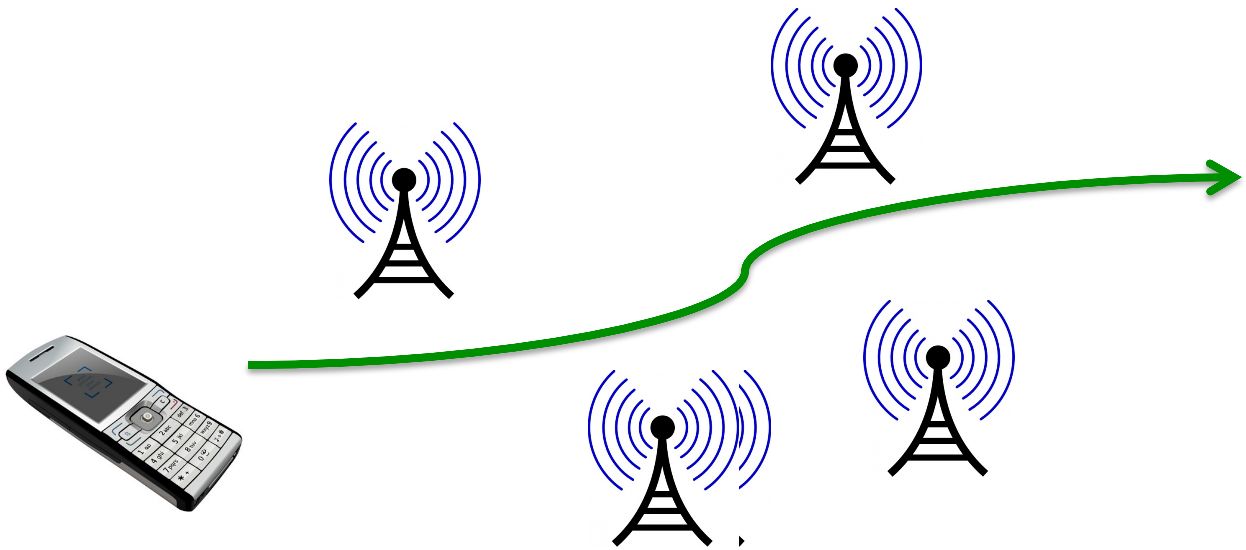
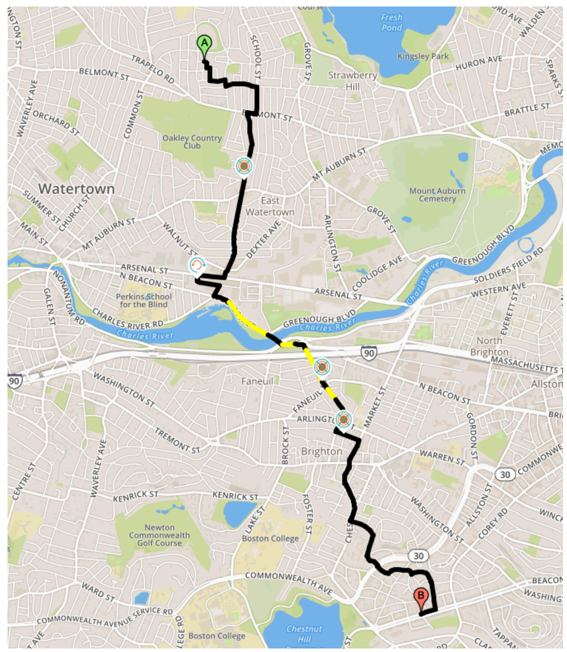
Accurate, Low Energy Trajectory Mapping For Mobile Phones



Arvind Thiagarajan, Lenin Ravindranath,
Hari Balakrishnan, Sam Madden, Lewis Girod
MIT CSAIL

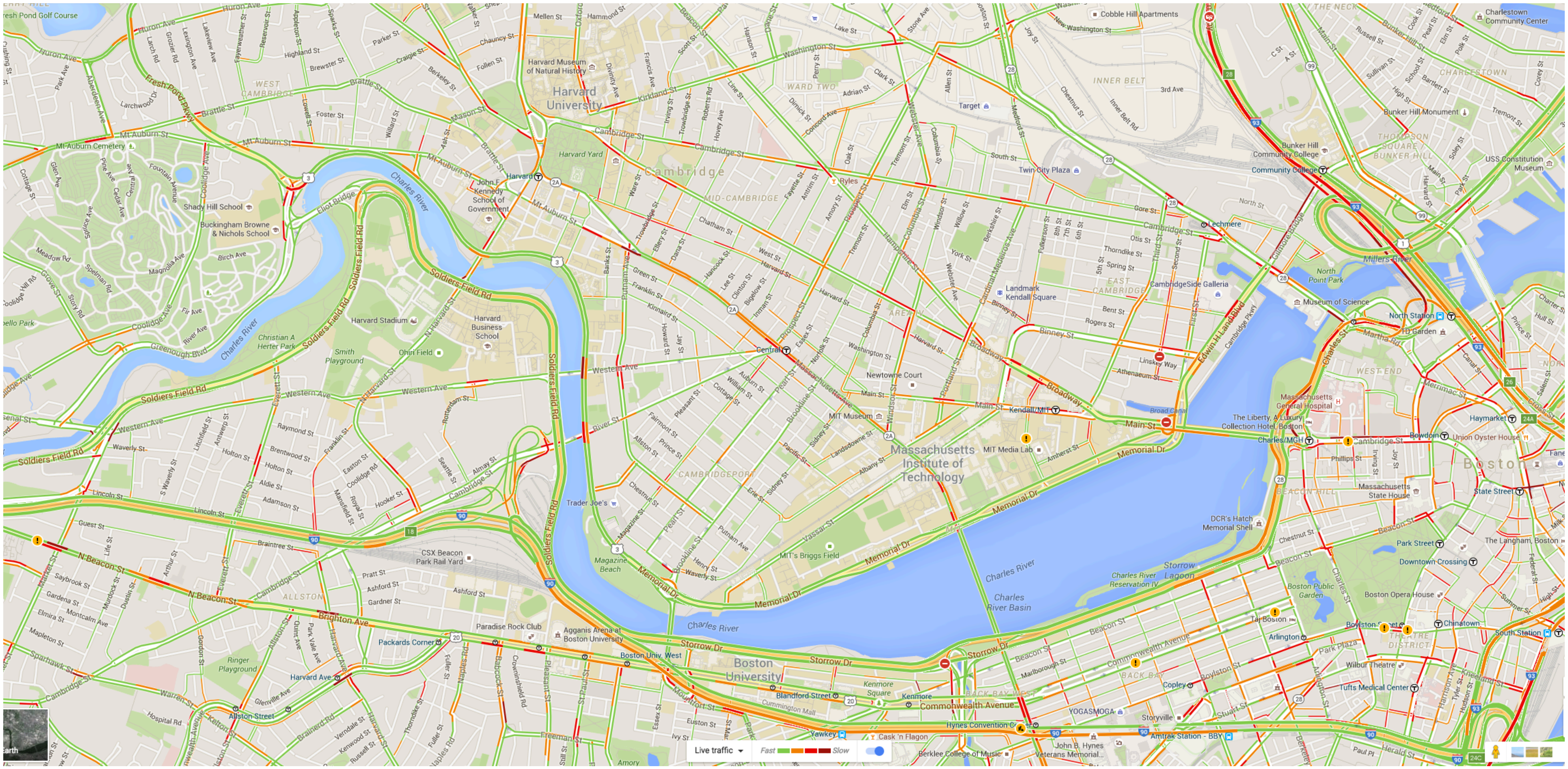
Goal

- Find the *trajectory* i.e. *sequence of locations* visited by a mobile device

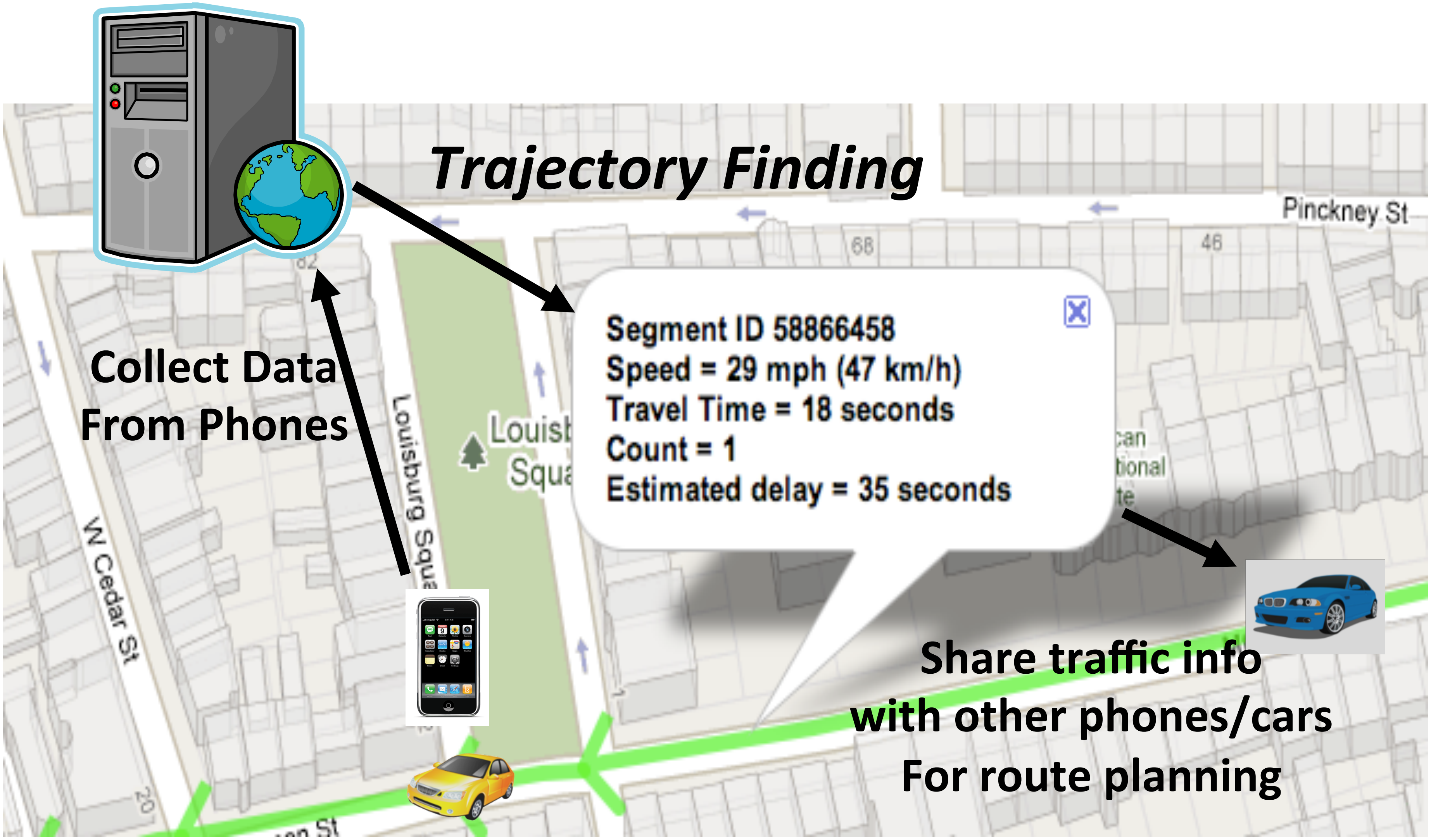


- Applications need to find path both ***accurately*** and ***energy-efficiently***

Traffic Estimation



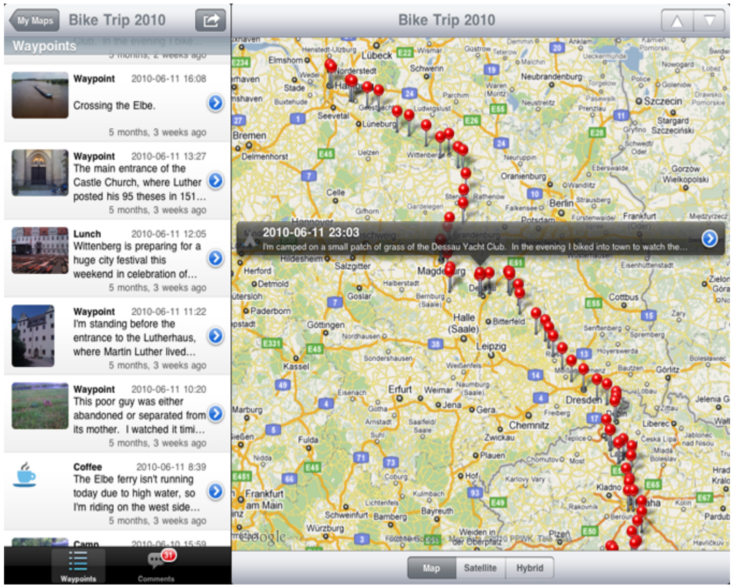
Crowdsourced Traffic Monitoring



Battery dies in ~6 hours if monitoring with GPS

Bike Routes

http://www.jonathanokeeffe.com/strava/multi-ride-mapper/



TrackMyTour

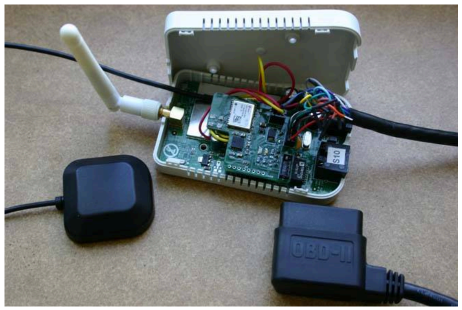
Allows users to keep track of their trips and annotate them

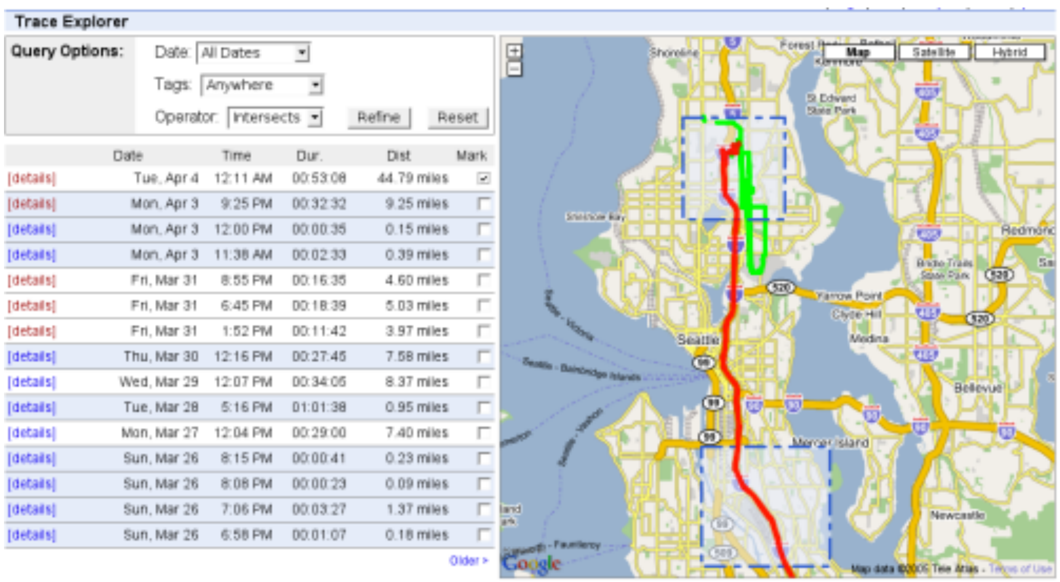
Running

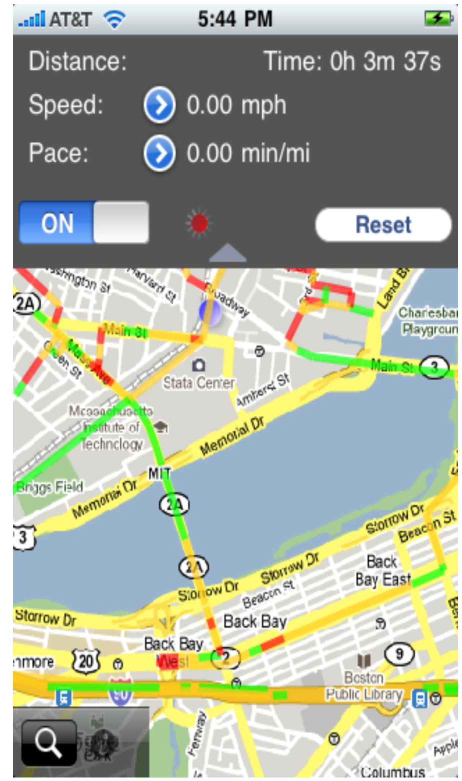
Trash Track

Yogurt Container
Trashed at
1350 N 34th St
Seattle, WA 98103
Traveled
35.05 Miles,
3 Days and 16 Hours
Category
Plastic
Jul 12, 2009
+ 6 Days
Jul 12, 2009
Fremont
Wallingford
Queen Anne
SEATTLE
Alki
Beacon Hill
Aug 16, 2009, 1:11 PM
En Route
Yogurt
Container
Last seen from:
1350 N 34th St
Seattle, WA 98103

