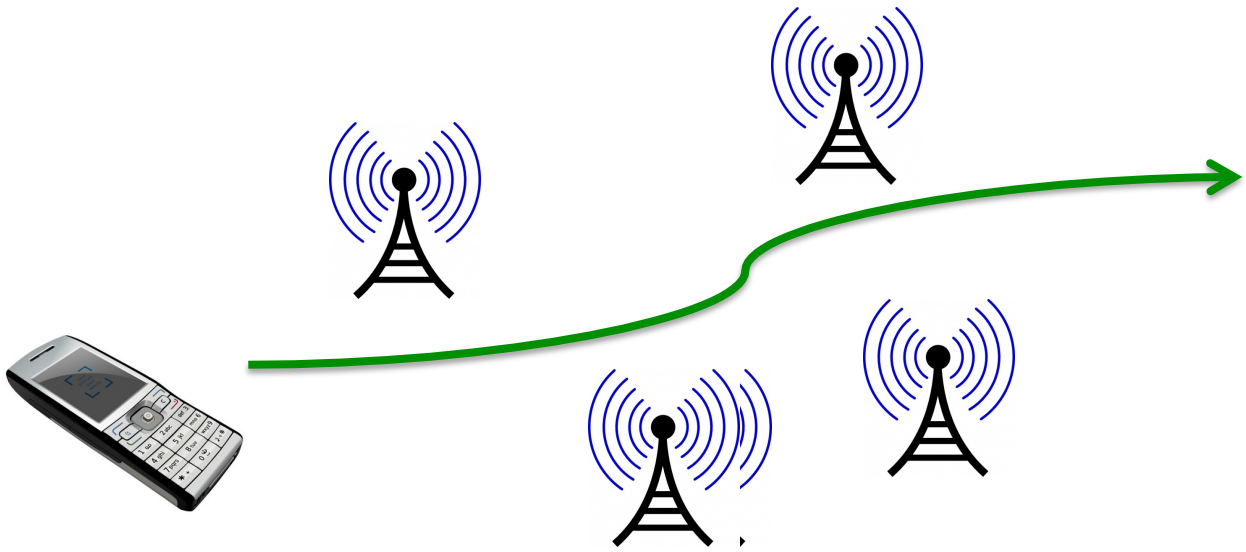
Accurate, Low Energy Trajectory Mapping For Mobile Phones



