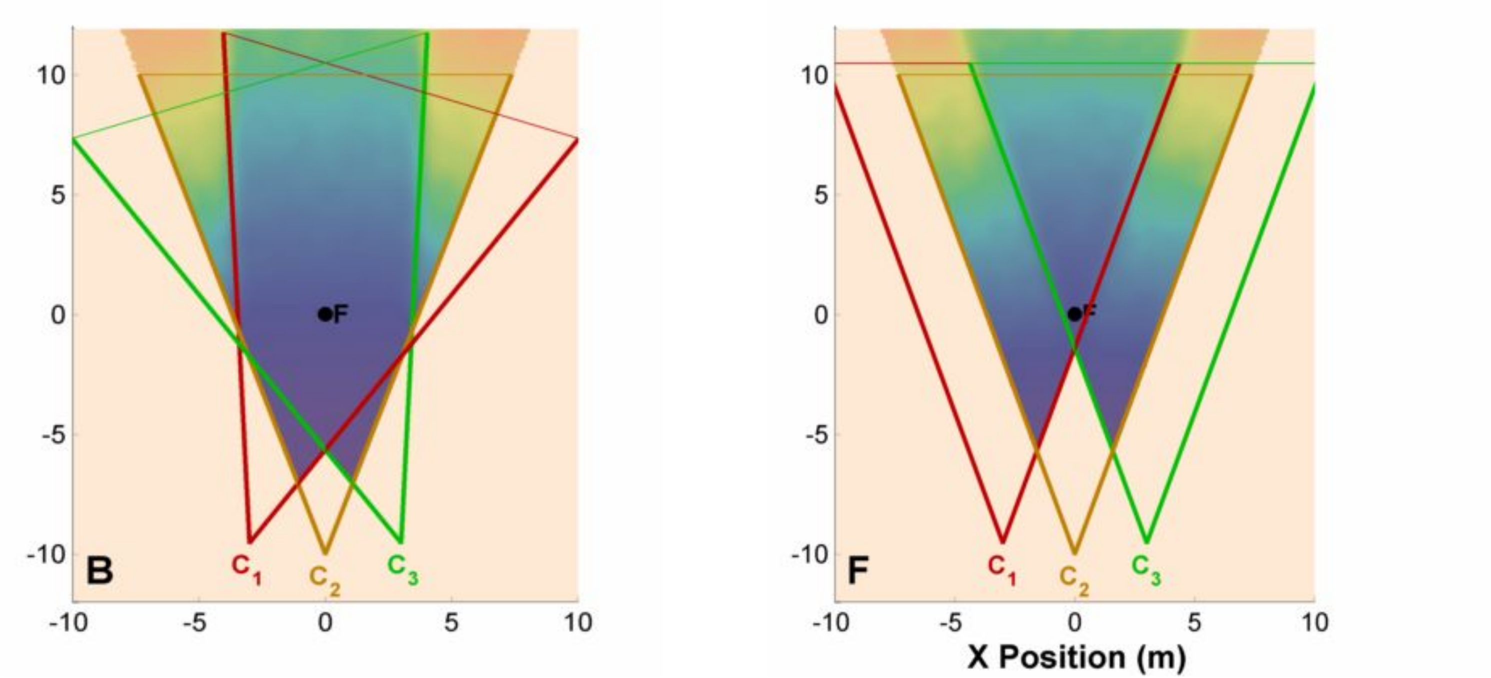
Data association of image dots != Depth Map

Correct camera placement was easy to implement

We lost valuable time because we guessed instead of planned.



Parallel image planes were even worse than we thought



And that is how I spent 3 years wondering which way was up and if time moved forwards.

50 bats → 200 bats with **no algorithm changes**.

[Alternate Link]

Moral of the Story

Two problems that appear superficially similar may actually be very different

No fancy algorithm would save us from data that broke our objective function.

You must design your data collection to match your problem

Or you will burn precious time, unless you get very lucky

How do I use this every day?

In the real world, you don’t operate on nice, clean academic data sets.

Data collection, logging, sanitization IS the work.

Data-driven business decisions require good data.

Good data starts with good planning.

Good planning requires detailed understanding of the problem you are trying to solve.

How do I use this every day?

Understand the product goals you are trying to serve

Identify the tactical decisions that you need to make.

How you will know that you made the right decisions?
What information will you need in order to change your decisions?

What data collection do you need so that you can calculate the metrics you need to make decisions? Don't forget to cover your denominators.

Design your data collection to serve your problem.
Don't guess and hope for the best. It rarely works out.

Questions

</>
Tracking
Advanced Data Association and The Importance of Data Collection

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March 30, 2021