Context: CarTel Project



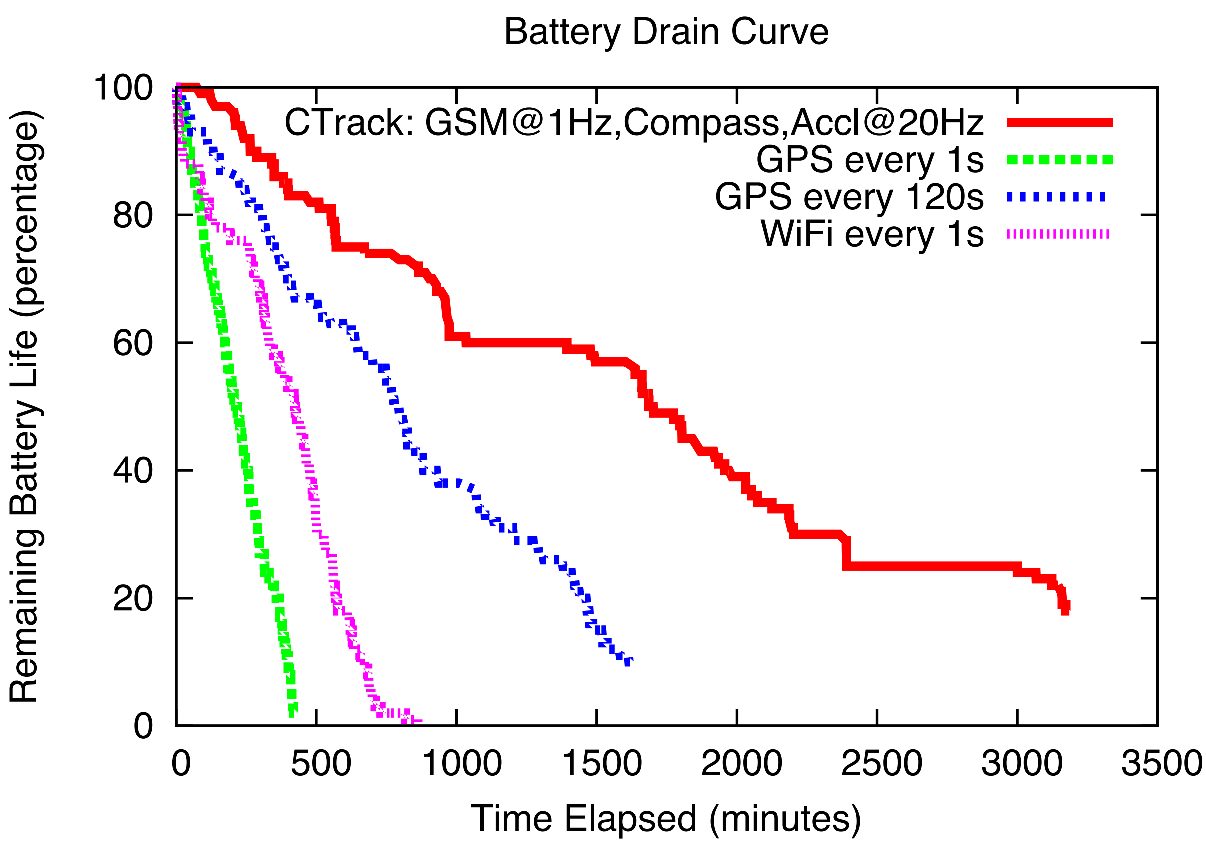




Crowdsource tracks to estimate traffic on road segments

Limitation of GPS: Energy

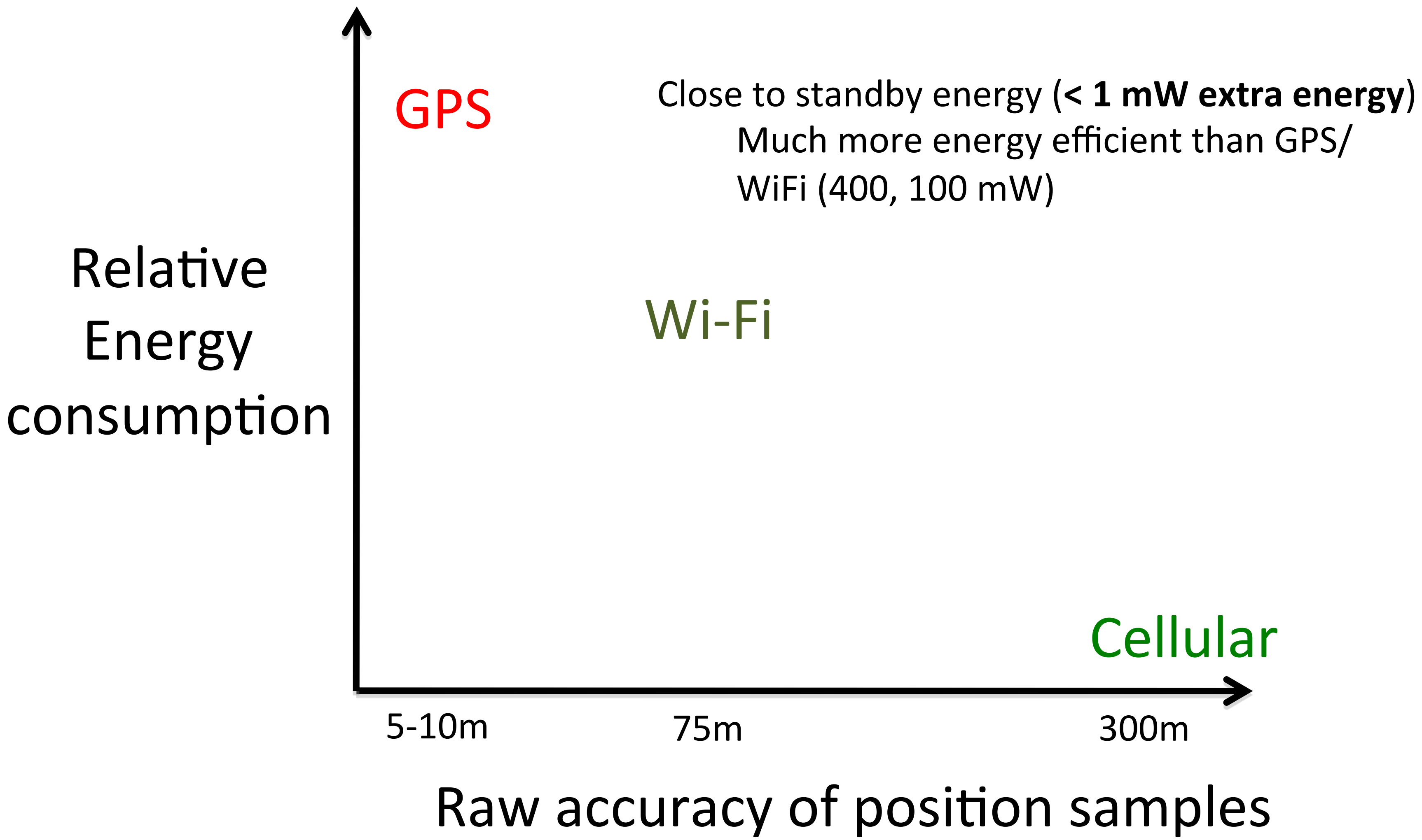
- GPS signals are energy-intensive to acquire & process
- Frequent GPS sampling drains battery fast
- This data is from 2010-11, but the same trends persist today



Android G1 phone: 6-8 hours with 1 Hz GPS

6 hrs on iPhone 3GS vs 18 hrs w/o GPS (dim screen)

Approach: Use low-power sensors

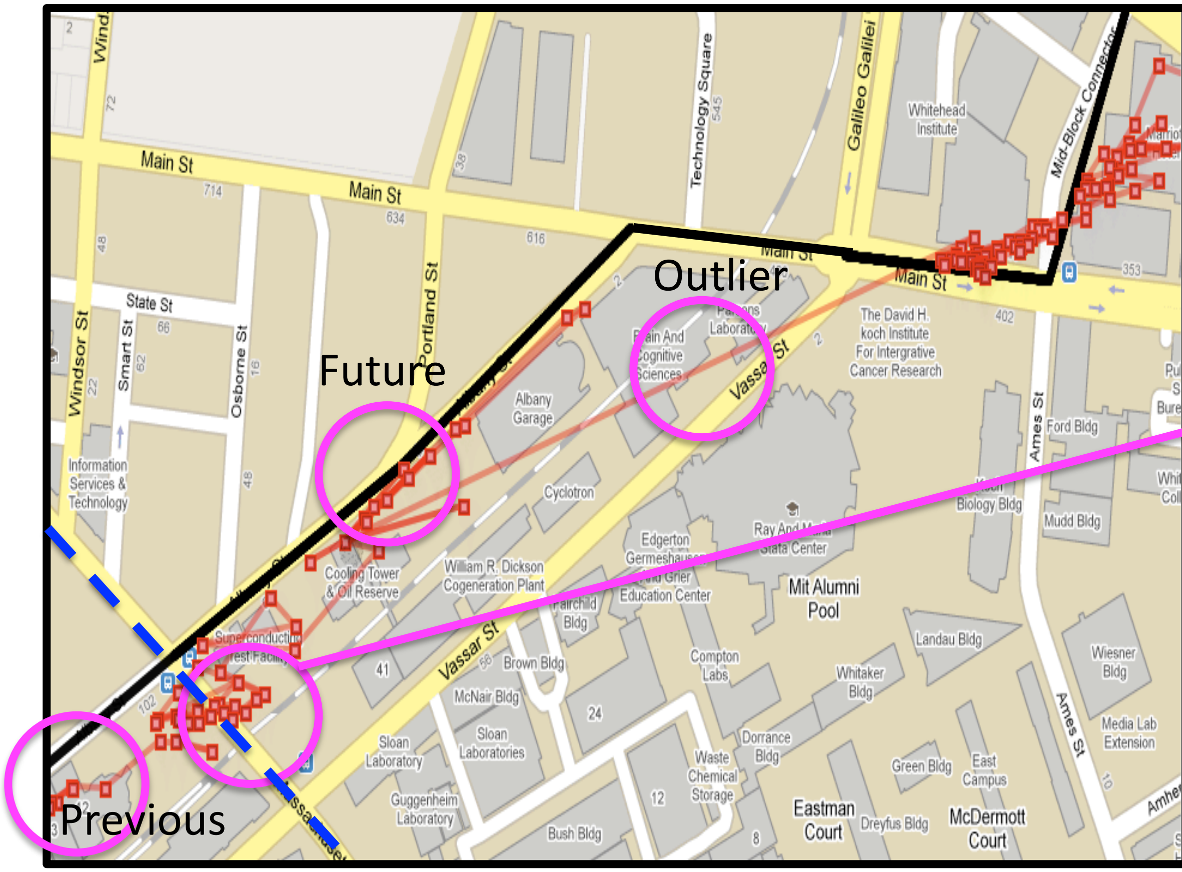


Outline

- Prior work
  - Intermittent GPS (Microsoft Krumm et al.)
  - Vtrack − uses Wi-Fi data – from same group that did the Ctrack work (CarTel project)

- CTrack paper
  - Cellular fingerprints
  - Better energy
  - Accuracy?

Background: Vtrack Algorithm
Noisy Data (Wi-Fi example)

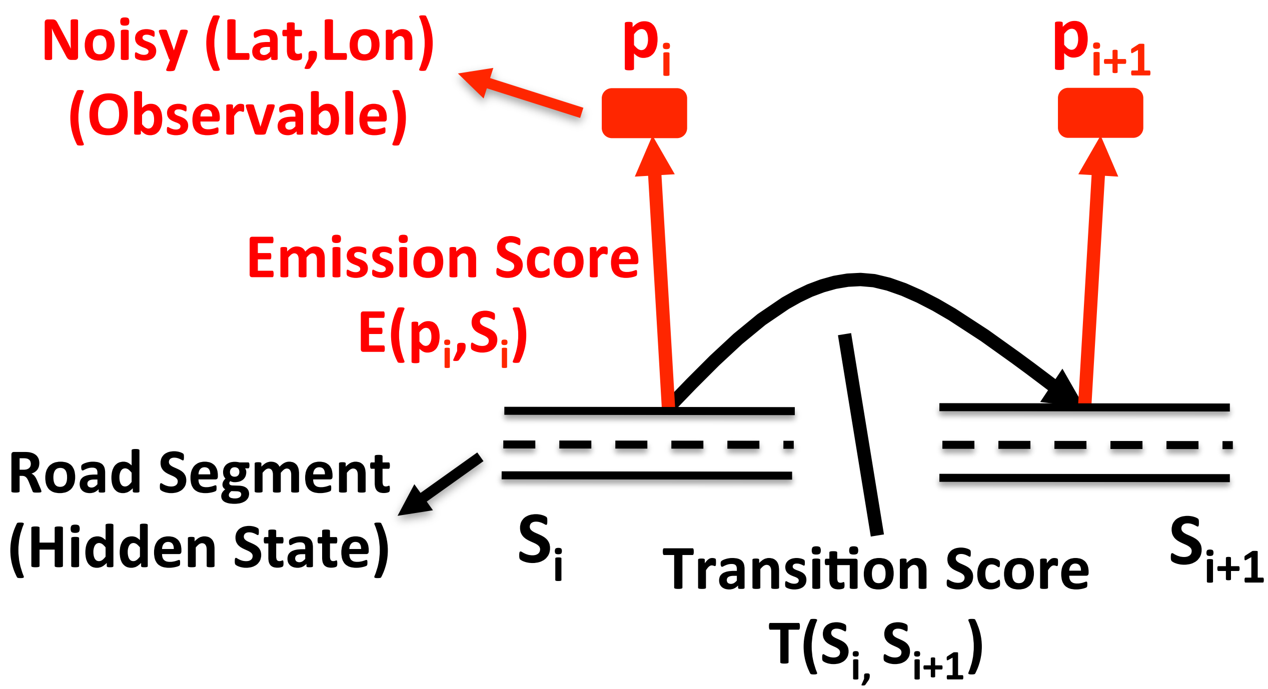


The closest road to a position sample is **not** where it originally came from

- Exploit both previous and future location information
- Don't overly weight *any one* location sample
- Find a *continuous (unbroken) sequence* of roads

Solution: Hidden Markov Model

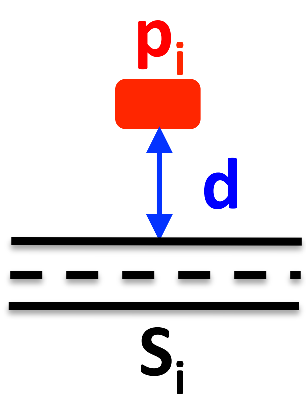
- Maps noisy observations (coordinates) to hidden states (underlying road segments)

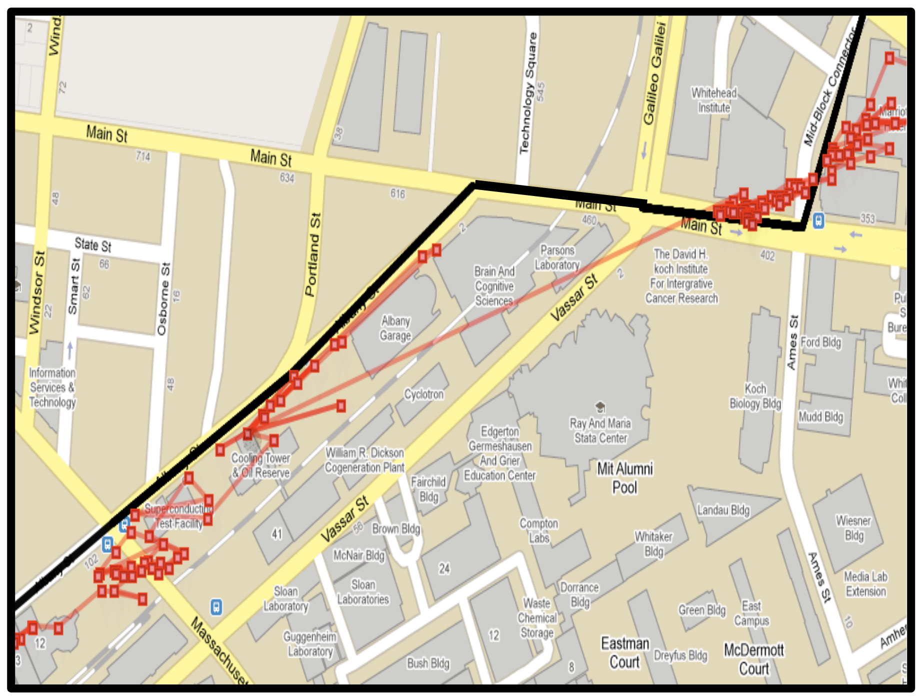


Dynamic Program Finds Best State Sequence (cf. Viterbi)
"Best" => Max Product of Emission and Transition Scores

Emission Score

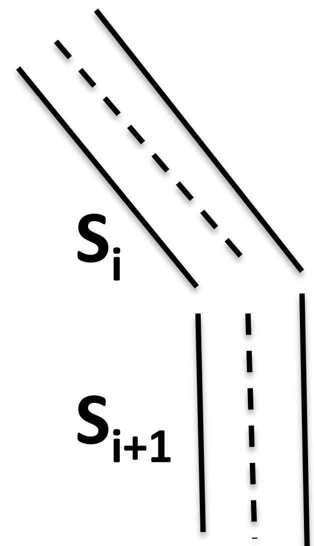
- Emission Score $E(p_i,S_i) = e^{-d^2/\sigma^2_{sensor}}$
  - Intuition: pts closer to a segment are more likely to come from it
  - σ_{sensor} depends on GPS/WiFi/Cellular



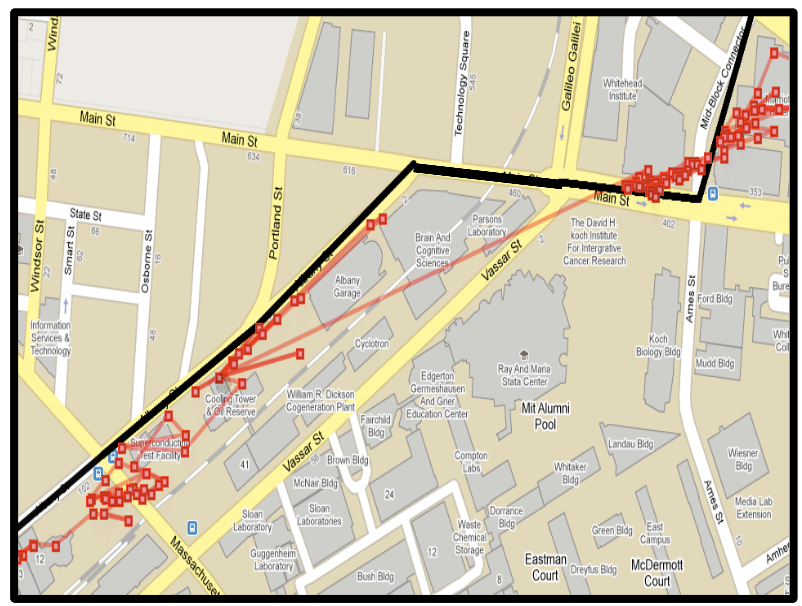


Transition Score

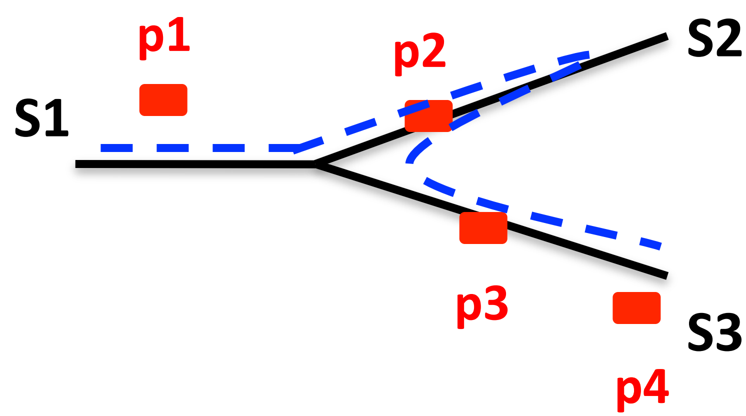
- Transition Score $T(S_i, S_{i+1})$
  - 0 if segments are not adjacent or not enough time has been spent on S_i
  - 1 if segments are adjacent and enough time has been spent on S_i



- Speed constraint is essential: because algorithm jumps around and follows noise in the input data without it
  - Decreases error significantly

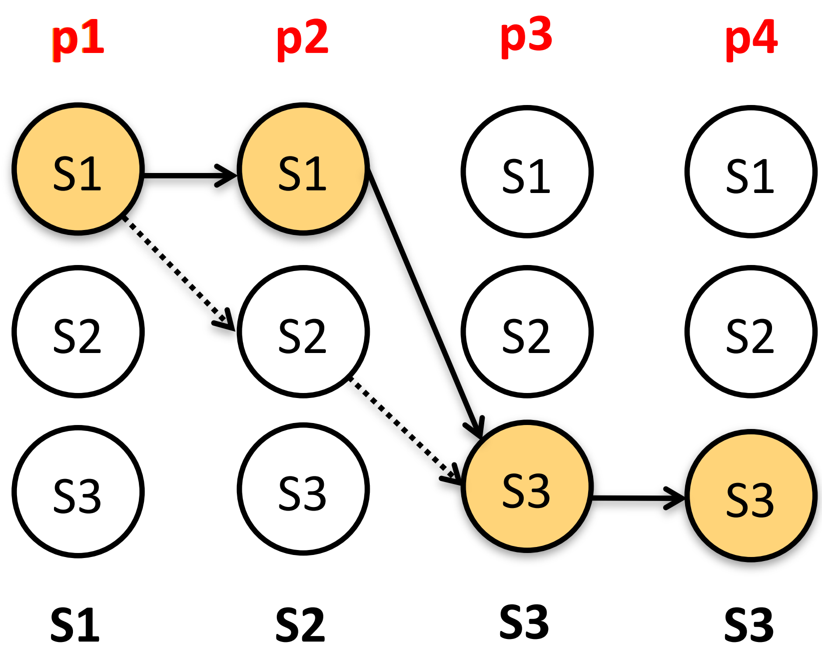


VTrack In Action



S1 S1 S3 S3 is most likely match

S1 S2 S3 S3 has score 0, isn't permitted (speed constraint)

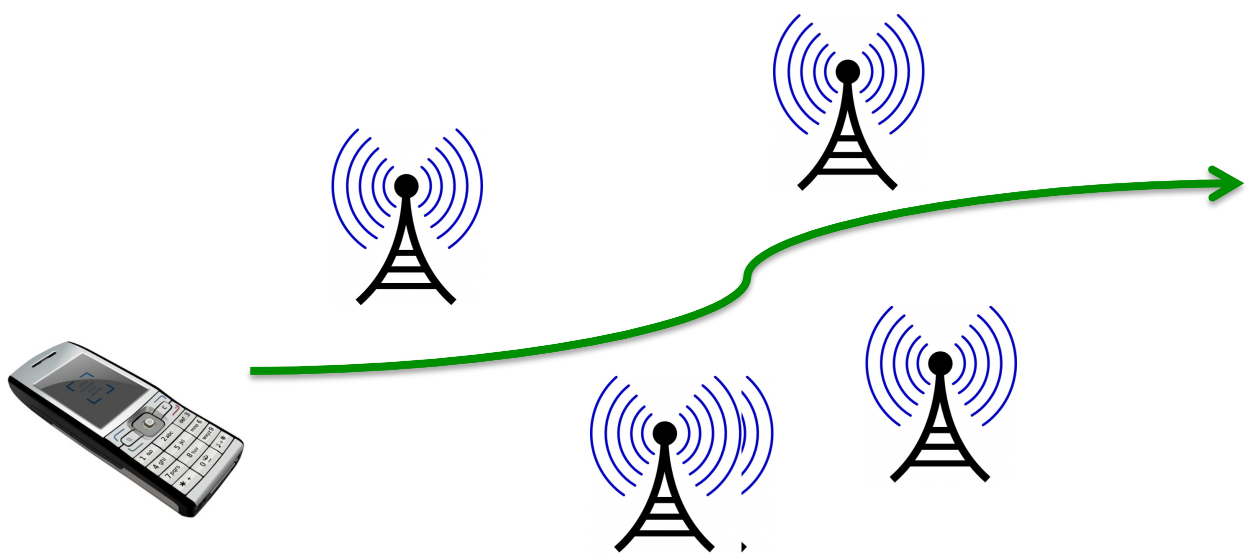


Handling Gaps: Interpolation

- VTrack's HMM maps input to output samples one-to-one
- We need frequent (1 Hz) input because we want output to be continuous (so we can enforce adjacency constraint)
- Interpolate gaps, *then* run HMM (linear interpolation)

CTrack Problem Statement

- Can we develop techniques to process cellular signal information to produce accurate trajectories?
- How accurate?