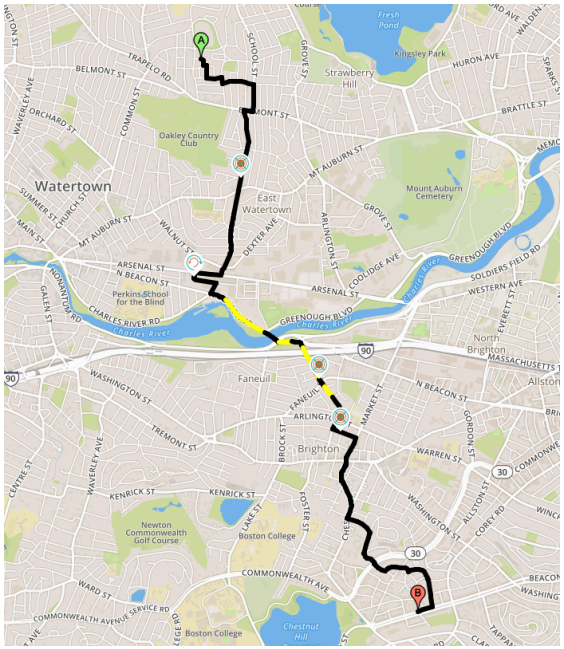
Arvind Thiagarajan, Lenin Ravindranath,

Hari Balakrishnan, Sam Madden, Lewis Girod

MIT CSAIL

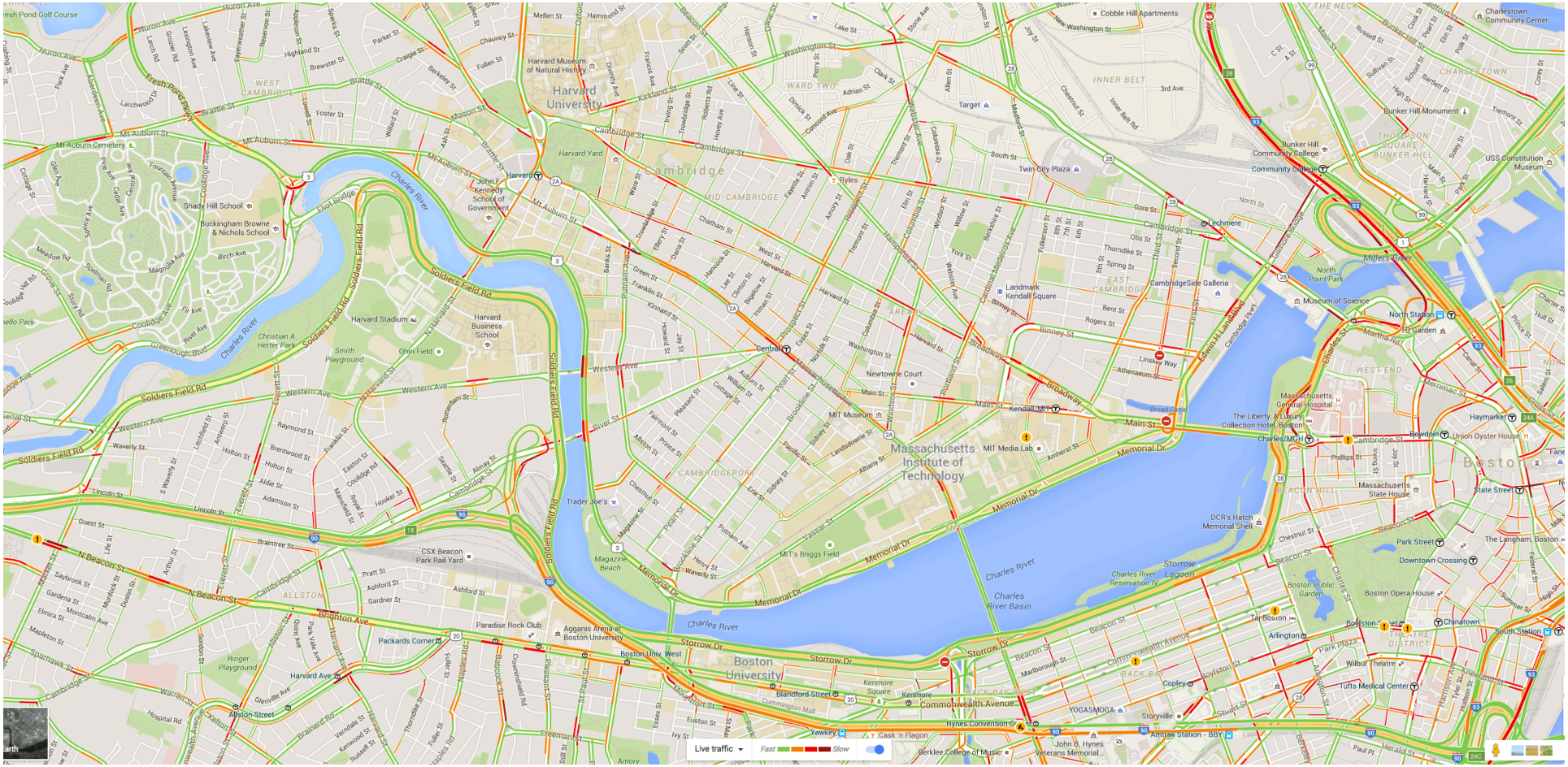
Goal

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

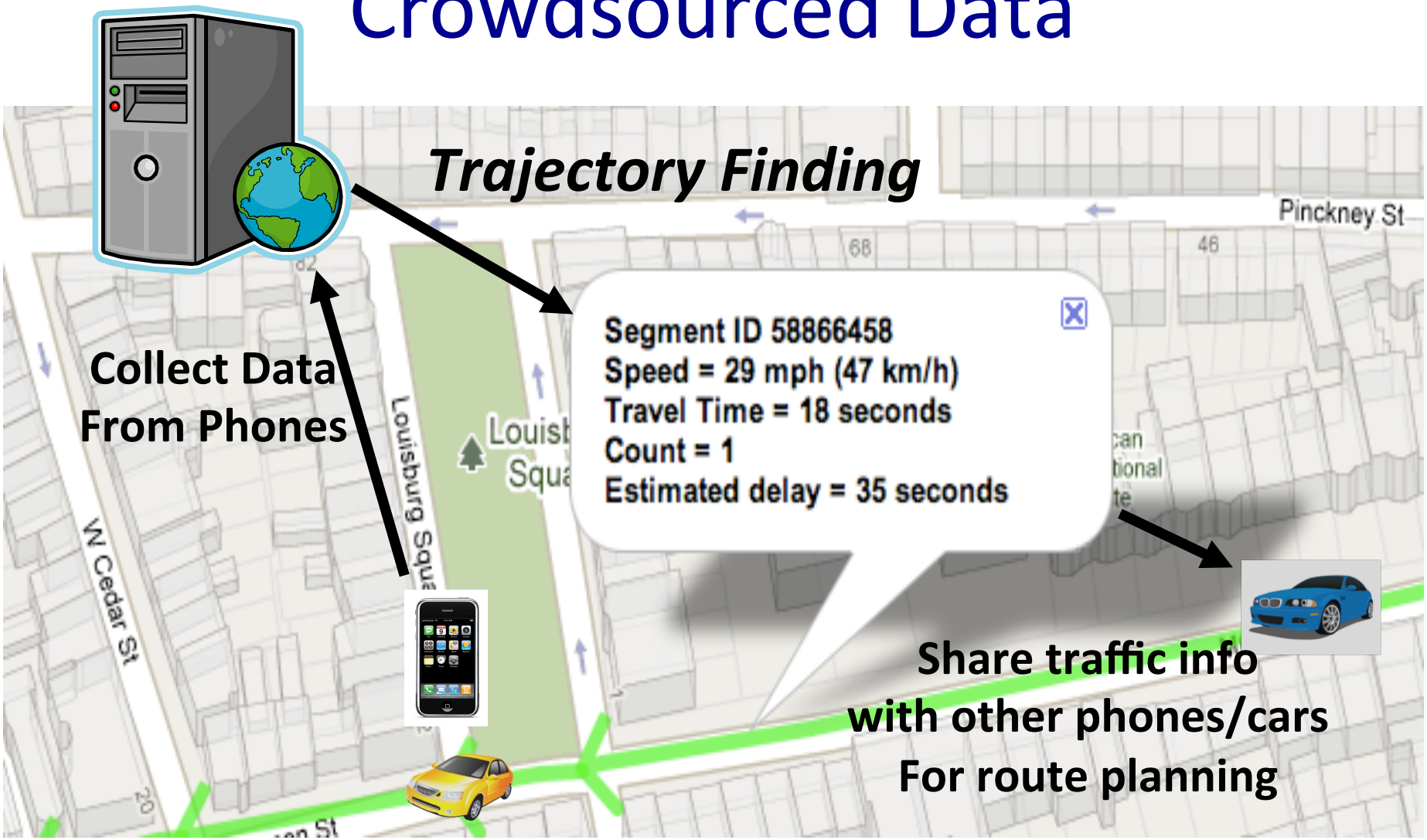


- Applications need to find path both ***accurately*** and ***energy-efficiently***

Traffic Estimation



Crowdsourced Data

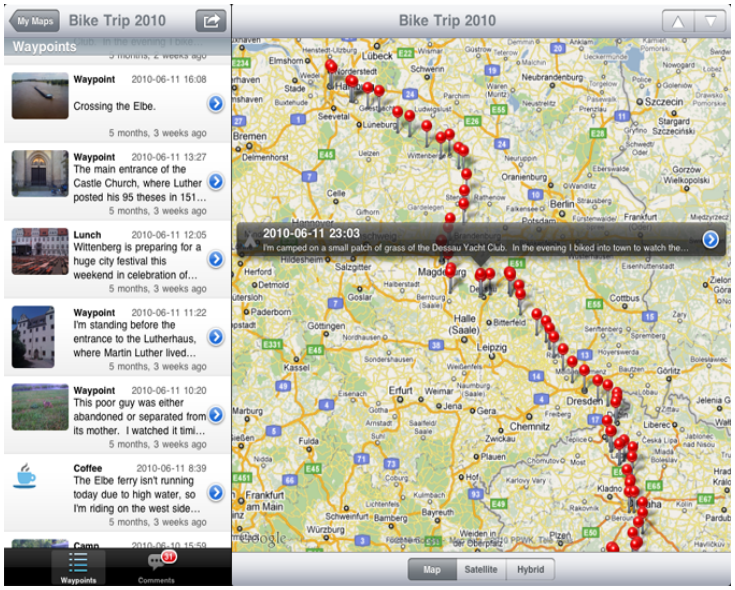


Battery dies in ~6 hours if monitoring with GPS

Bike Routes



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



TrackMyTour iPhone App:

Allows users to keep track of their trips and annotate them

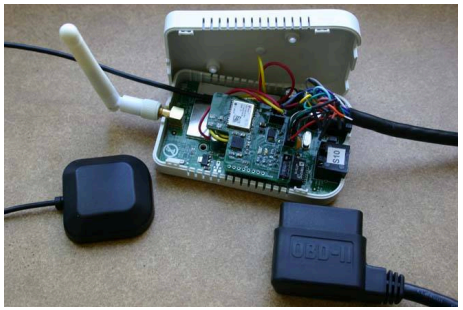


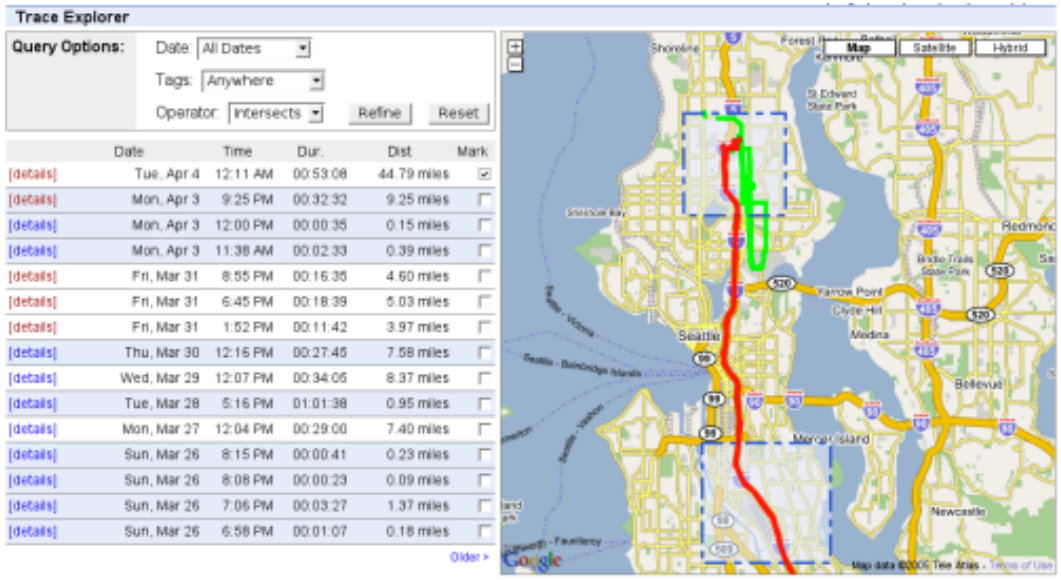
Running

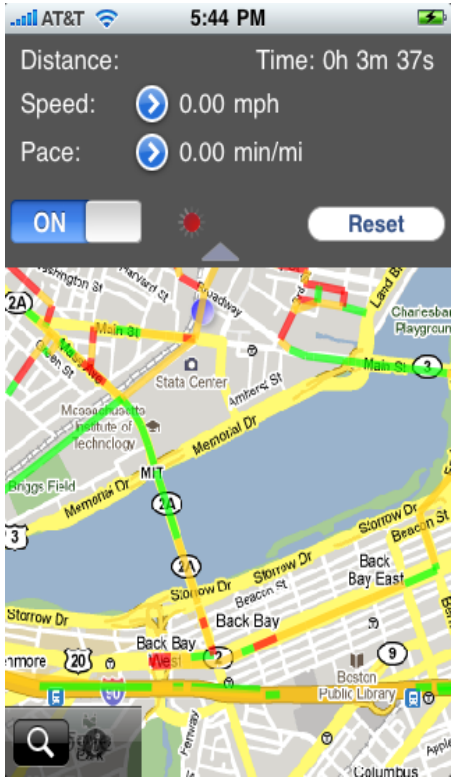
Trash Track


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



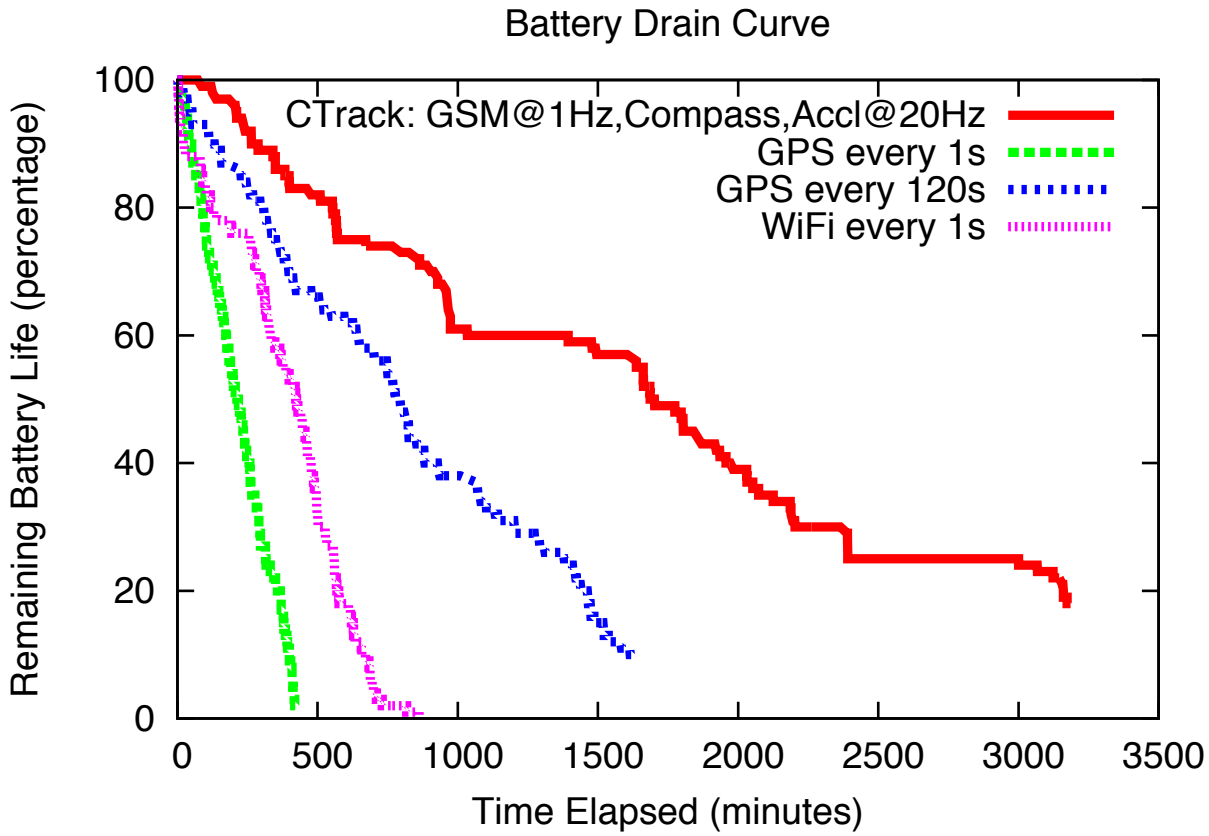




Crowdsource tracks to estimate traffic on road segments

Limitation of GPS: Energy

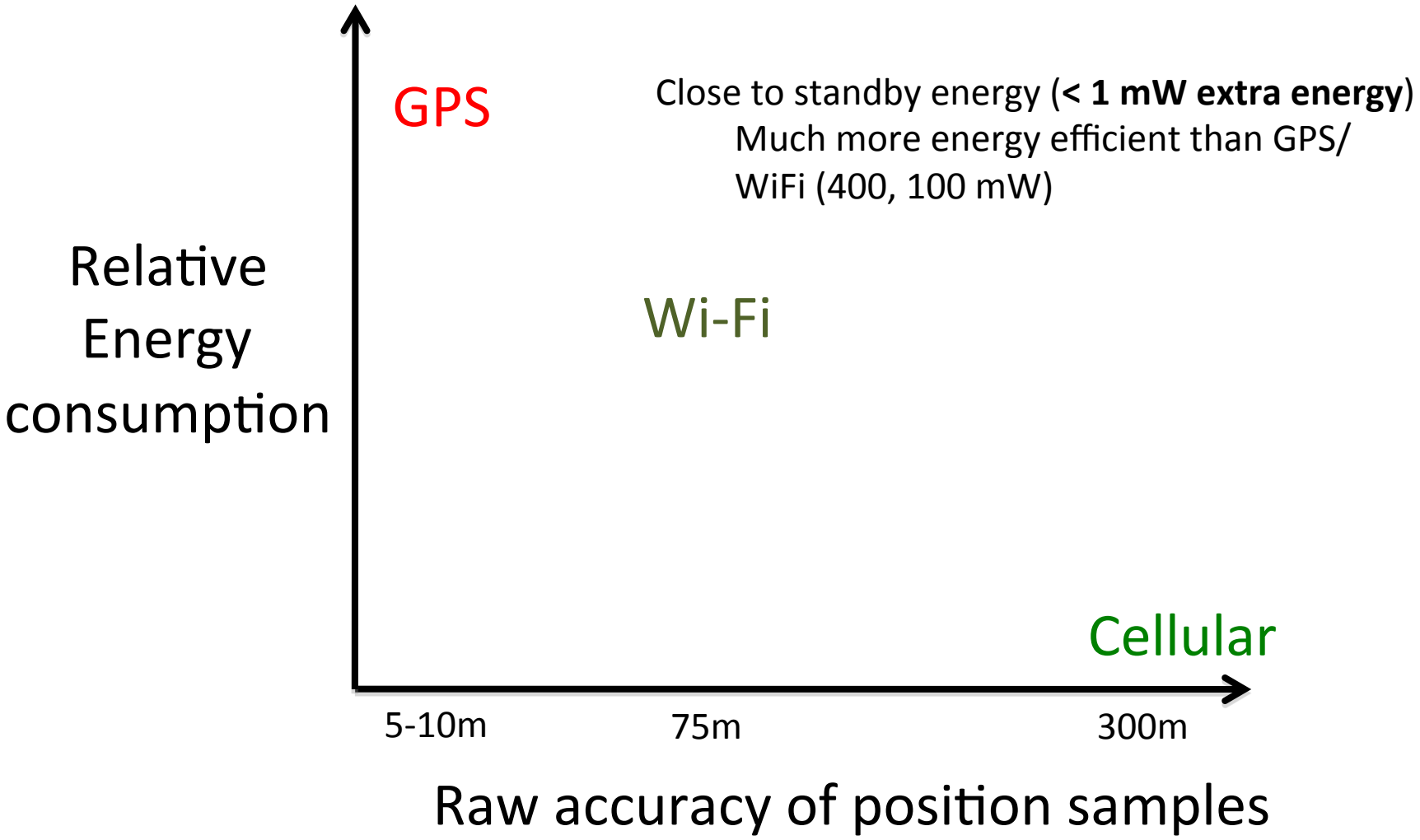
- GPS signals are energy-intensive to acquire & process
- Frequent GPS sampling drains battery fast