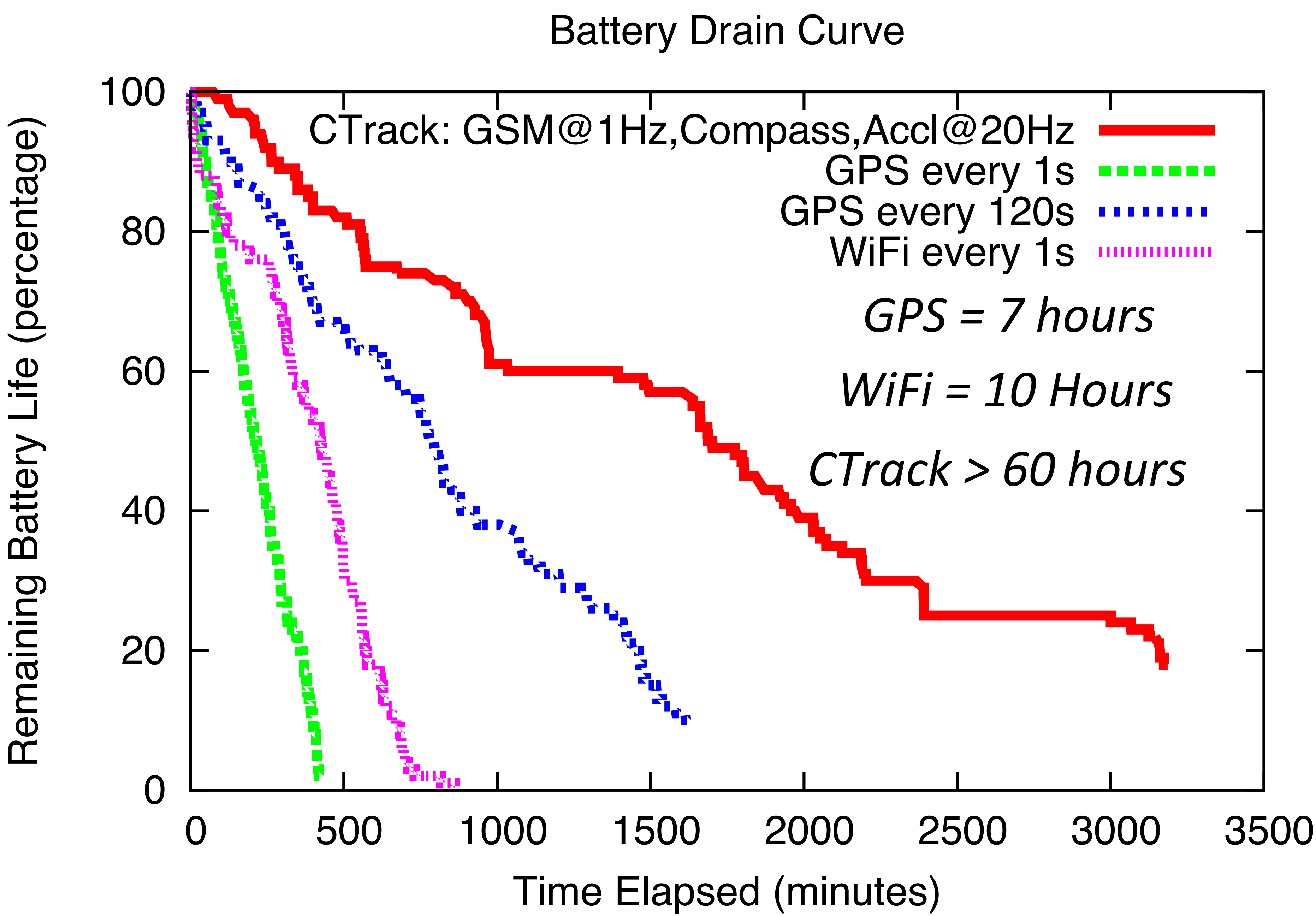


CTrack: Accurate Trajectory Mapping with Inaccurate Cellular Signals

- Consumes *no* extra energy

- New techniques achieve good enough accuracy for track-based apps
  - "75% as accurate as 1 Hz GPS"
  - "As accurate as GPS every 2 minutes"
  - As energy-efficient as GPS every 4 minutes and much more accurate"
  - Over "3x better" than previous cellular (GSM) systems
  - (I'll explain what these mean)

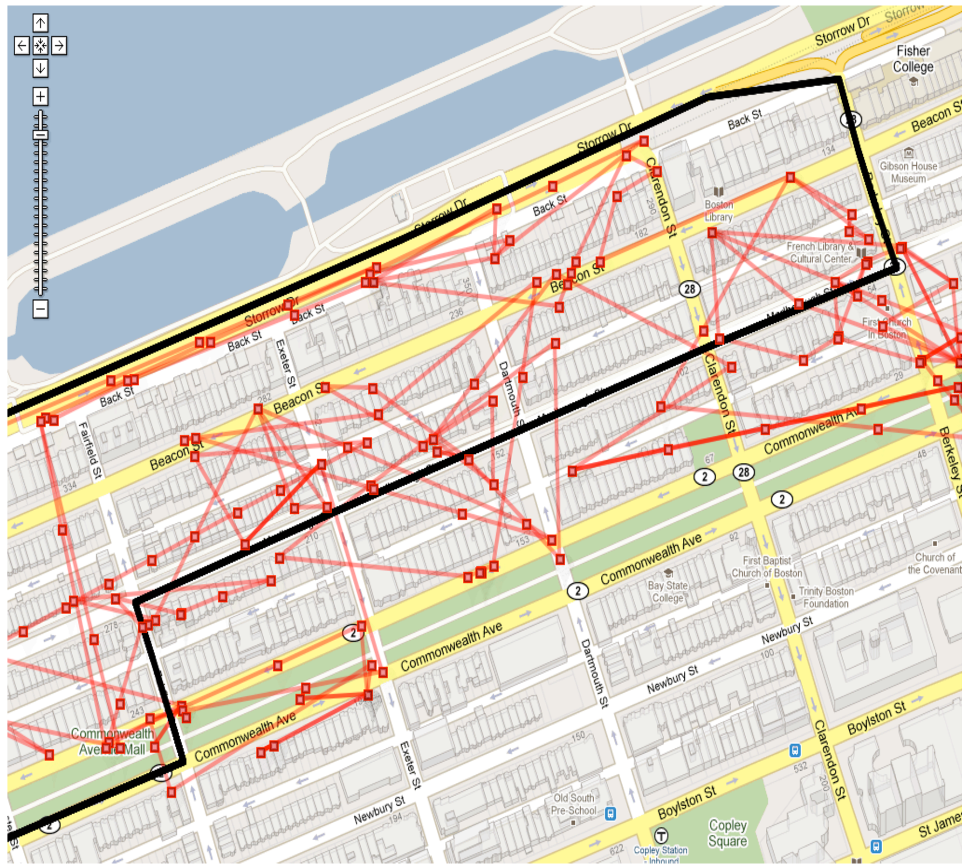
- Optionally, augment with low-energy *"sensor hints*"
  - Compass to detect turns (15 µW @ 1 Hz)
  - Accelerometer to detect movement (60 µW @ 10 Hz)



Android G1 phone

Existing Cellular Location Systems Aren't Good Enough To Find Tracks

- State-of-the-art is "radio fingerprinting"
  (E.g. PlaceLab)
- OK for best static localization estimate
- But poor at identifying tracks



Existing Map-Matching Algorithms Perform Poorly w/ Cellular Radios

```
d8:30:62:5f:be:da, RSSI -94
00:0f:b5:3d:43:20, RSSI -58
00:18:0a:30:00:a3, RSSI -51
. . . . . . . . . . . . . .
```

```
42.361,-71.09
42.361,-71.09
42.362,-71.091
. . . . . . . .
```

```
42.361,-71.09
42.361,-71.09
42.362,-71.091
. . . . . . . .
```

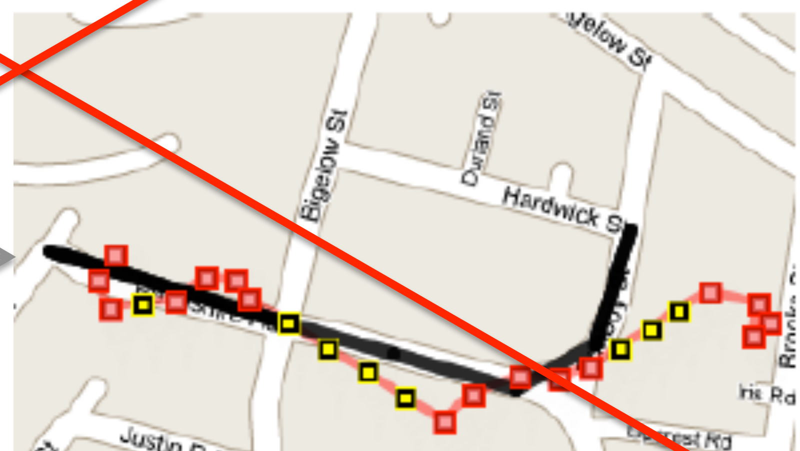
Krumm et al. (SAE World Congress '07), VTrack (SenSys '09)

Existing Map-Matching Algorithms Ok For GPS/WiFi, But Poor For GSM

```
d8:30:62:5f:be:da, RSSI -94
00:0f:b5:3d:43:20, RSSI -58
00:18:0a:30:00:a3, RSSI -51
. . . . . . . . . . . . . .
```

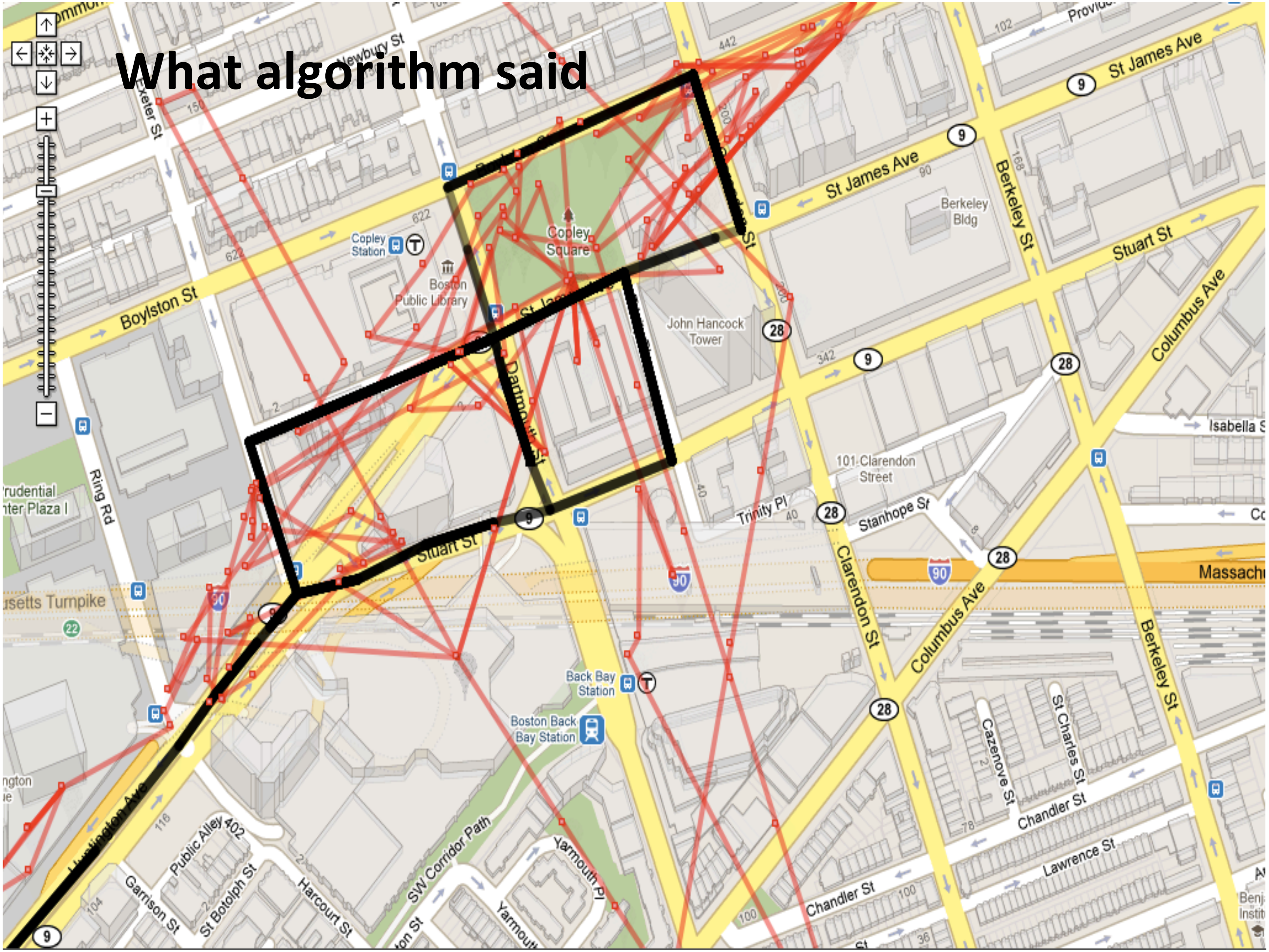
```
 42.361,-71.09
 42.361,-71.09
42.362,-71.091
. . . . . . . .
```

```
 42.361,-71.09
 42.361,-71.09
42.362,-71.091
. . . . . . . .
```

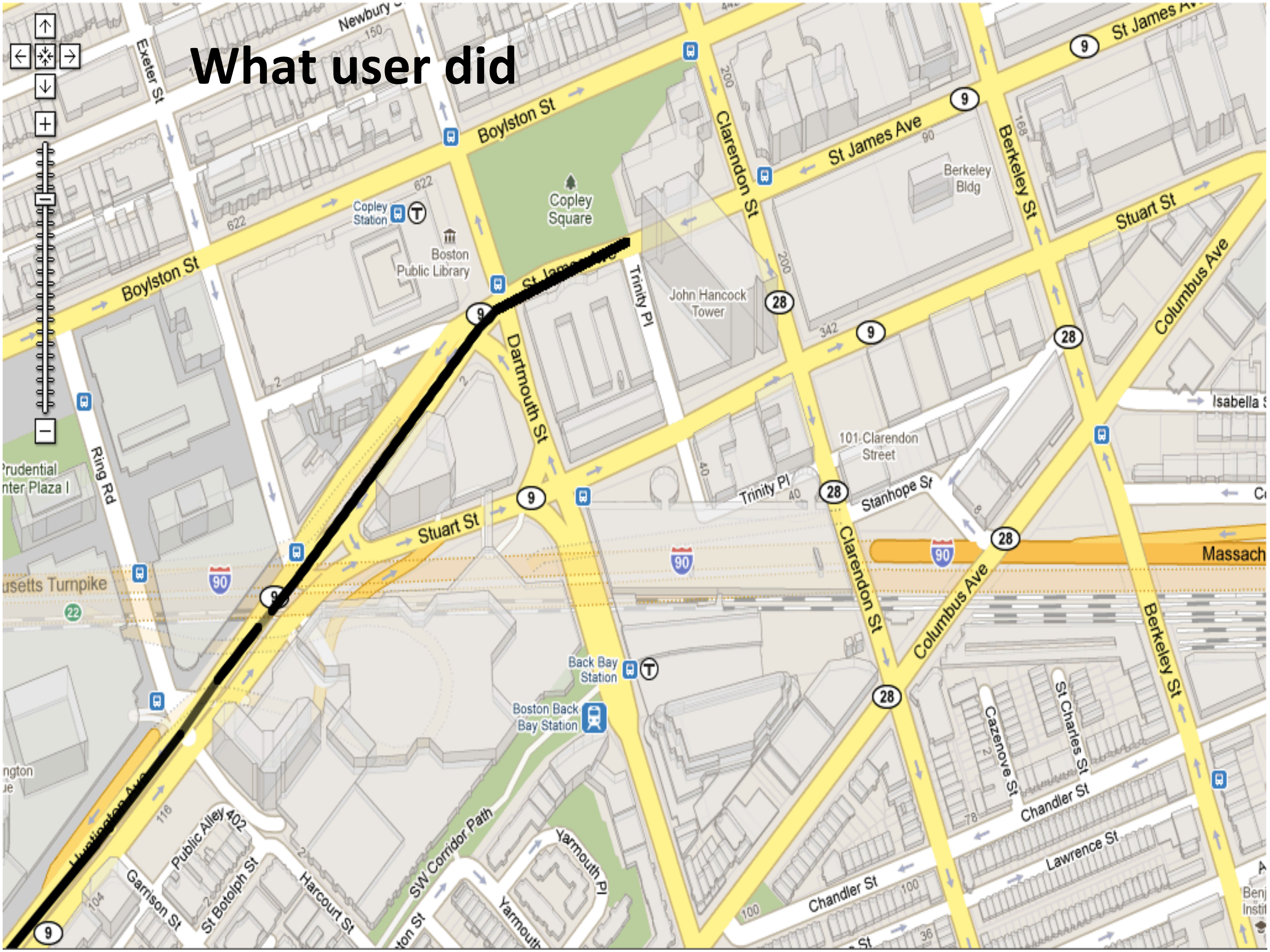


Krumm et al. (SAE World Congress '07), VTrack (SenSys '09)