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

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

Approach: Use low-power sensors

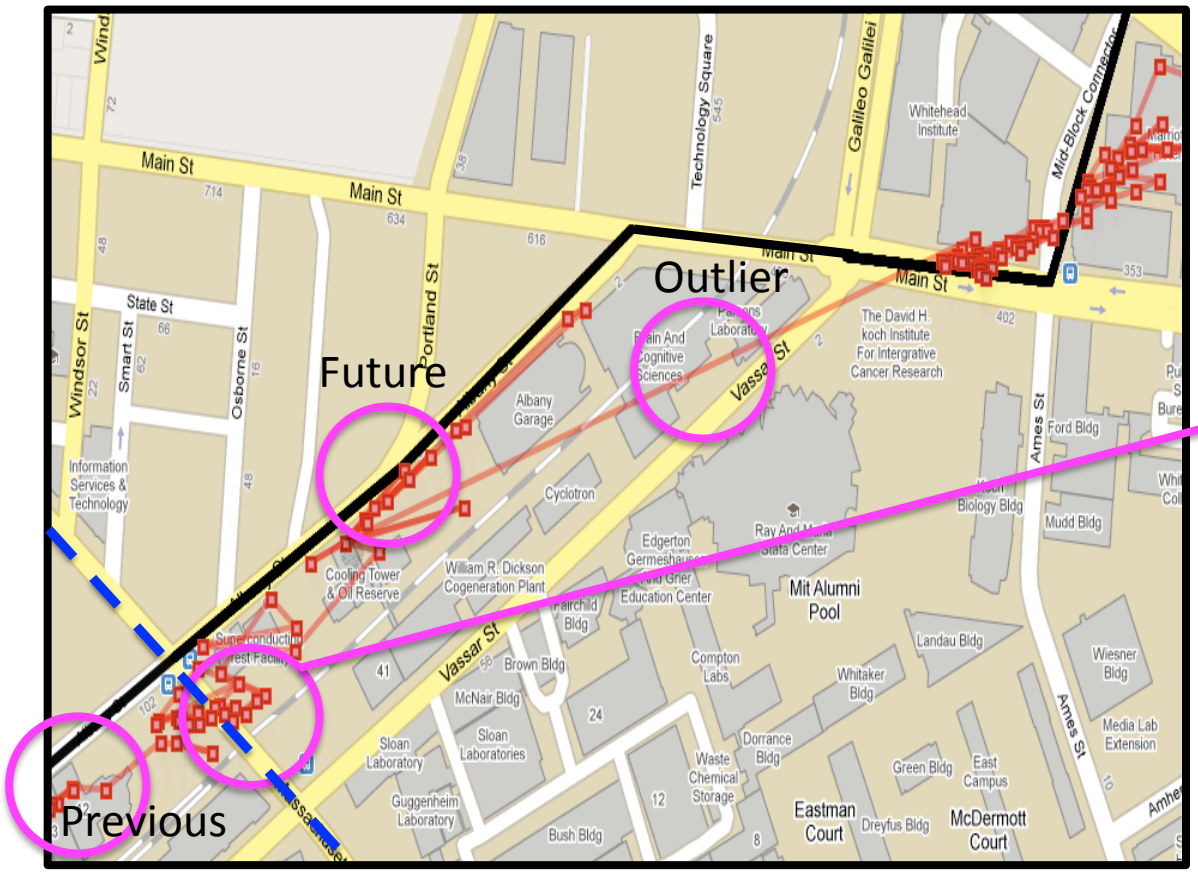


Outline

- Prior work
  - Intermittent GPS (Microsoft – Krumm)
  - Wi-Fi (VTrack – from same group as CTrack – CarTel project)

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

Noisy Data (Wi-Fi example)

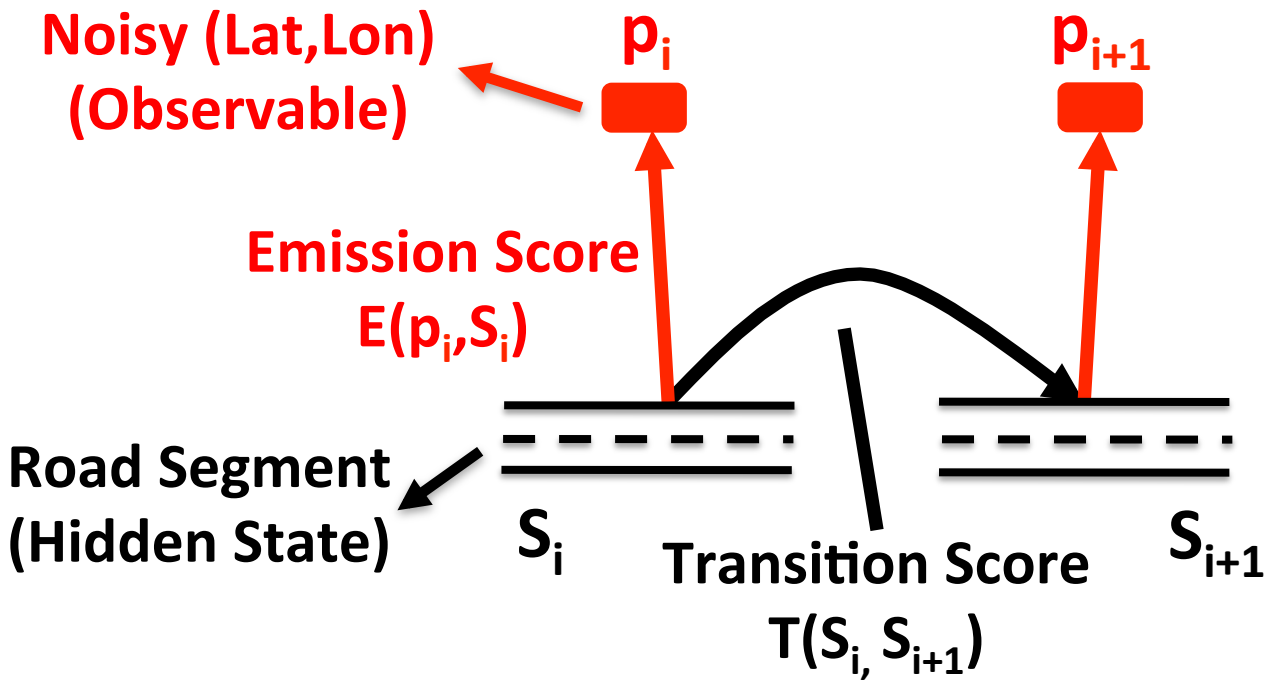


The closest road to a position sample is **not** where it originally came from

- 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

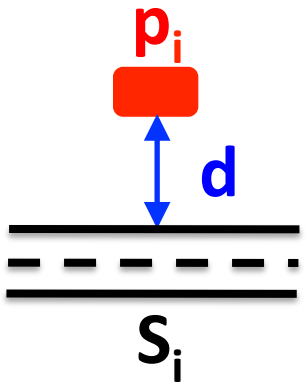
- Maps noisy observations (coordinates) to hidden states (underlying road segments)