What algorithm said



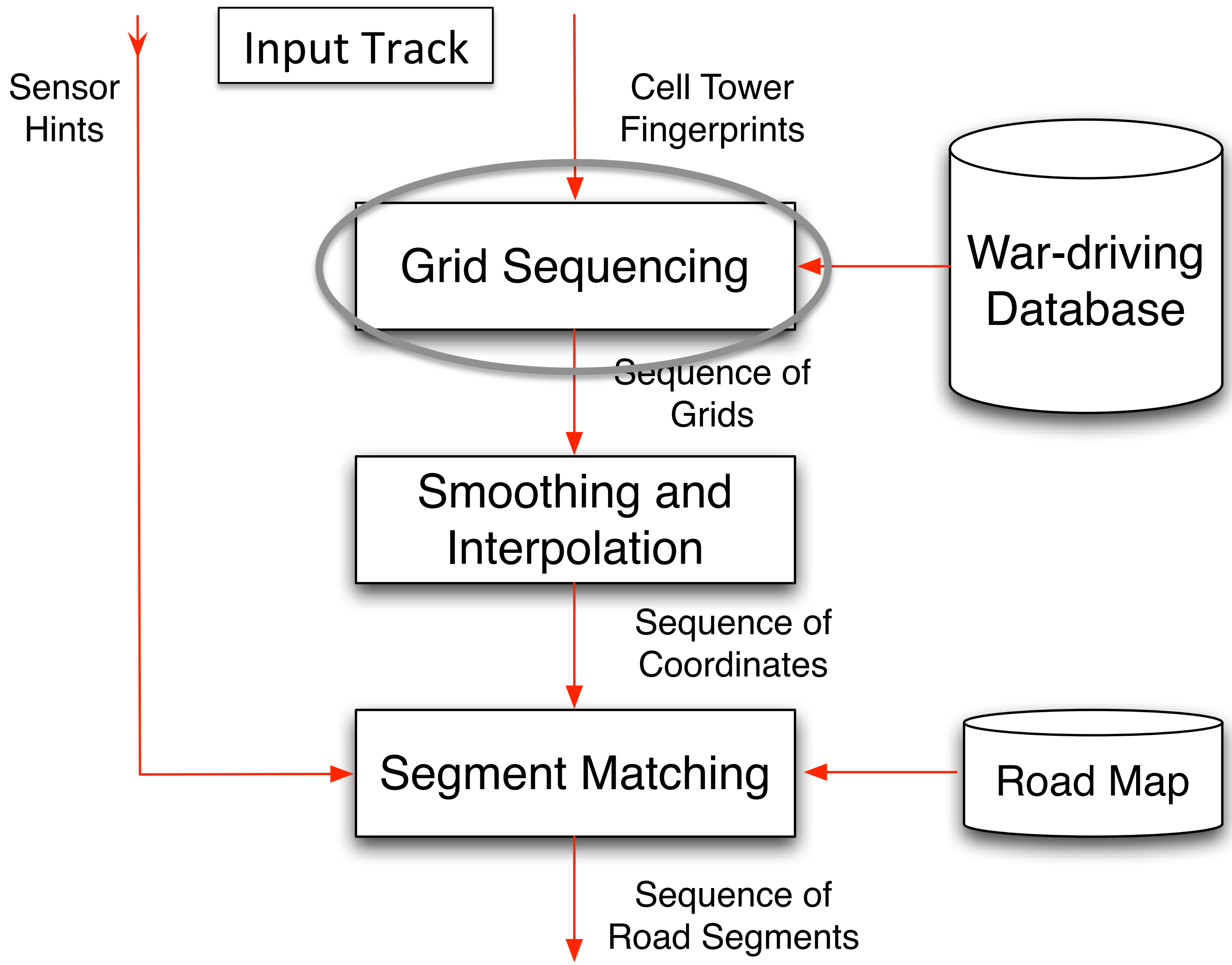
What user did



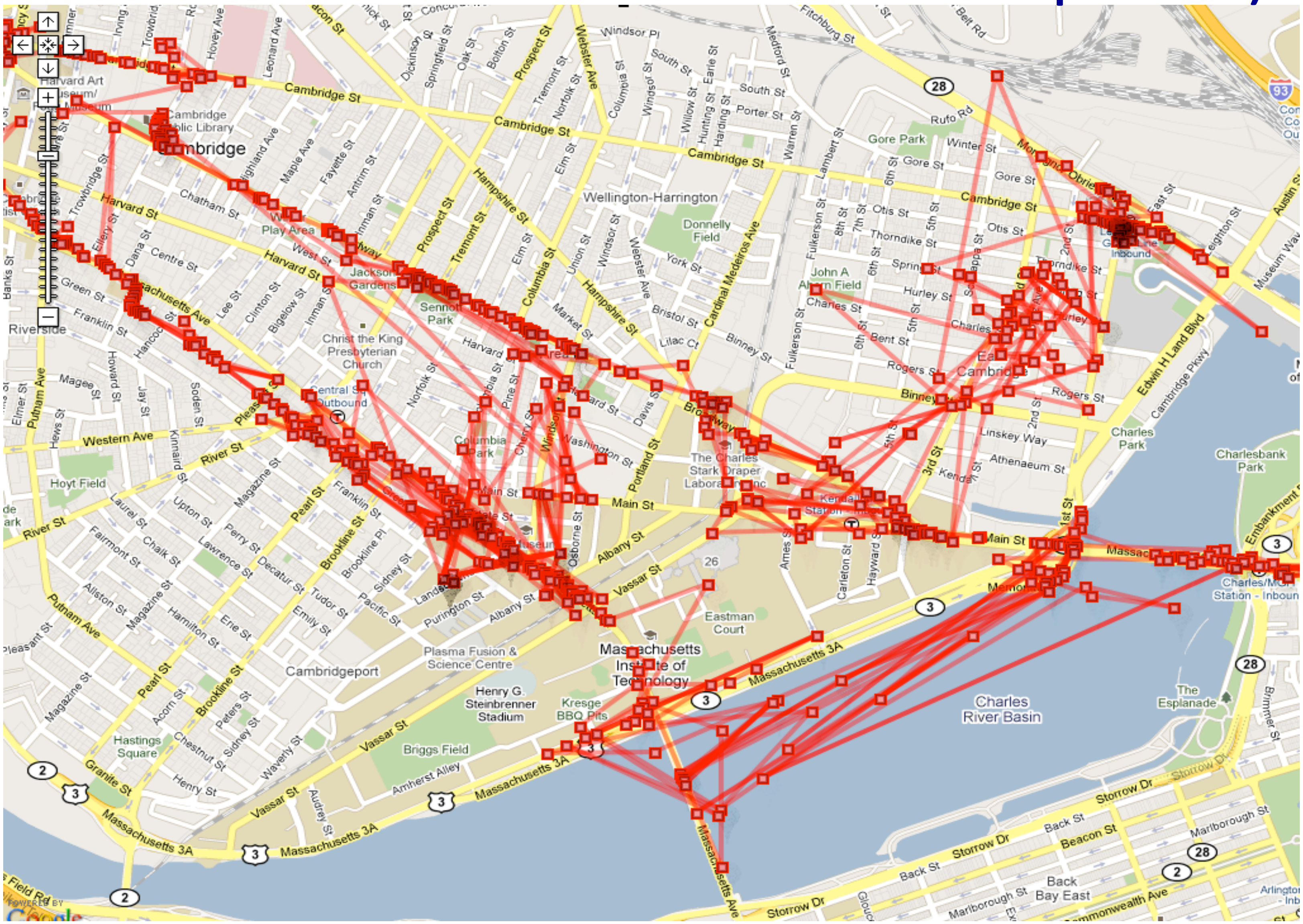
Key Insight in CTrack

- Do *not* convert radio fingerprints to (lat, lon) coordinates and then sequence them on map
- Instead, first *sequence* GSM fingerprints on a spatial grid
- This insight is crucial: it reduces error by 3x

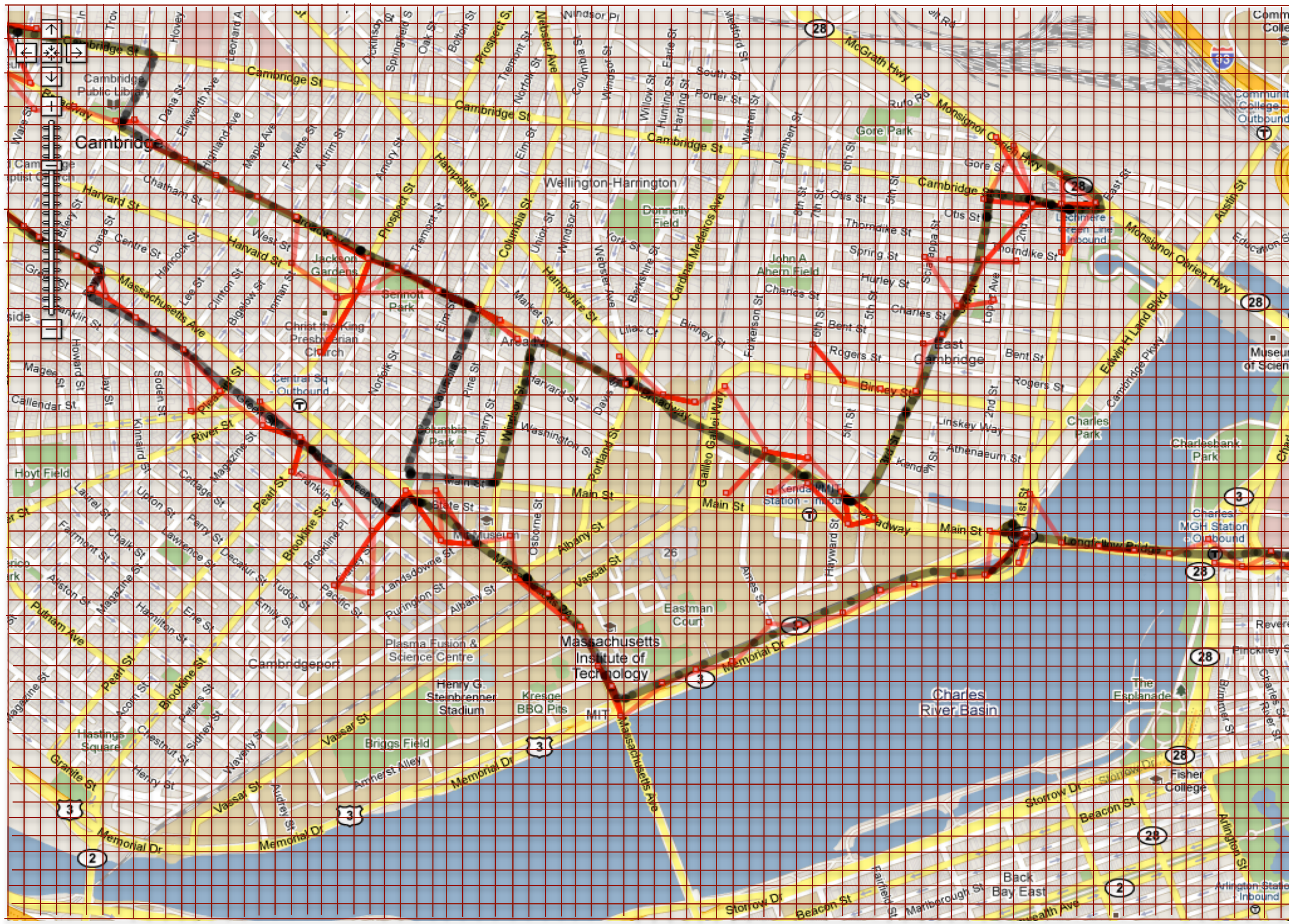
CTrack FlowChart



Raw points (using Placelab for illustration – Ctrack does not use these "raw" points)



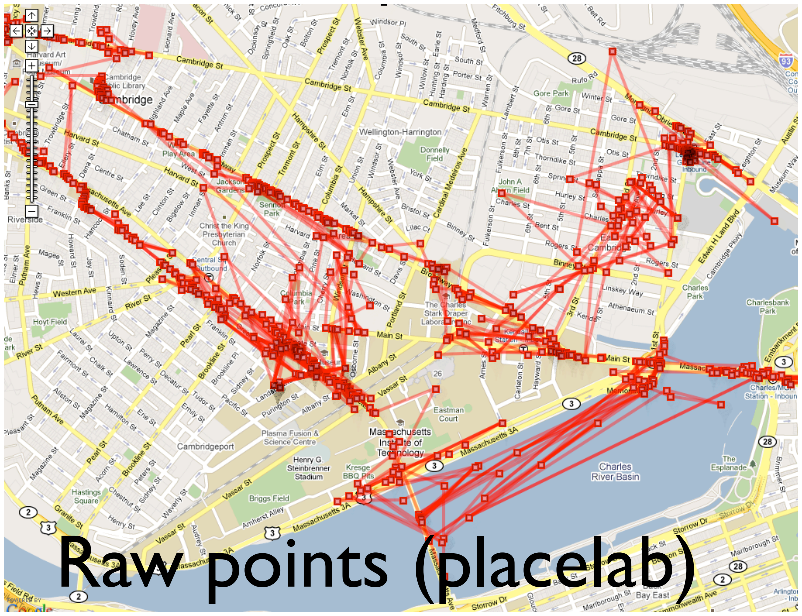
Grid Sequence

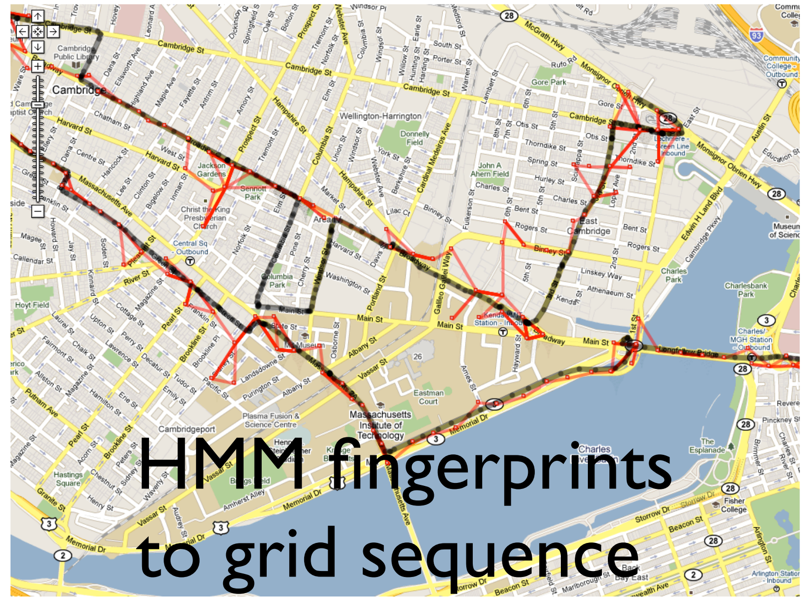


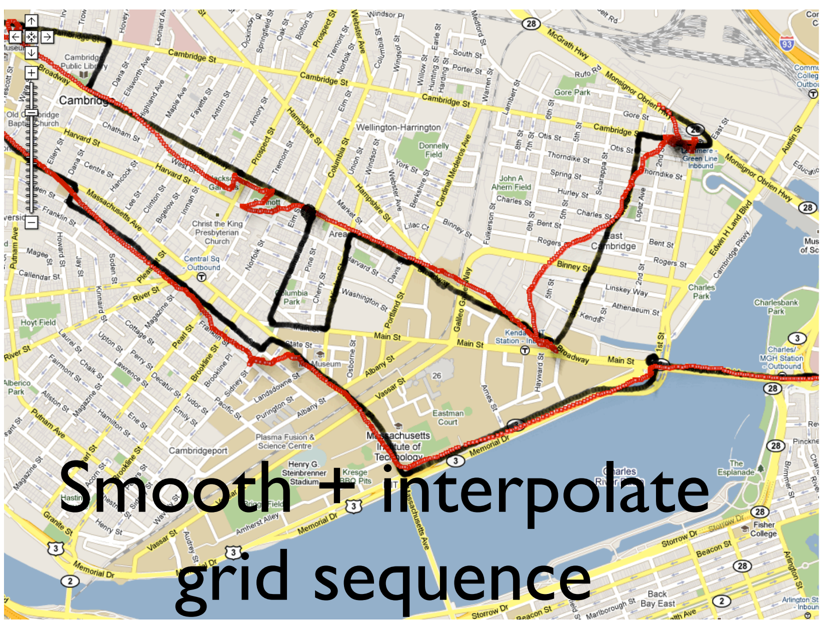
Smooth + Interpolate Grid Sequence

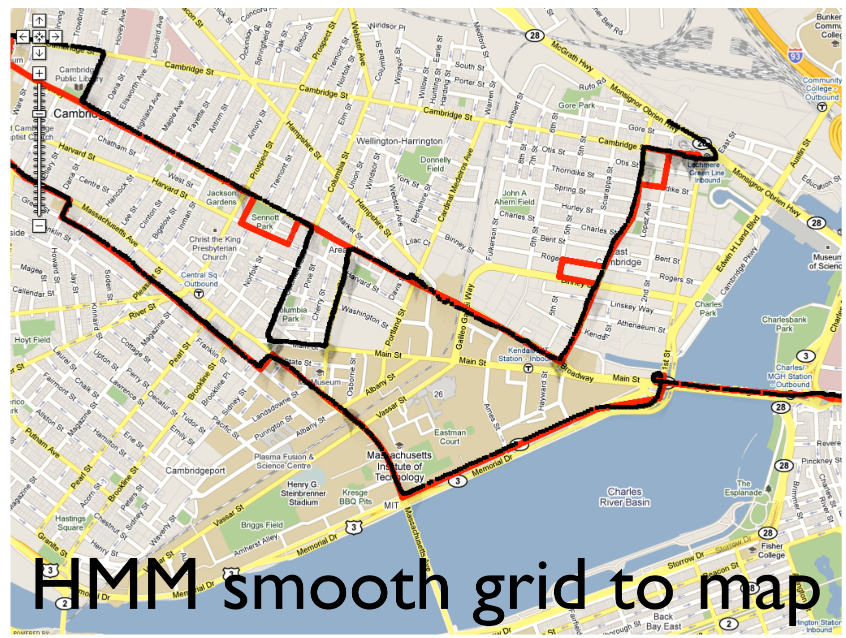
Smoothed Grid → Road Segments

CTrack Steps





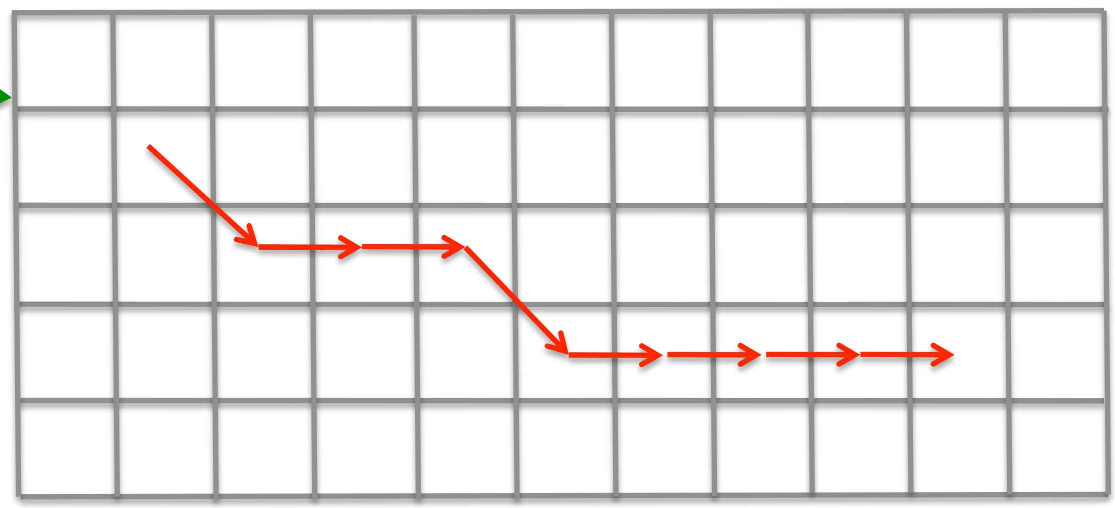




Grid Sequencing

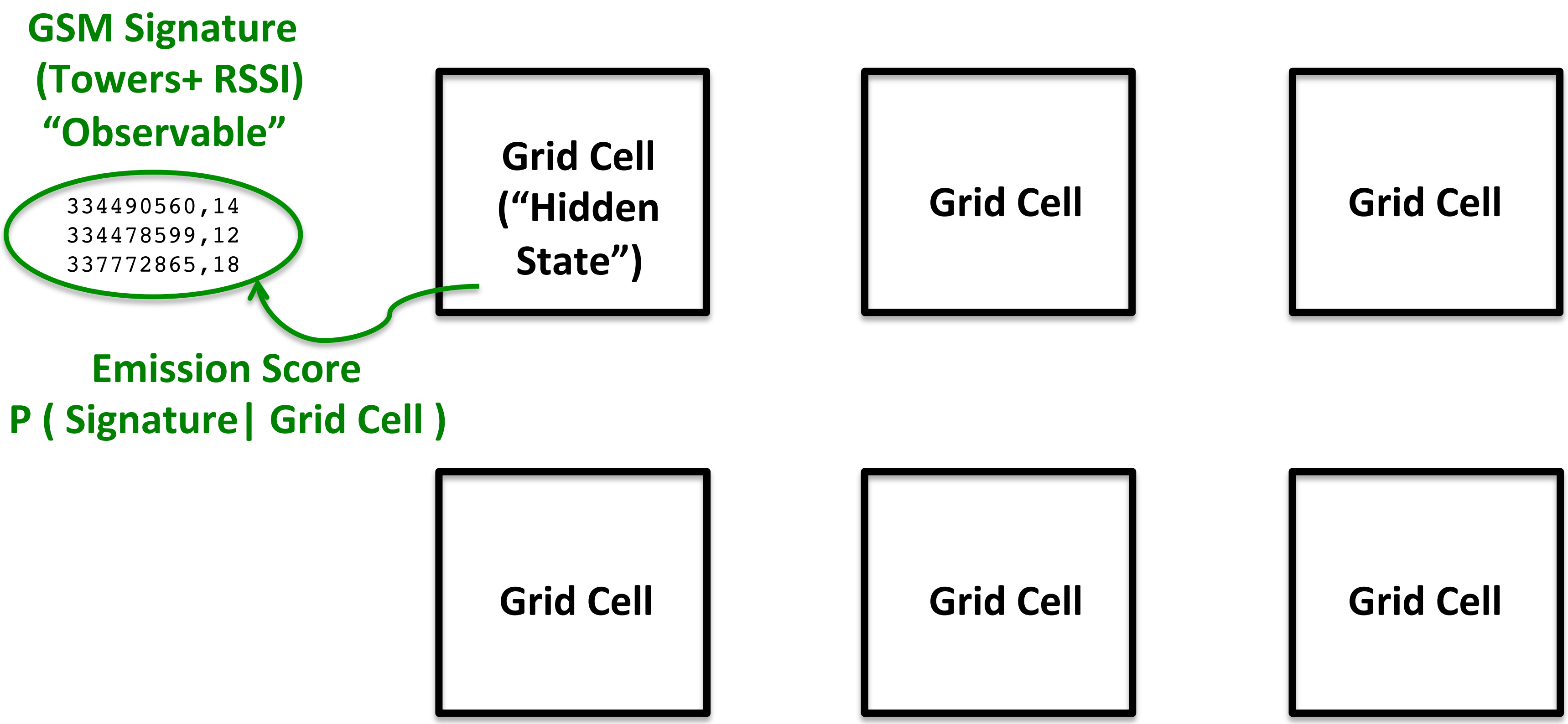
Time	TowerId	RSSI
18.03	334490560	14
	334478599	12
	337772865	18
	334478600	14
	334470539	12
	334490699	12
19.01	. . .	. .

Size of grid = 125 meters
Why?

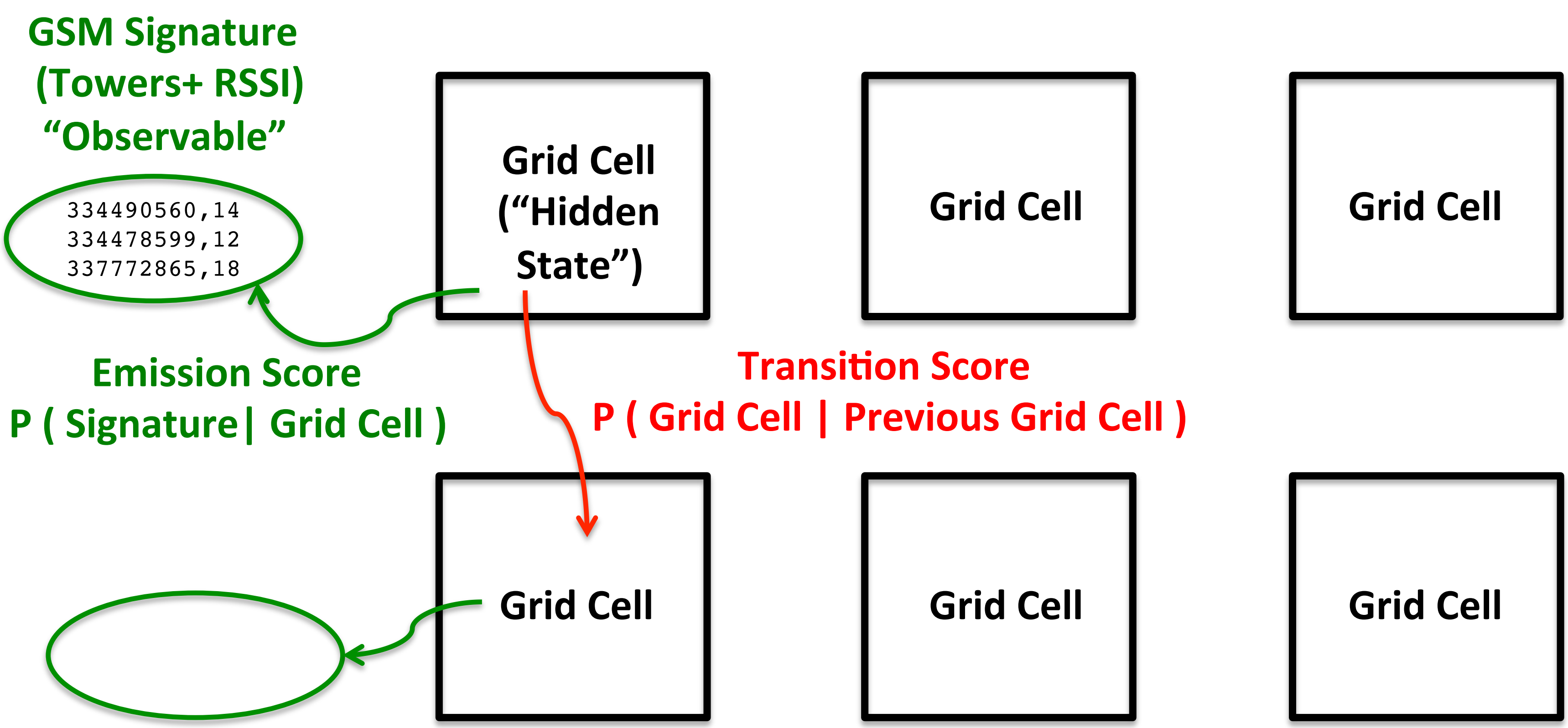


Given a sequence of GSM fingerprints (TowerID, RSSI), what is the most likely sequence of grid cells?

HMM For Grid Sequencing



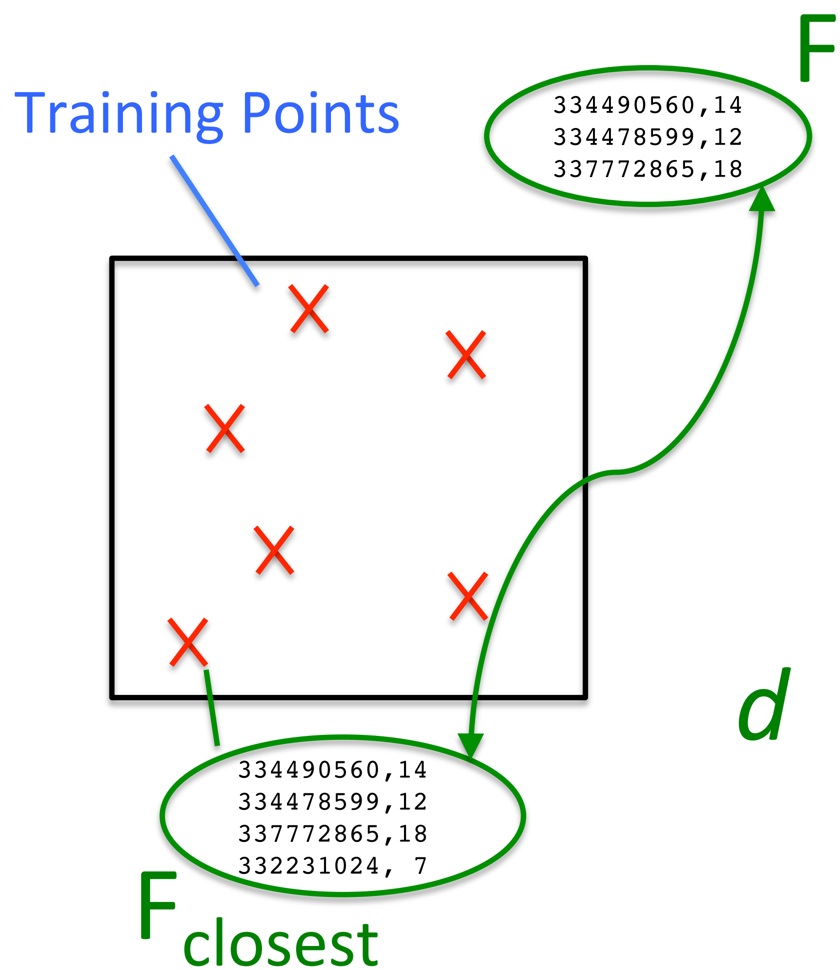
HMM For Grid Sequencing



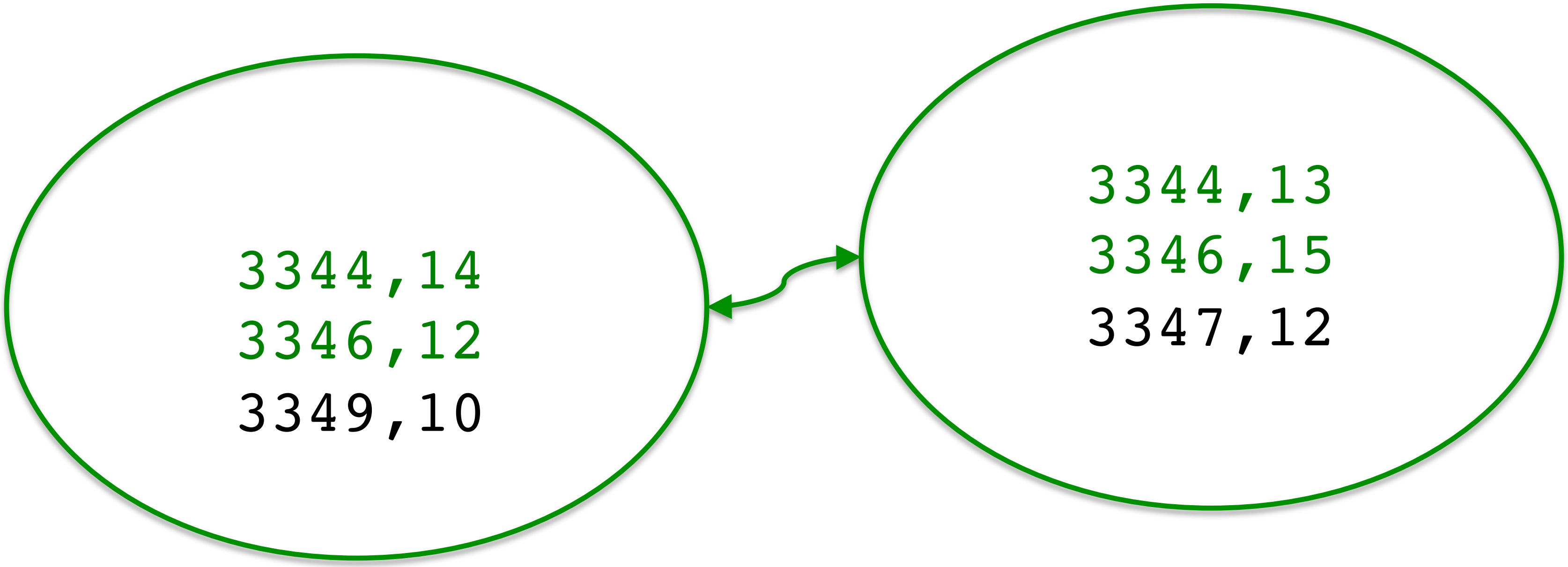
Dynamic Programming Finds Best Grid Sequence (cf. Viterbi)
“Best” => Max (Emission Score * Transition Score)

Emission Score
(Grid Cell G, Fingerprint F)

- Find *closest* matching fingerprint $F_{closest}$ to F in all training data for grid cell G
- Score is *inversely proportional* to “distance” *d* of $F_{closest}$ from F in signal strength space
- Better match => smaller *d* => higher score



Example



$$d = \lambda * 2 + (d_{max} - 0.5 * \mathrm{sqrt}(\ (14-13)^2 + (12-15)^{\ 2})$$

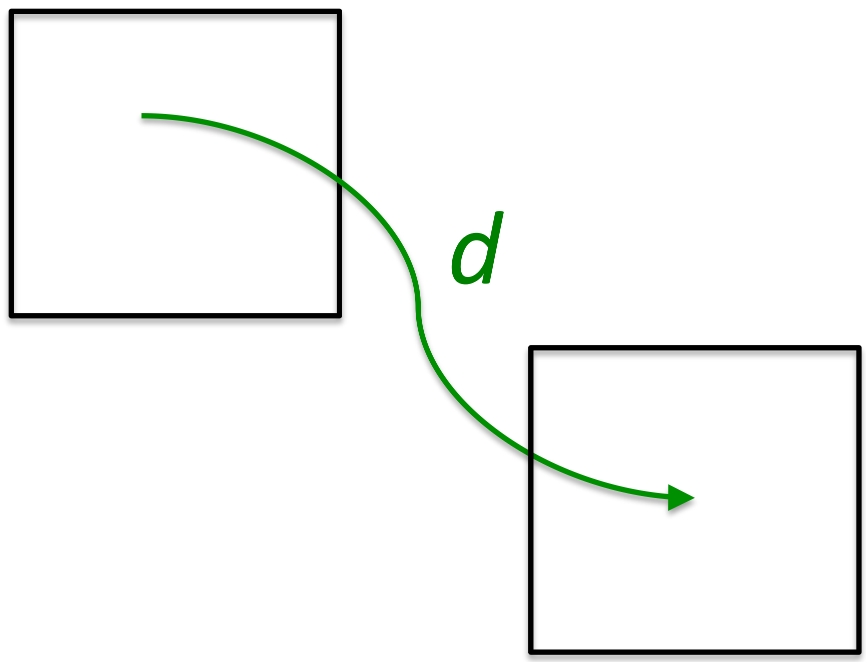
With $\lambda=3$ and $d_{max} = 32$,

Emission Score $=38 - \mathrm{sqrt}(10)/2$

Normalize this to (0,1] range

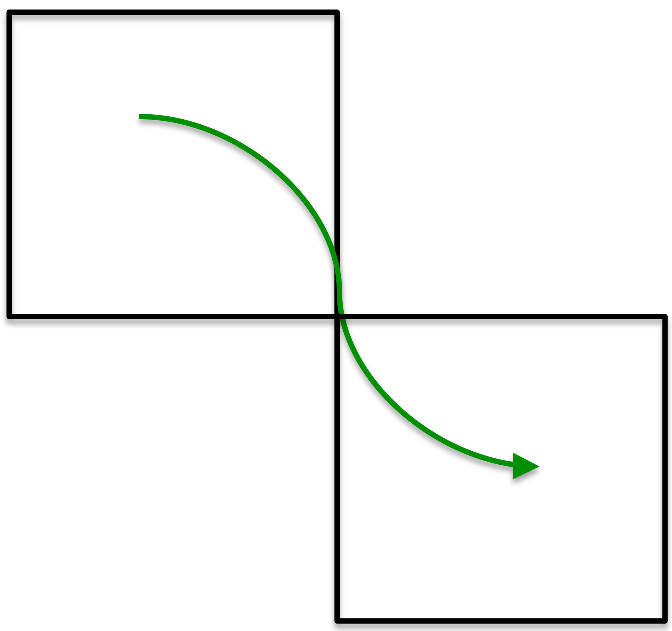
Tolerant Transition Score

- Inversely proportional to distance between grid cells
- The score is ***very tolerant*** of jumps between non-adjacent grid cells
- Necessary to tolerate large outliers/regions of poor coverage in the GSM data