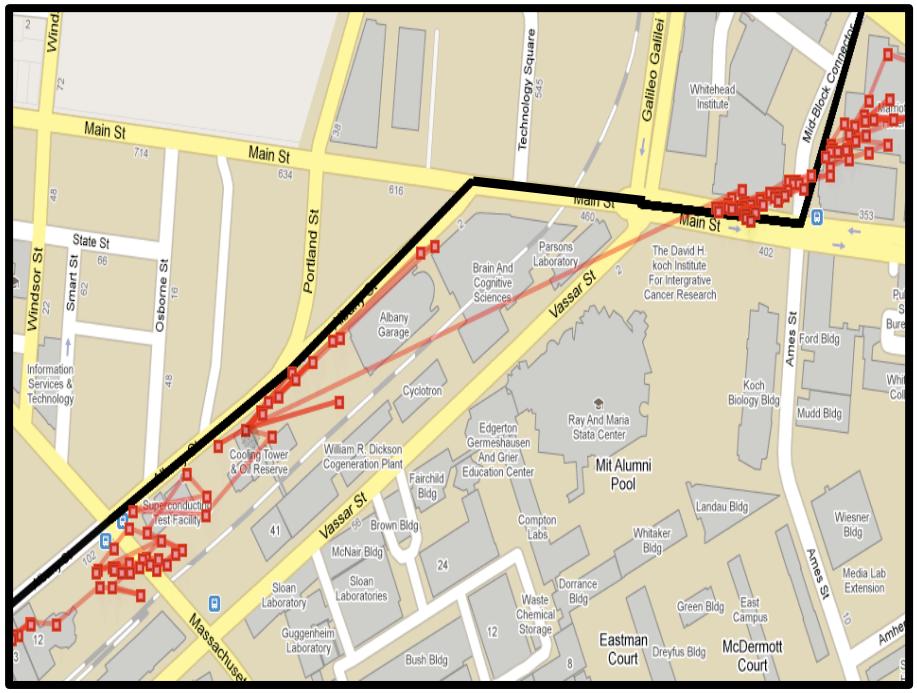


Dynamic Program Finds Best State Sequence (cf. Viterbi)
"Best" => Max Product of Emission and Transition Scores

Emission Score

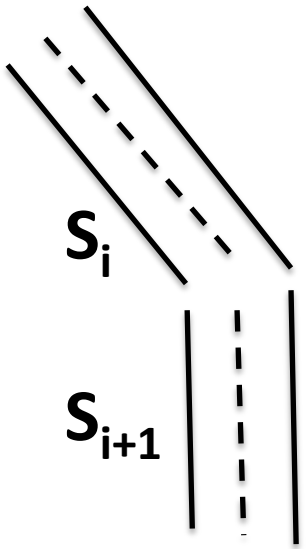
- Emission Score $E(p_i,S_i) = e^{-d^2/\sigma^2_{sensor}}$
  - Intuition: pts closer to a segment are more likely to come from it
  - σ_{sensor} depends on GPS/WiFi/Cellular



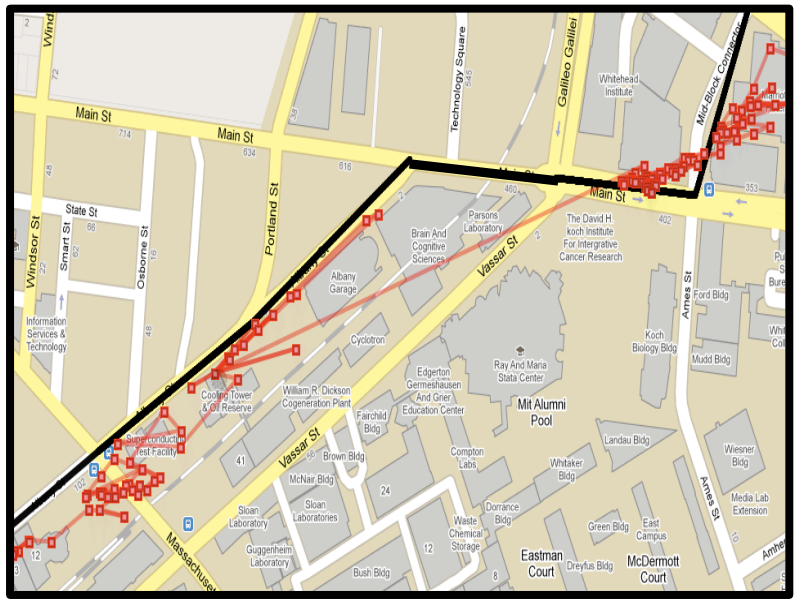


Transition Score

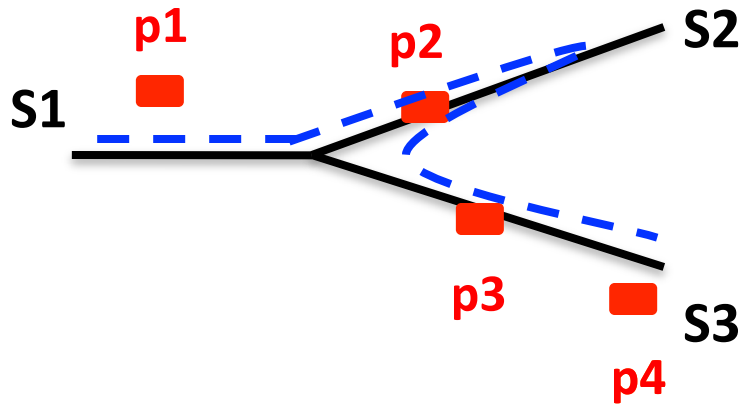
- Transition Score $T(S_i,S_{i+1})$
  - 0 if segments are not adjacent or not enough time has been spent on S_i
  - 1 if segments are adjacent and enough time has been spent on S_i