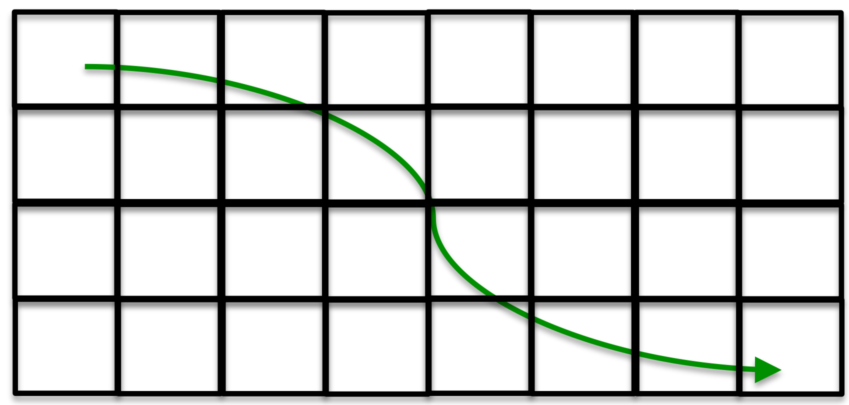


Score = 1/d

Example



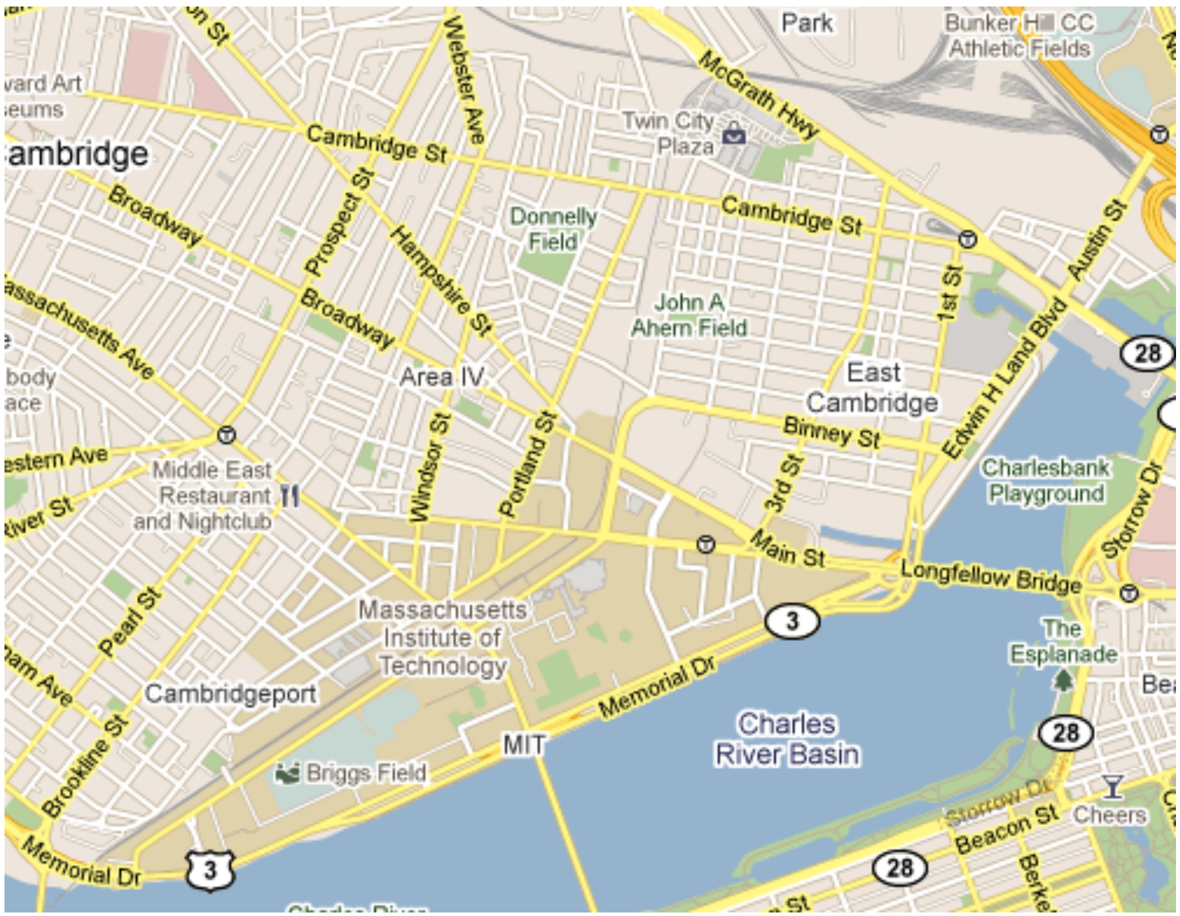
Transition Score = 1



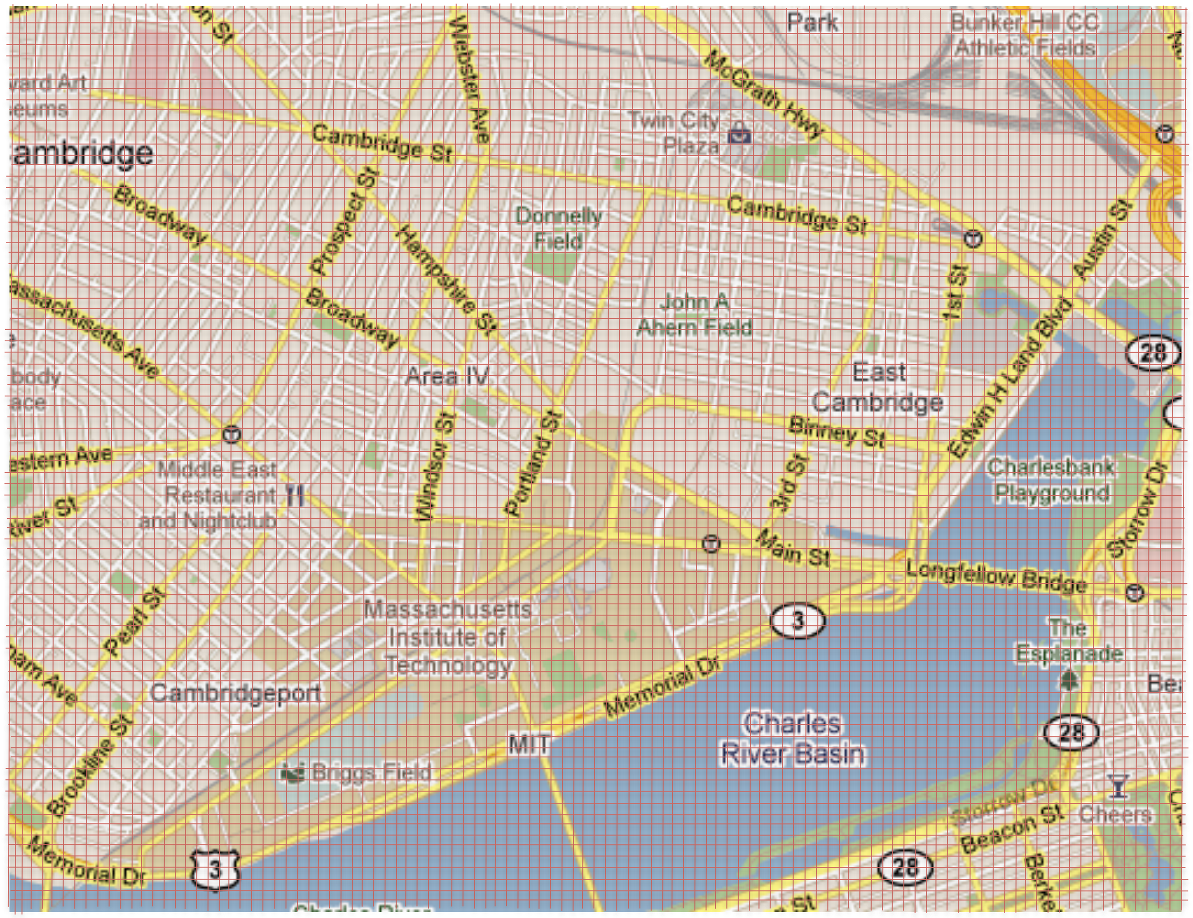
d = 7

Transition Score = 1/7

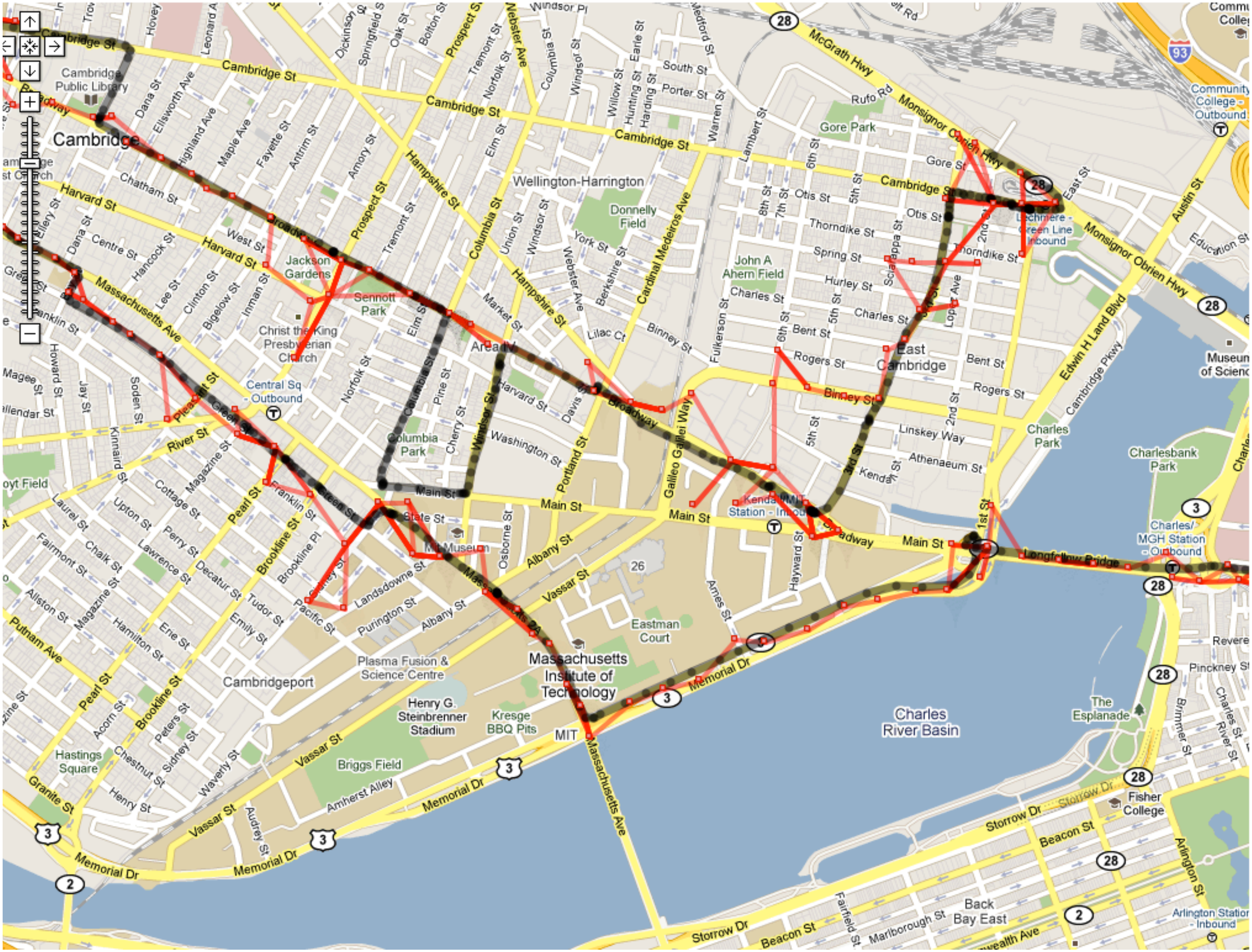
Grid Sequencing In Action



Grid Sequencing In Action



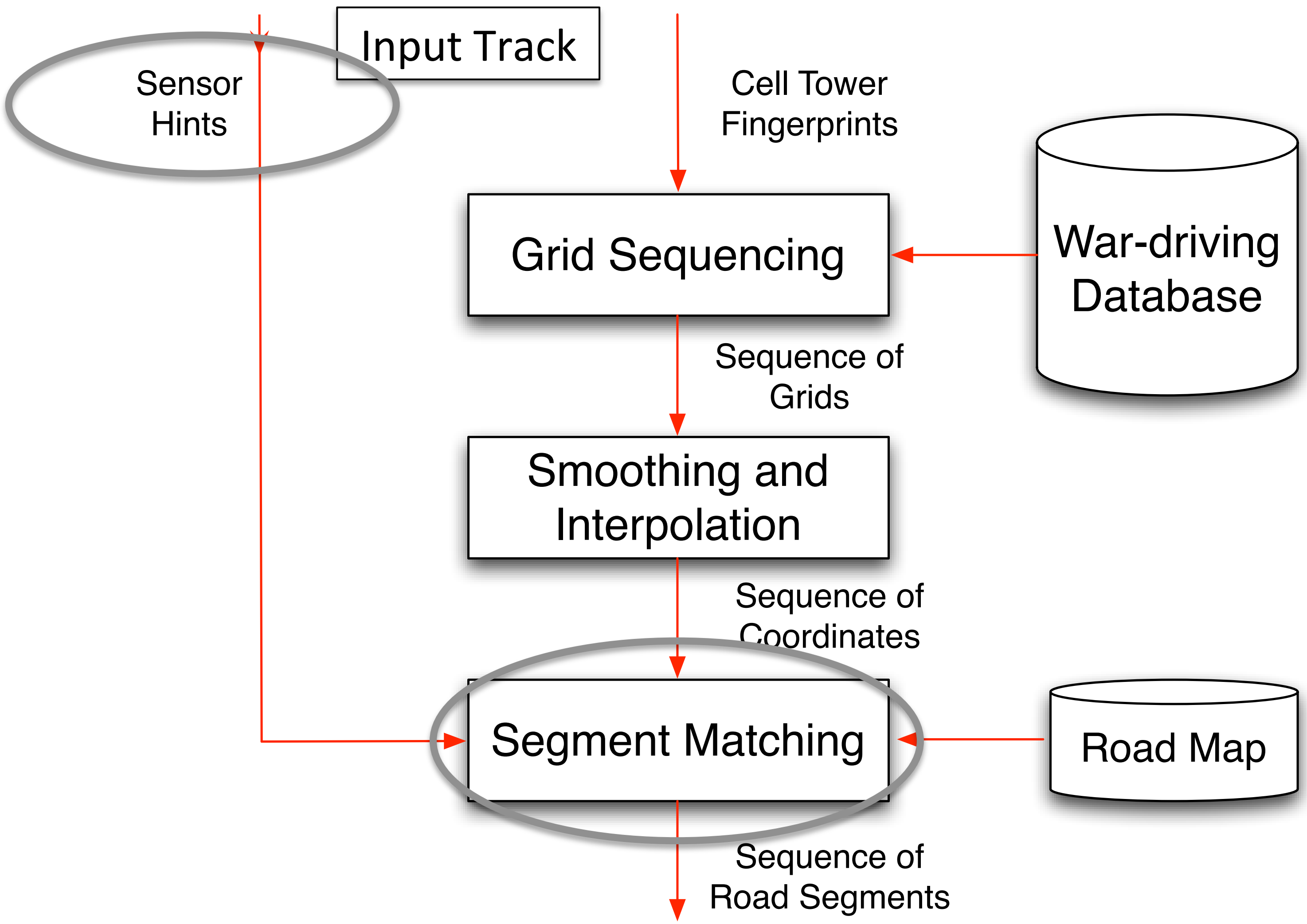
Grid Sequencing In Action



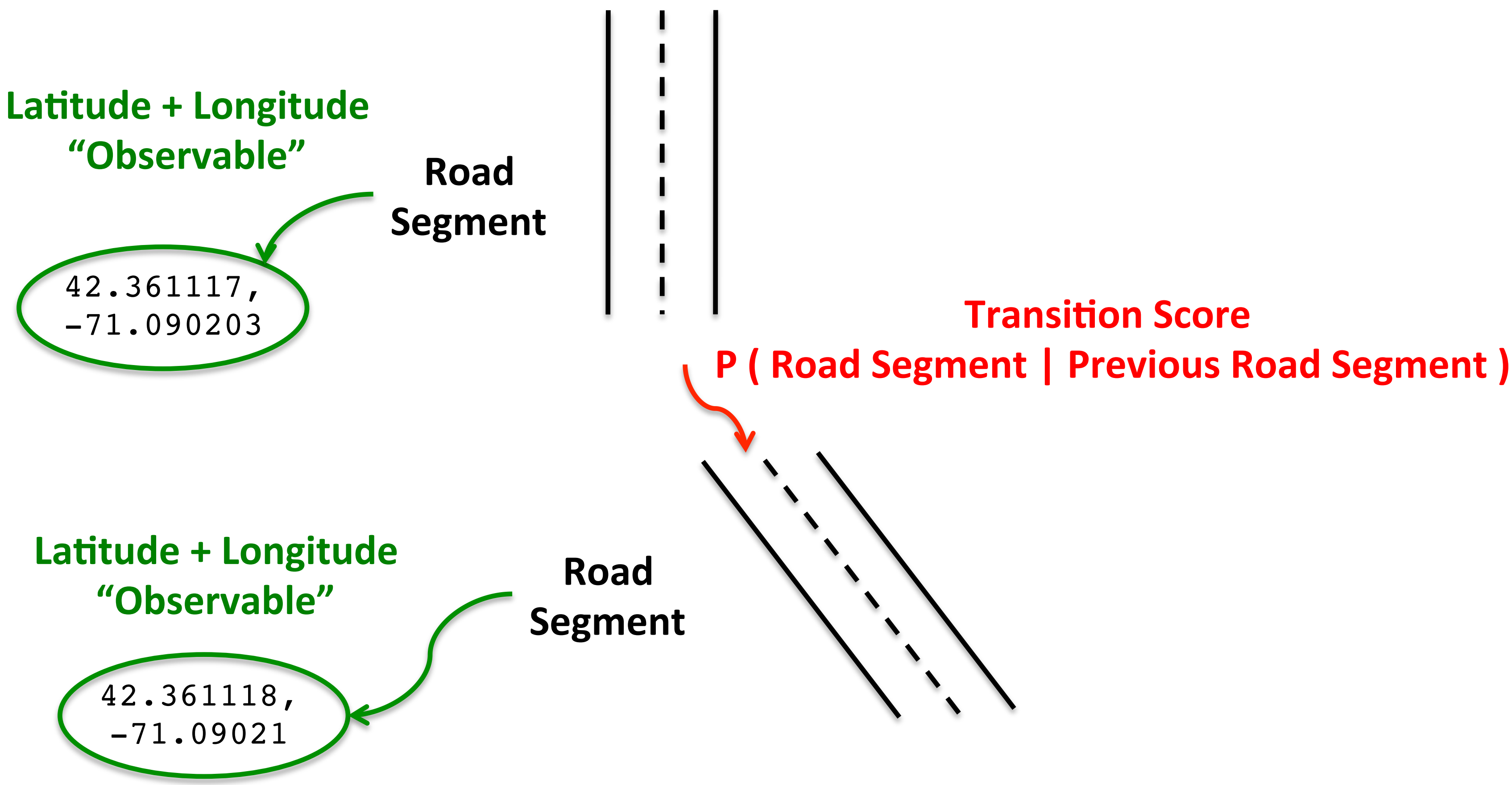
Cambridge
Cambridge Public Library
Cambridge St
Harvard St
Broadway
Massachusetts Ave
Hampshire St
Prospect St
Columbia St
Windsor St
Main St
Cardinal Medeiros Ave
Wellington-Harrington
Donnelly Field
Jackson Gardens
Sennott Park
Christ the King Presbyterian Church
Central Sq - Outbound
Columbia Park
Area IV
Binney St
Galileo Galilei Way
John A Ahern Field
East Cambridge
Kendall/MIT Station - Inbound
Lechmere - Green Line Inbound
Monsignor Obrien Hwy
McGrath Hwy
Gore Park
Community College - Outbound
Museum of Science
Charles Park
Charlesbank Park
Charles/MGH Station - Outbound
Longfellow Bridge
Edwin H Land Blvd
Cambridge Pkwy
Memorial Dr
Massachusetts Institute of Technology
Eastman Court
MIT Museum
Plasma Fusion & Science Centre
Henry G. Steinbrenner Stadium
Kresge BBQ Pits
MIT
Briggs Field
Cambridgeport
Hastings Square
Charles River Basin
The Esplanade
Storrow Dr
Beacon St
Fisher College
Back Bay East
Arlington Station - Inbound
Marlborough St
Vassar St
Albany St
Pearl St
Brookline St
River St
Green St
Franklin St
Putnam Ave
Magazine St
Sidney St
Landsdowne St
Purington St
Portland St
Ames St
Hayward St
3rd St
1st St
Binney St
Rogers St
Bent St
Charles St
Spring St
Thorndike St
Otis St
Gore St
Austin St
East St
Pinckney St
Revere
Brimmer St
Arlington St