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

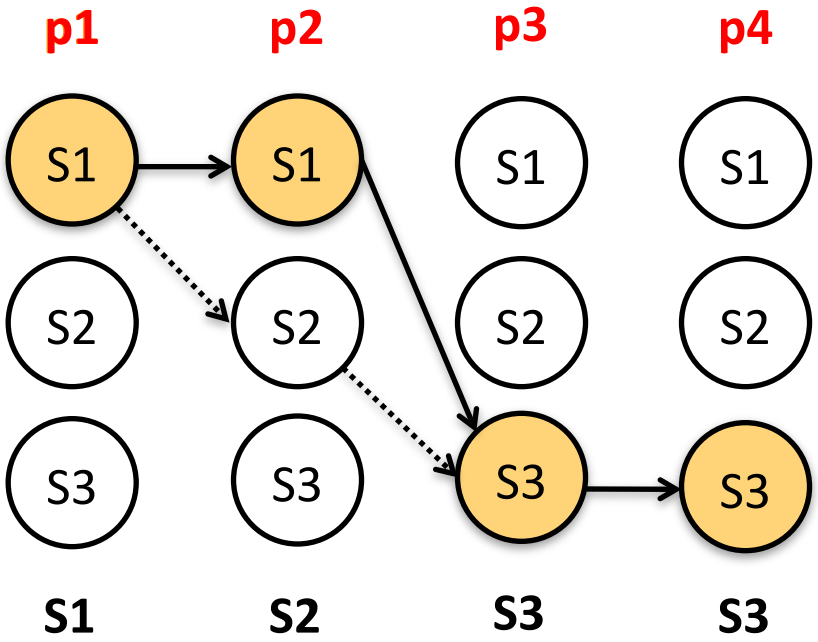


VTrack In Action



S1 S1 S3 S3 is most likely match

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



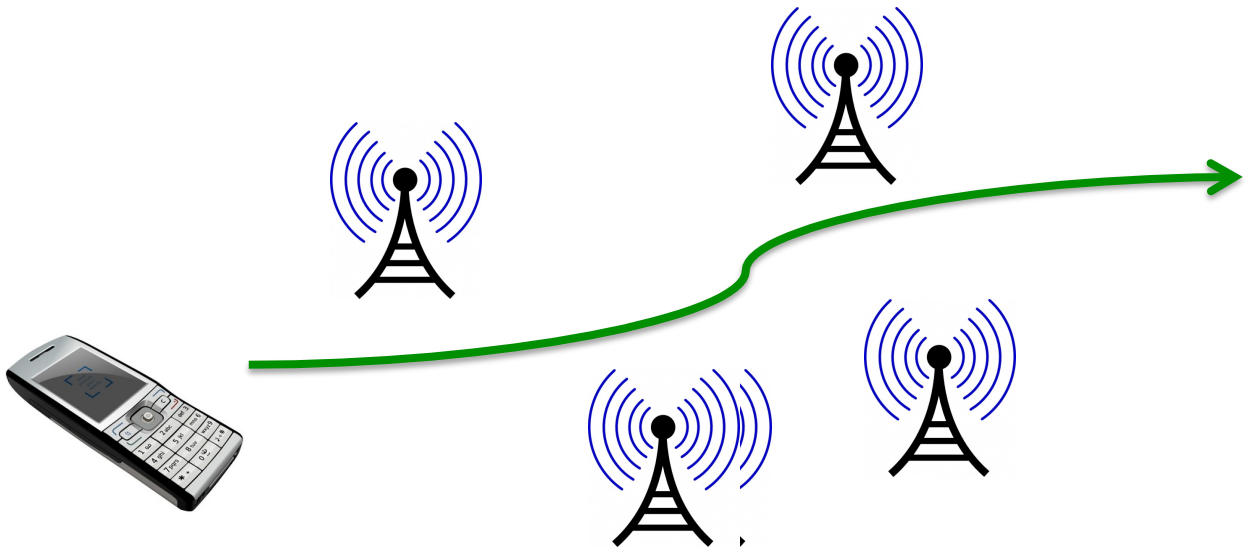
Handling Gaps: Interpolation

- 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?

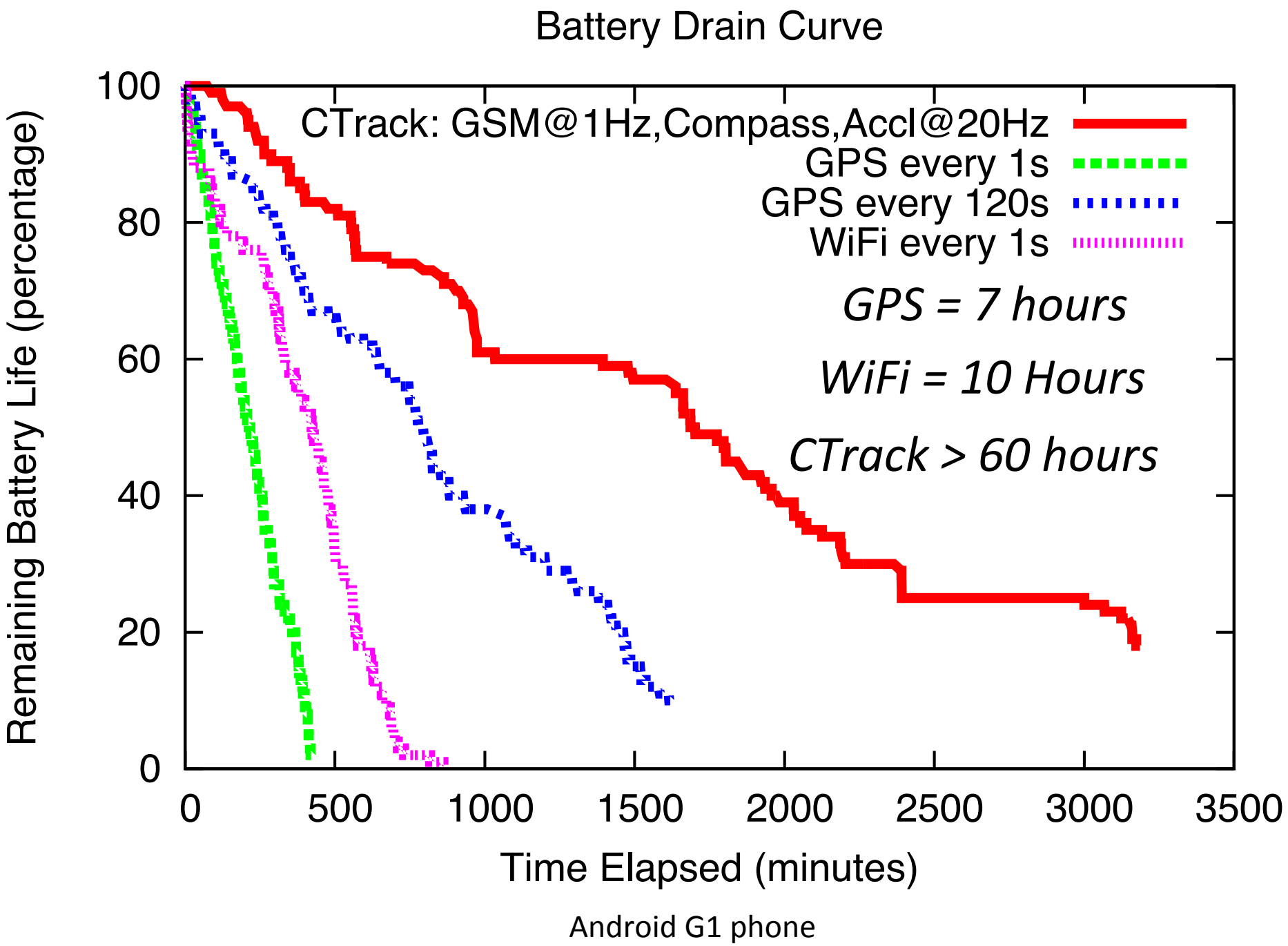


CTrack: Accurate Trajectory Mapping with Inaccurate Cellular Signals

- 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)

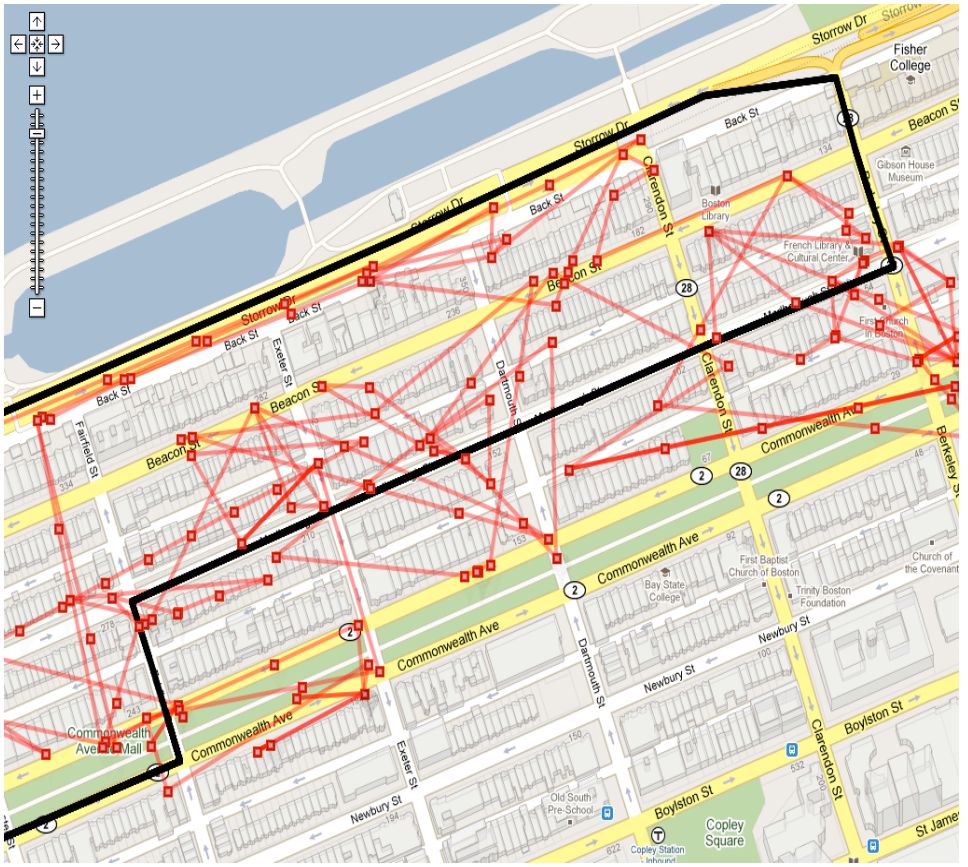
- Optionally, augment with low-energy "*sensor hints*"
  - Compass to detect turns (15 µW @ 1 Hz)
  - Accelerometer to detect movement (60 µW @ 10 Hz)



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

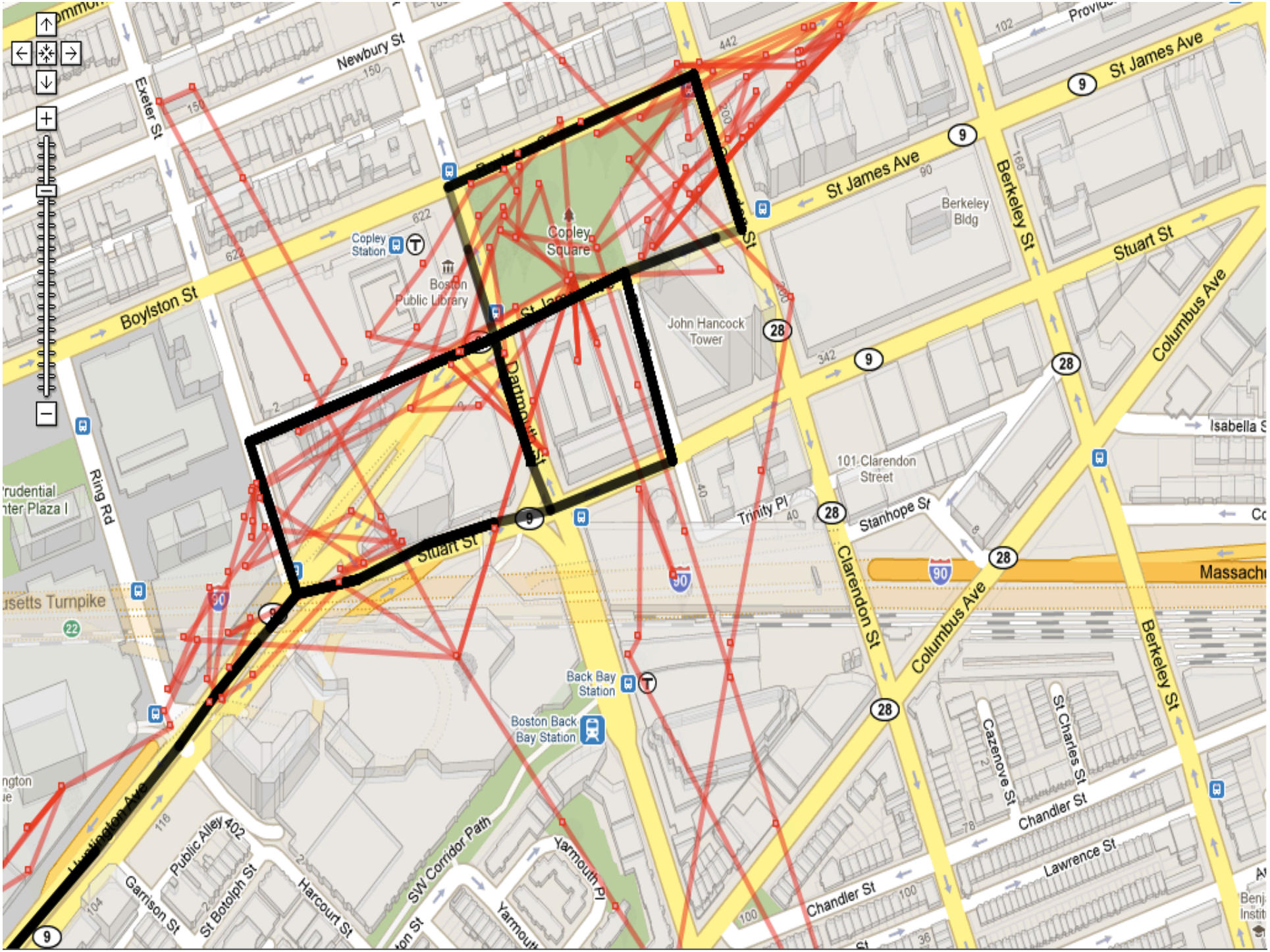
```
d8:30:62:5f:be:da, RSSI -94
00:0f:b5:3d:43:20, RSSI -58
00:18:0a:30:00:a3, RSSI -51
. . . . . .
```