Smoothing & Interpolation

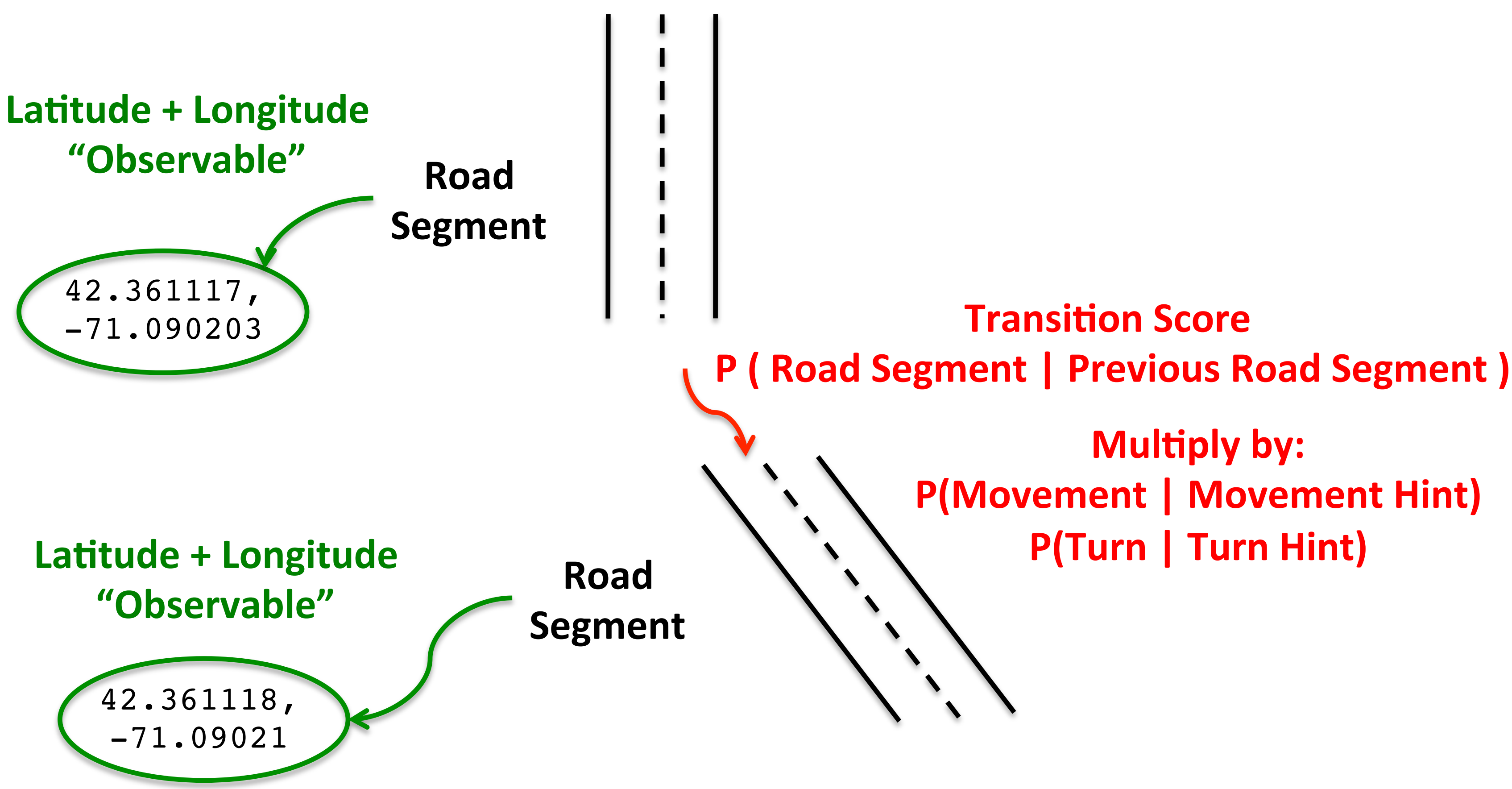
CTrack FlowChart



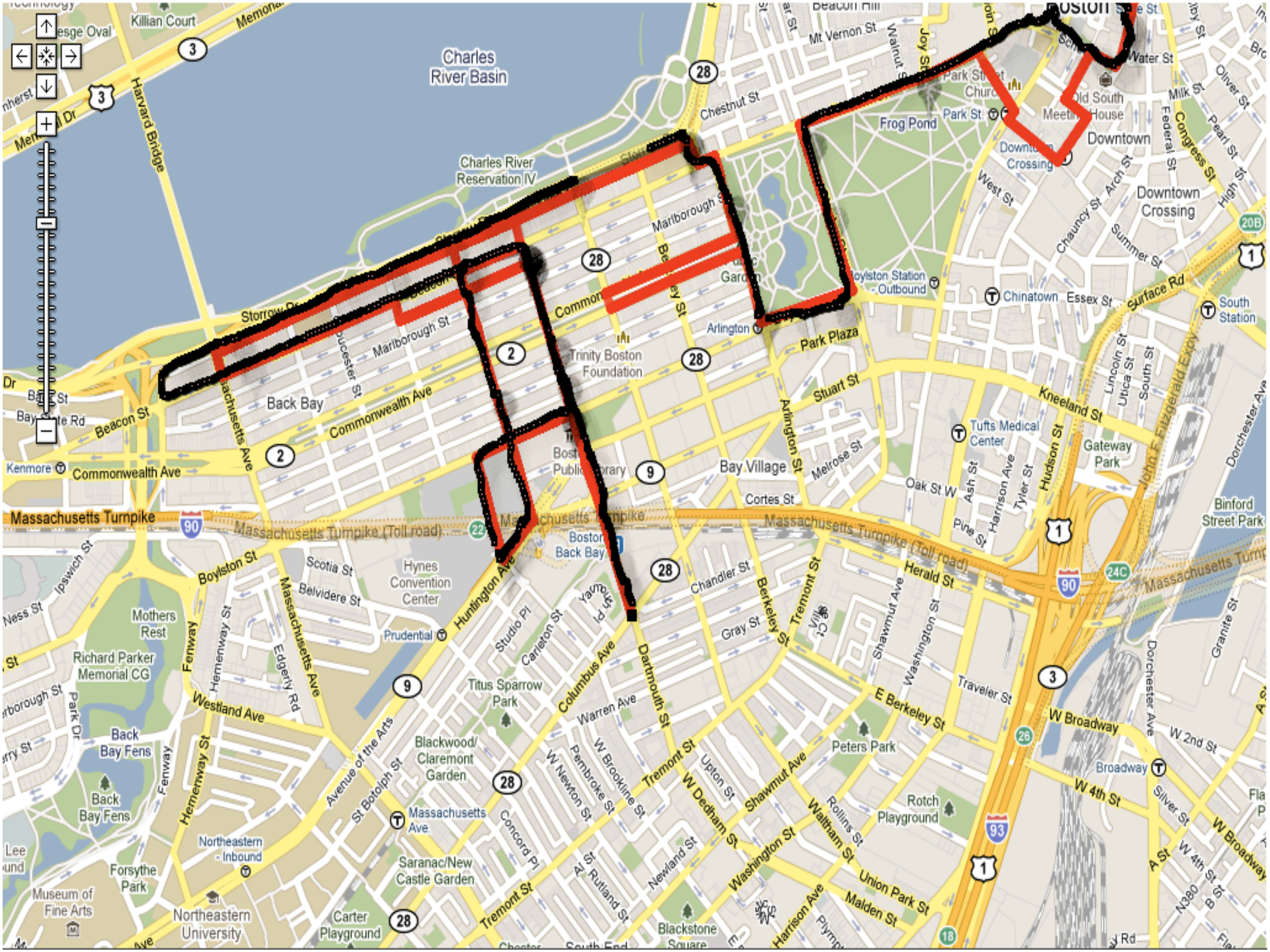
Matching (Lat, Lon) To Segments



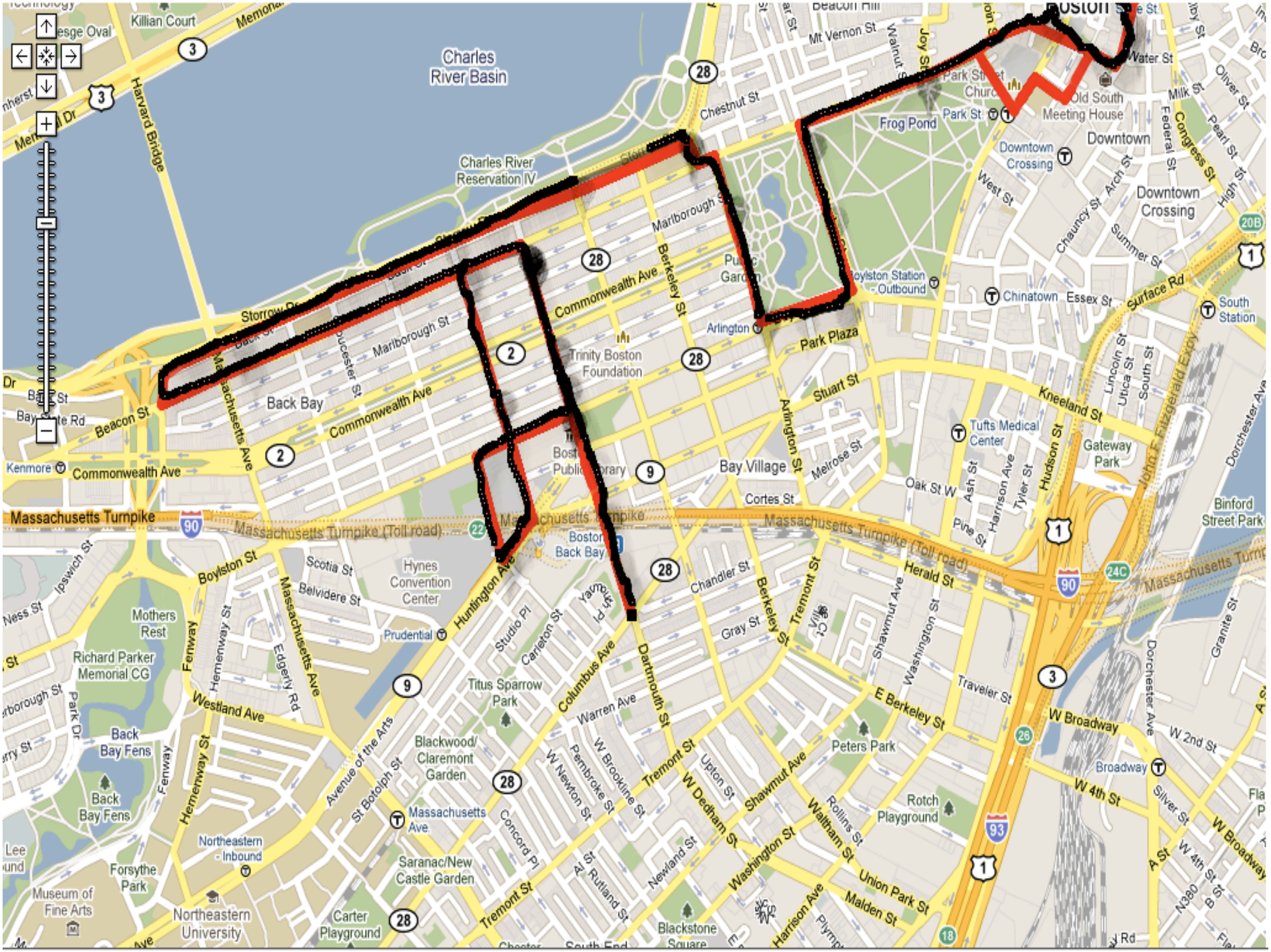
Matching (Lat, Lon) To Segments



Extract 0/1 (Binary) Movement and Turn Hints For Each Time Slot



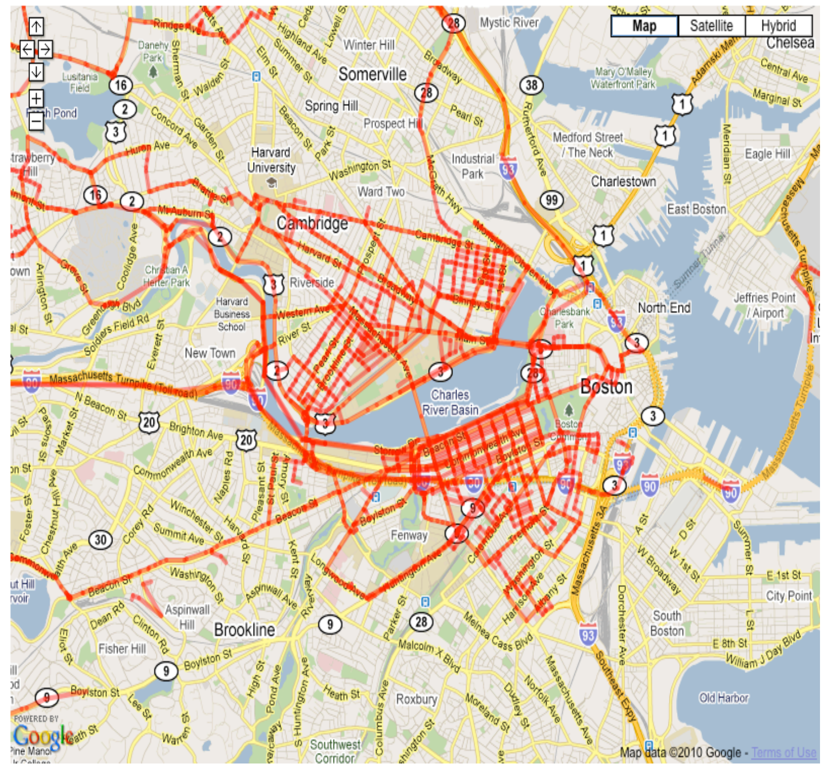
Charles River Basin
Charles River Reservation IV
Killian Court
Harvard Bridge
Back Bay
Beacon St
Marlborough St
Commonwealth Ave
Storrow Dr
Massachusetts Ave
Kenmore
Massachusetts Turnpike
Massachusetts Turnpike (Toll road)
Boylston St
Trinity Boston Foundation
Arlington
Park Plaza
Stuart St
Frog Pond
Park St
Chestnut St
Mt Vernon St
Beacon Hill
Water St
Old South Meeting House
Downtown
Downtown Crossing
West St
Chinatown
Essex St
Surface Rd
South Station
Kneeland St
Tufts Medical Center
Gateway Park
Bay Village
Cortes St
Herald St
Boston Back Bay
Hynes Convention Center
Prudential
Huntington Ave
Dartmouth St
Columbus Ave
Tremont St
Berkeley St
Chandler St
Gray St
Shawmut Ave
Washington St
E Berkeley St
Traveler St
W Broadway
Broadway
W 4th St
Peters Park
Rotch Playground
Union Park St
Malden St
Blackstone Square
Titus Sparrow Park
Blackwood/ Claremont Garden
Massachusetts Ave
Saranac/New Castle Garden
Carter Playground
Northeastern University
Museum of Fine Arts
Forsythe Park
Back Bay Fens
Richard Parker Memorial CG
Mothers Rest
Fenway
Hemenway St
Westland Ave
Scotia St
Belvidere St
Avenue of the Arts
St Botolph St
Warren Ave
W Newton St
Pembroke St
W Brookline St
W Dedham St
Upton St
Newland St
Rutland St
Concord Pl
Studio Pl
Carleton St
Arlington St
Melrose St
Oak St W
Pine St
Harrison Ave
Tyler St
Hudson St
Ash St
Lincoln St
Utica St
South St
John F. Fitzgerald Expy
Dorchester Ave
Binford Street Park
Granite St
Dorchester Ave
W 2nd St
Silver St
A St
W 4th St
B St
Congress St
Federal St
Milk St
Pearl St
High St
Oliver St
Summer St
Arch St
Chauncy St
Joy St
Walnut St
Boylston Station - Outbound
Northeastern - Inbound
Ipswich St
Edgerly Rd
Rollins St
Waltham St



Charles River Basin
Charles River Reservation IV
Killian Court
Harvard Bridge
Storrow Dr
Back St
Beacon St
Marlborough St
Commonwealth Ave
Back Bay
Massachusetts Ave
Berkeley St
Chestnut St
Beacon Hill
Mt Vernon St
Walnut St
Joy St
Park Street Church
Park St
Frog Pond
Old South Meeting House
Water St
Milk St
Downtown Crossing
Downtown
West St
Chauncy St
Arch St
Summer St
High St
Federal St
Congress St
Pearl St
Oliver St
Public Garden
Boylston Station - Outbound
Arlington
Park Plaza
Chinatown
Essex St
Surface Rd
South Station
Trinity Boston Foundation
Stuart St
Kneeland St
Tufts Medical Center
Gateway Park
Hudson St
Lincoln St
Utica St
South St
John F. Fitzgerald Expy
Dorchester Ave
Boston Public Library
Bay Village
Melrose St
Arlington St
Oak St W
Cortes St
Massachusetts Turnpike
Massachusetts Turnpike (Toll road)
Boston Back Bay
Chandler St
Berkeley St
Tremont St
Herald St
Shawmut Ave
Washington St
Gray St
Binford Street Park
Hynes Convention Center
Prudential
Huntington Ave
Boylston St
Scotia St
Belvidere St
Kenmore
Bay State Rd
Ipswich St
Mothers Rest
Richard Parker Memorial CG
Fenway
Hemenway St
Edgerly Rd
Westland Ave
Back Bay Fens
Avenue of the Arts
St Botolph St
Massachusetts Ave.
Northeastern - Inbound
Northeastern University
Museum of Fine Arts
Forsythe Park
Titus Sparrow Park
Blackwood/Claremont Garden
Saranac/New Castle Garden
Carter Playground
Columbus Ave
Warren Ave
Dartmouth St
W Newton St
Pembroke St
W Brookline St
Concord Pl
Rutland St
Newland St
W Dedham St
Upton St
Peters Park
Rotch Playground
E Berkeley St
Traveler St
W Broadway
W 4th St
W 2nd St
Broadway
Silver St
Union Park St
Malden St
Waltham St
Rollins St
Harrison Ave
Blackstone Square
Studio Pl
Carleton St
Yarmouth Pl

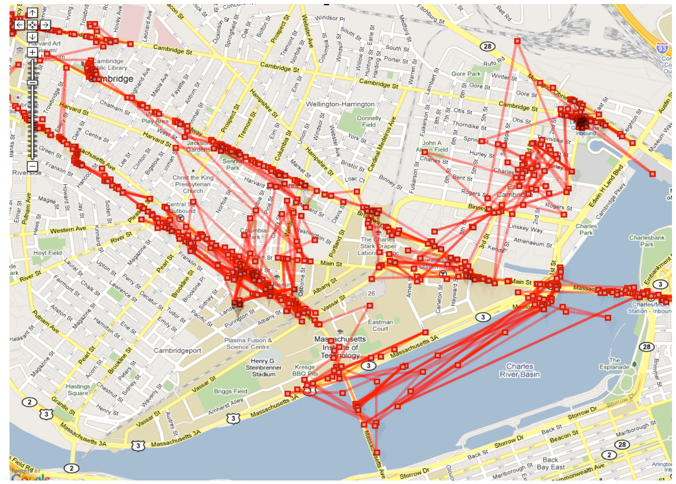
Evaluation

- 125 Hours (312 “Drives”)
  - From 16 Android phones
  - Logged GPS ground truth, GSM, accel, compass
- Selected subset of 53 drives (28 hours) as “test drives”
  - Tests lie in dense cov. area
  - Tests have good GPS accuracy
  - Mean drive length: 30-35 mins
- Leave-one-out evaluation
  - Train on all but test, evaluate on test drive

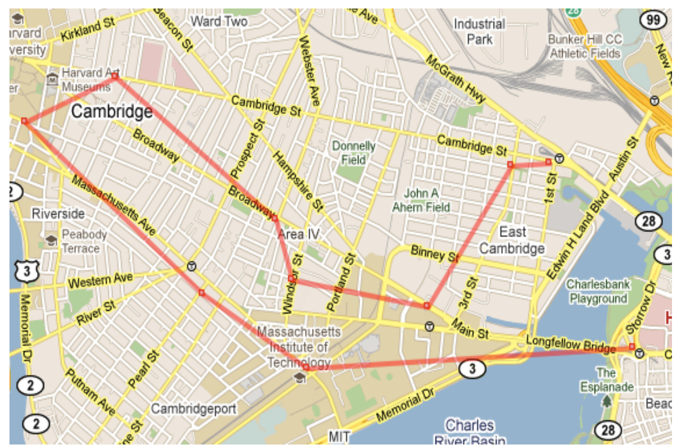


We Compared CTrack To…

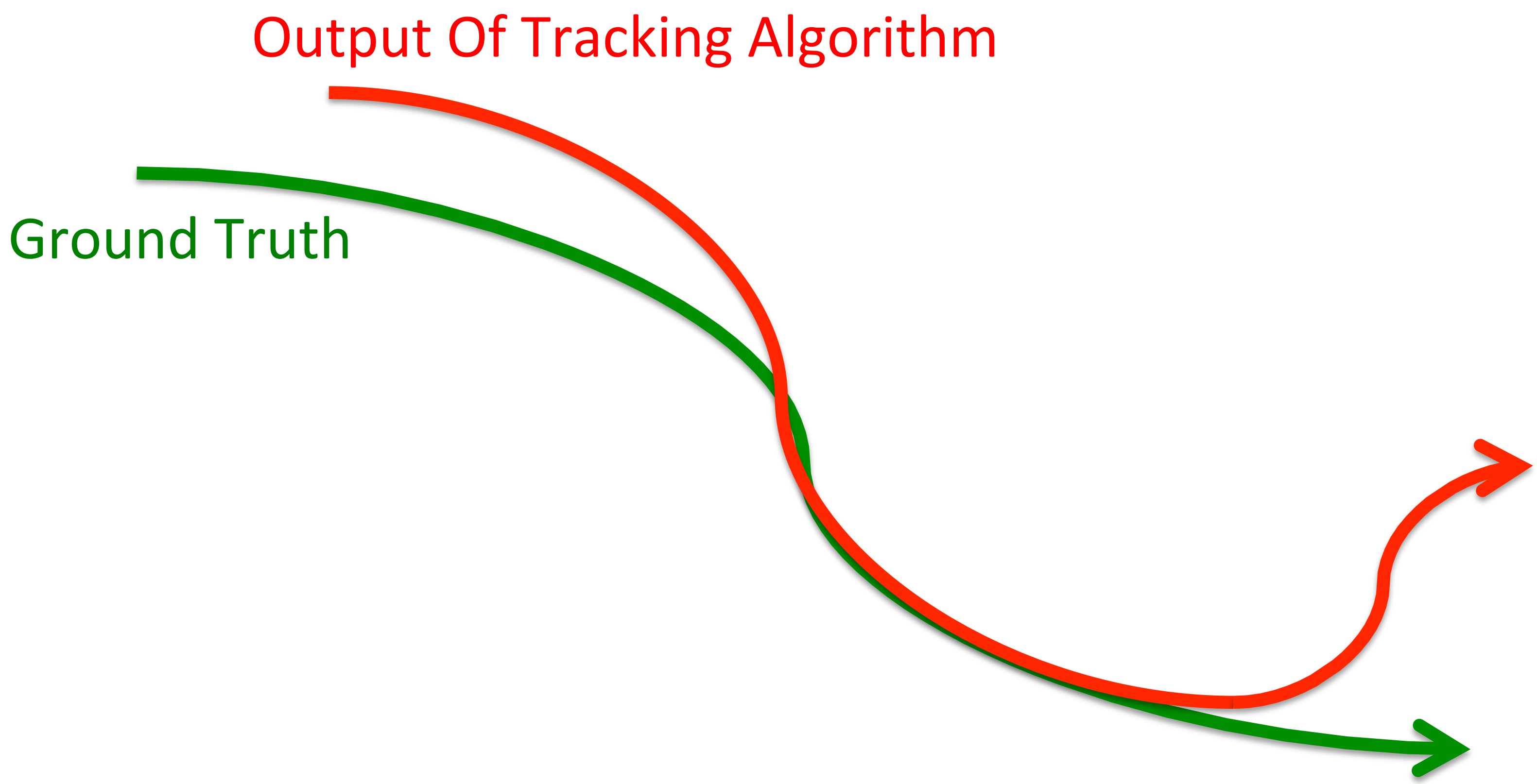
- Placelab + VTrack
  - Look up single best matching GSM fingerprint for each time
  - Match (lat, lon) using VTrack



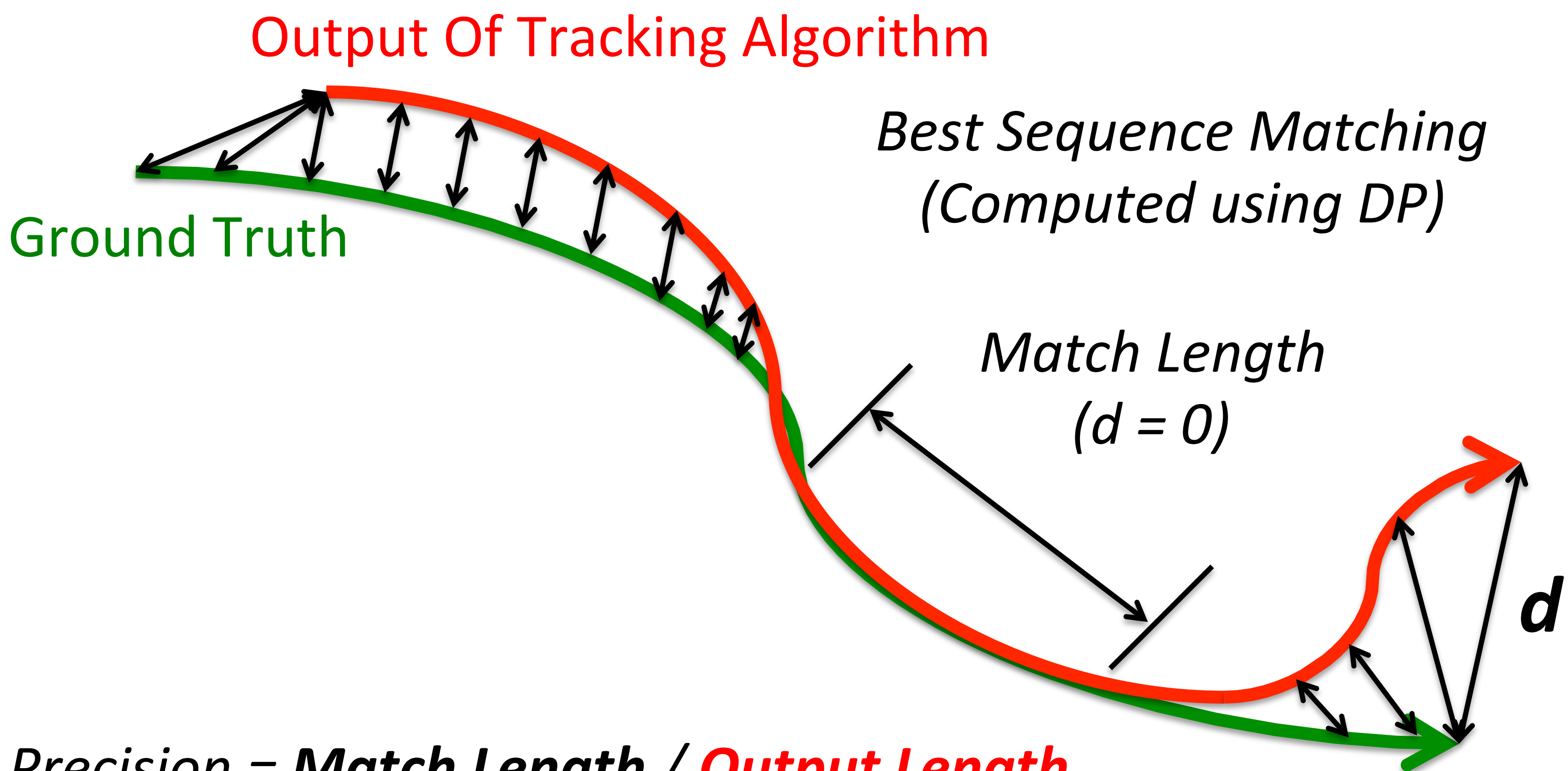
- *GPS k* + VTrack
  - Get a GPS sample every k secs
  - Match (lat, lon) using VTrack
  - k = 4 min is *energy-equivalent* to CTrack



Evaluation Metrics



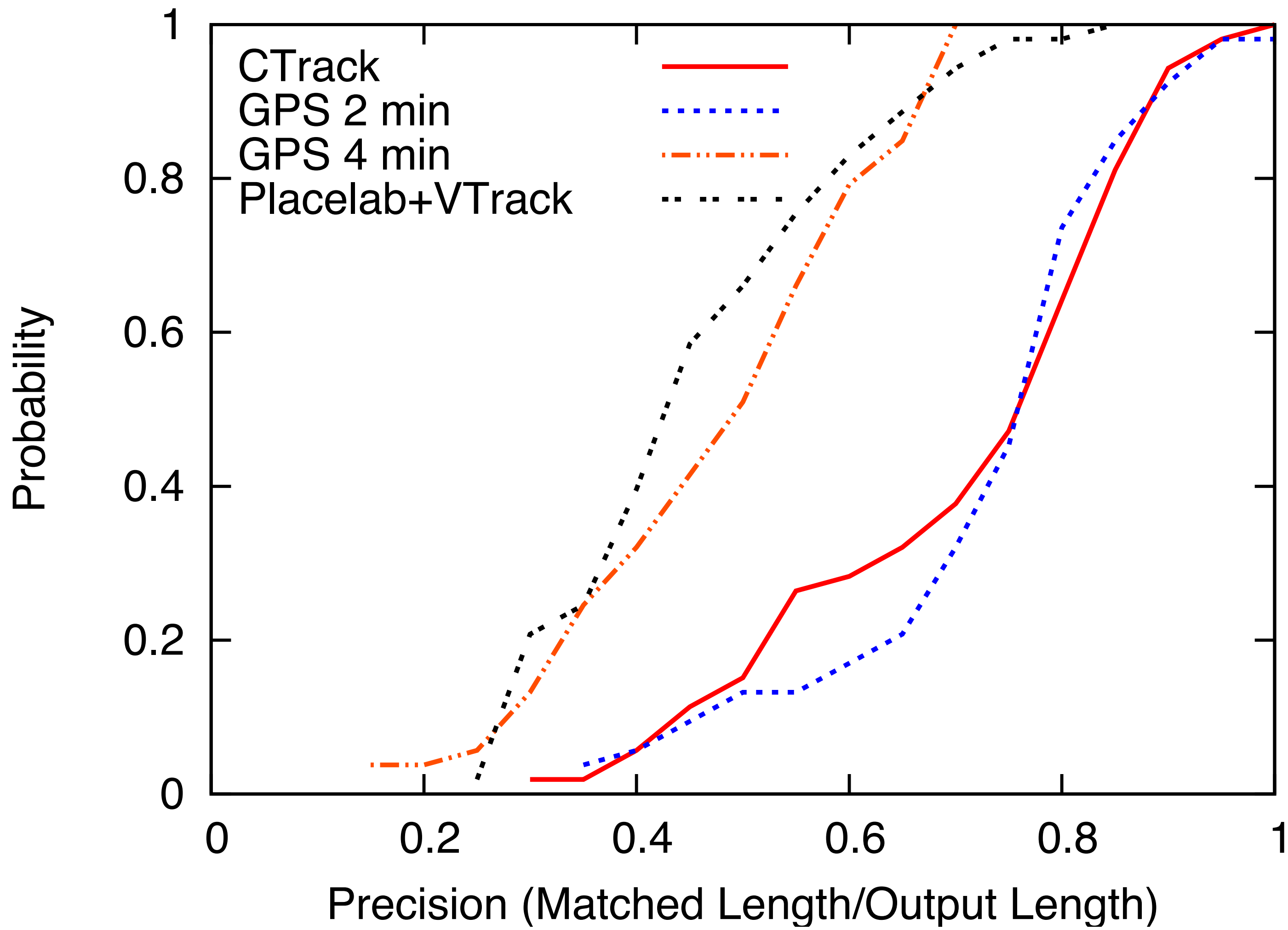
Evaluation Metrics



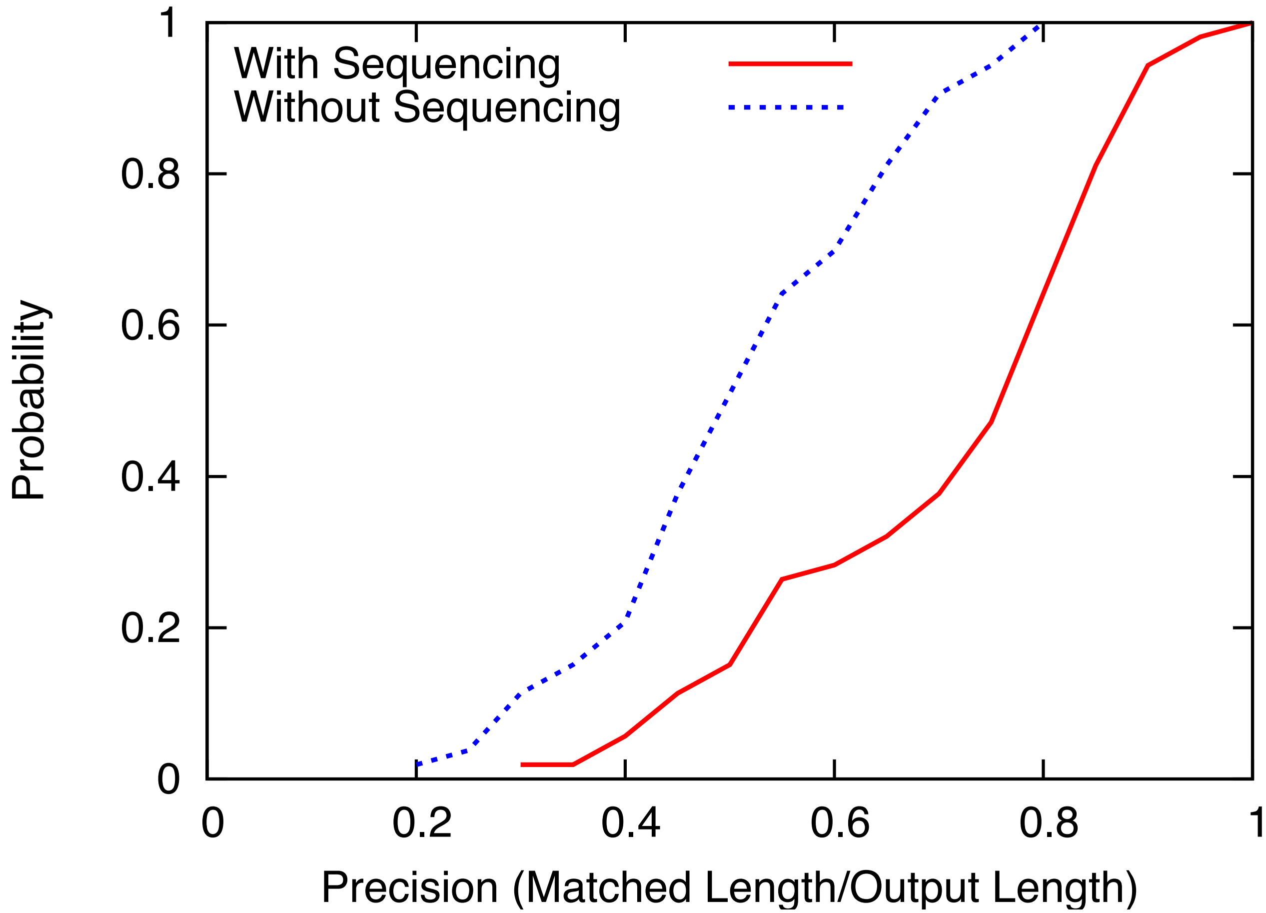
*Precision = **Match Length** / **Output Length***

*Recall = **Match Length** / **Ground Truth Length***

CTrack Has 75% Precision: 3x Less Error Than Placelab+VTrack, GPS k



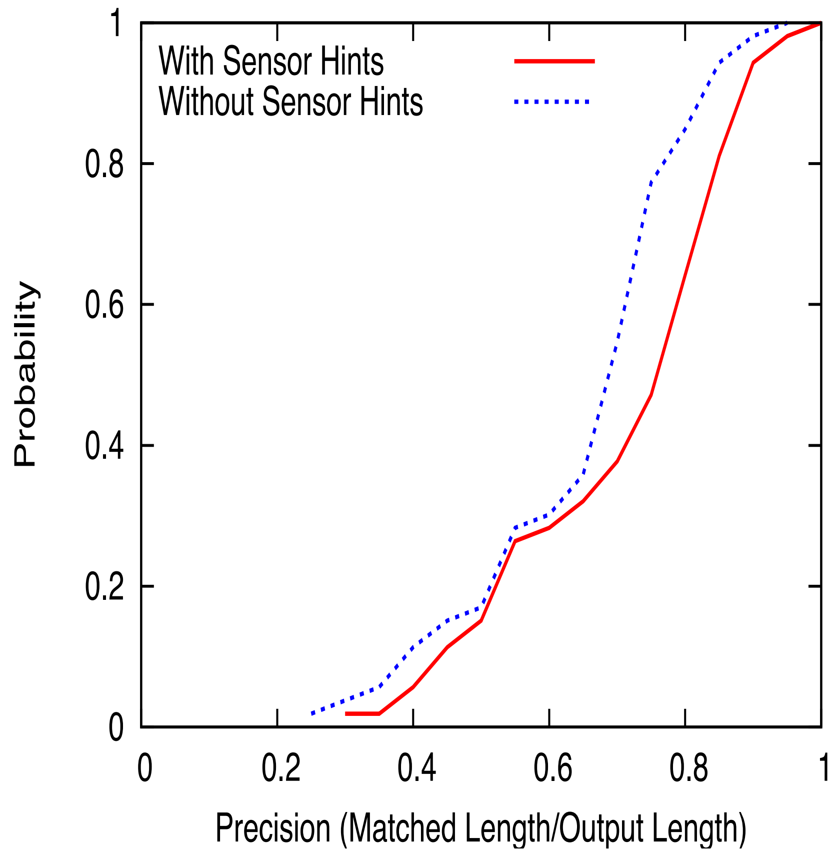
Grid Sequencing Step is Critical



Sequencing First Before Converting to (Lat, Lon) Coordinates is Critical

Impact Of Sensor Hints

- Small in quantitative terms
  - 6% precision, 3% recall
- But help correct some systematic errors
  - Turn hints fix "kinks" in output track
  - Movement hints fix "looping" in GSM signature



Makes sense to take advantage of hints when available (i.e. on a smartphone) – they are free in terms of energy!

Conclusion

- CTrack is a *cellular-only system* that:
  - Can recover over 75% of a user's track
  - Significantly (over 3x) better in energy/accuracy tradeoff than existing approaches

- Broader impact
  - Make large scale deployment of location-based apps feasible without running into energy barriers
  - Enable devices without GPS (was: 85% of phone market) to contribute to and benefit from location-based services
  - Many IoT devices may have cellular or other long-range low-power radios such as LoRaWAN or Sigfox, but no GPS