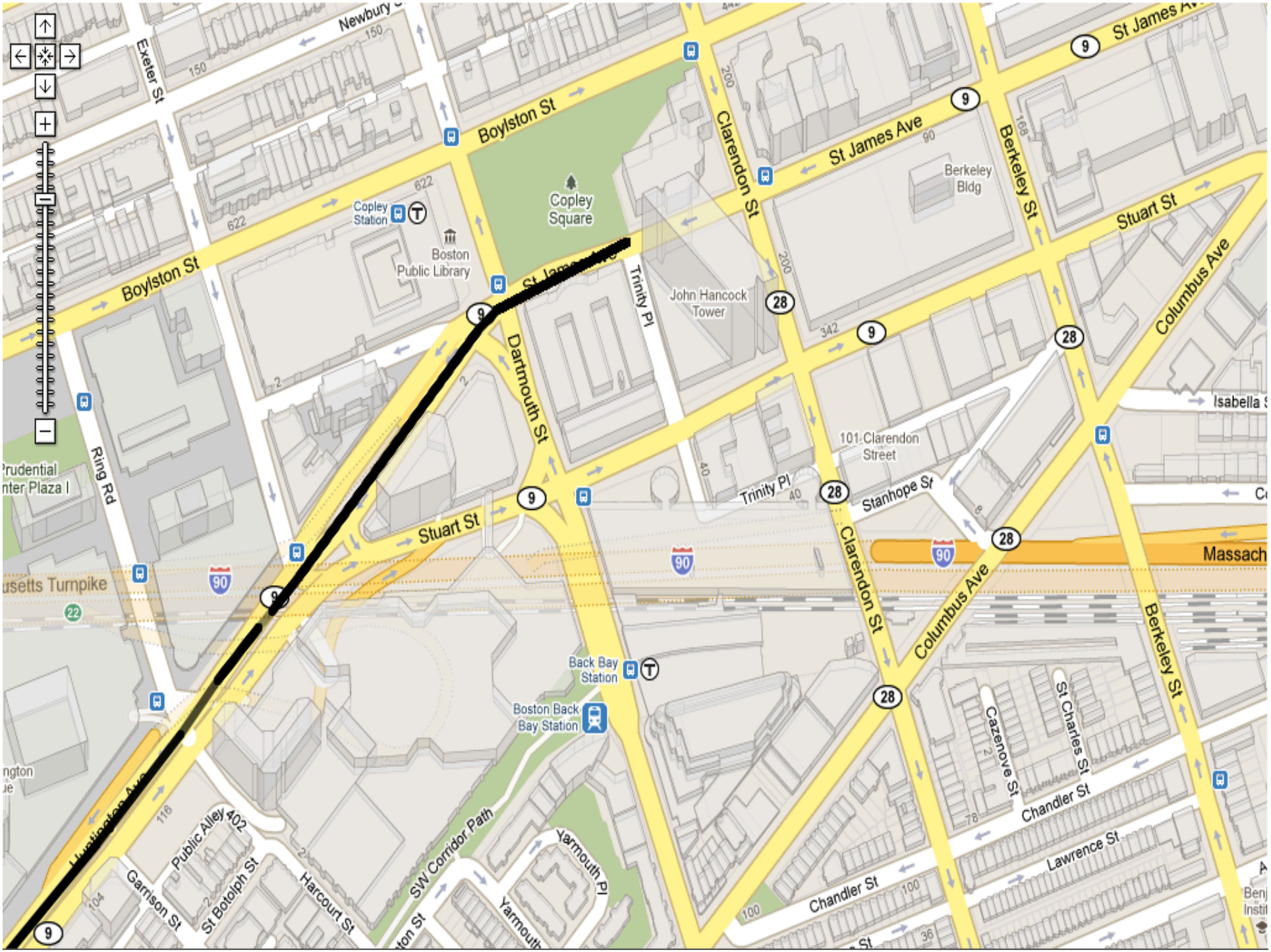
```
42.361,-71.09
42.361,-71.09
42.362,-71.091
. . . . . .
```

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



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


Newbury St
Exeter St
Boylston St
Copley Square
Copley Station
Boston Public Library
John Hancock Tower
Berkeley Bldg
St James Ave
Stuart St
Columbus Ave
Berkeley St
Clarendon St
Dartmouth St
Trinity Pl
101 Clarendon Street
Stanhope St
Ring Rd
Back Bay Station
Boston Back Bay Station
SW Corridor Path
Yarmouth Pl
Public Alley 402
St Botolph St
Harcourt St
Garrison St
Cazenove St
St Charles St
Chandler St
Lawrence St
Isabella St
Massachusetts Turnpike

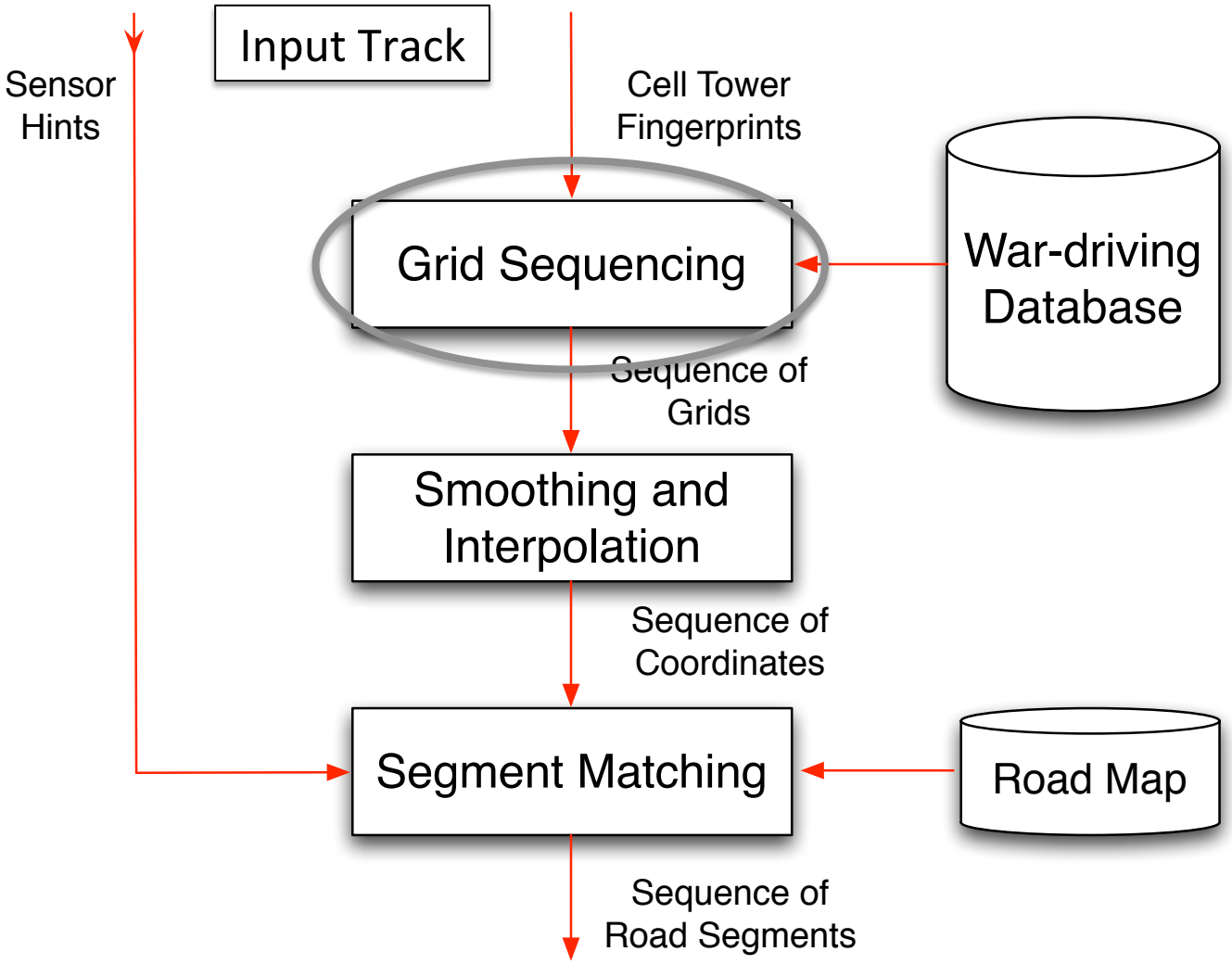


Newbury
Exeter St
Boylston St
Copley Square
Copley Station
Boston Public Library
St James Ave
Clarendon St
Berkeley Bldg
Berkeley St
Stuart St
Columbus Ave
Trinity Pl
John Hancock Tower
Dartmouth St
Ring Rd
Prudential
nter Plaza I
usetts Turnpike
101 Clarendon Street
Stanhope St
Isabella
Massach
Back Bay Station
Boston Back Bay Station
Huntington Ave
Public Alley 402
Garrison St
St Botolph St
Harcourt St
SW Corridor Path
Yarmouth Pl
Cazenove St
St Charles St
Chandler St
Lawrence St

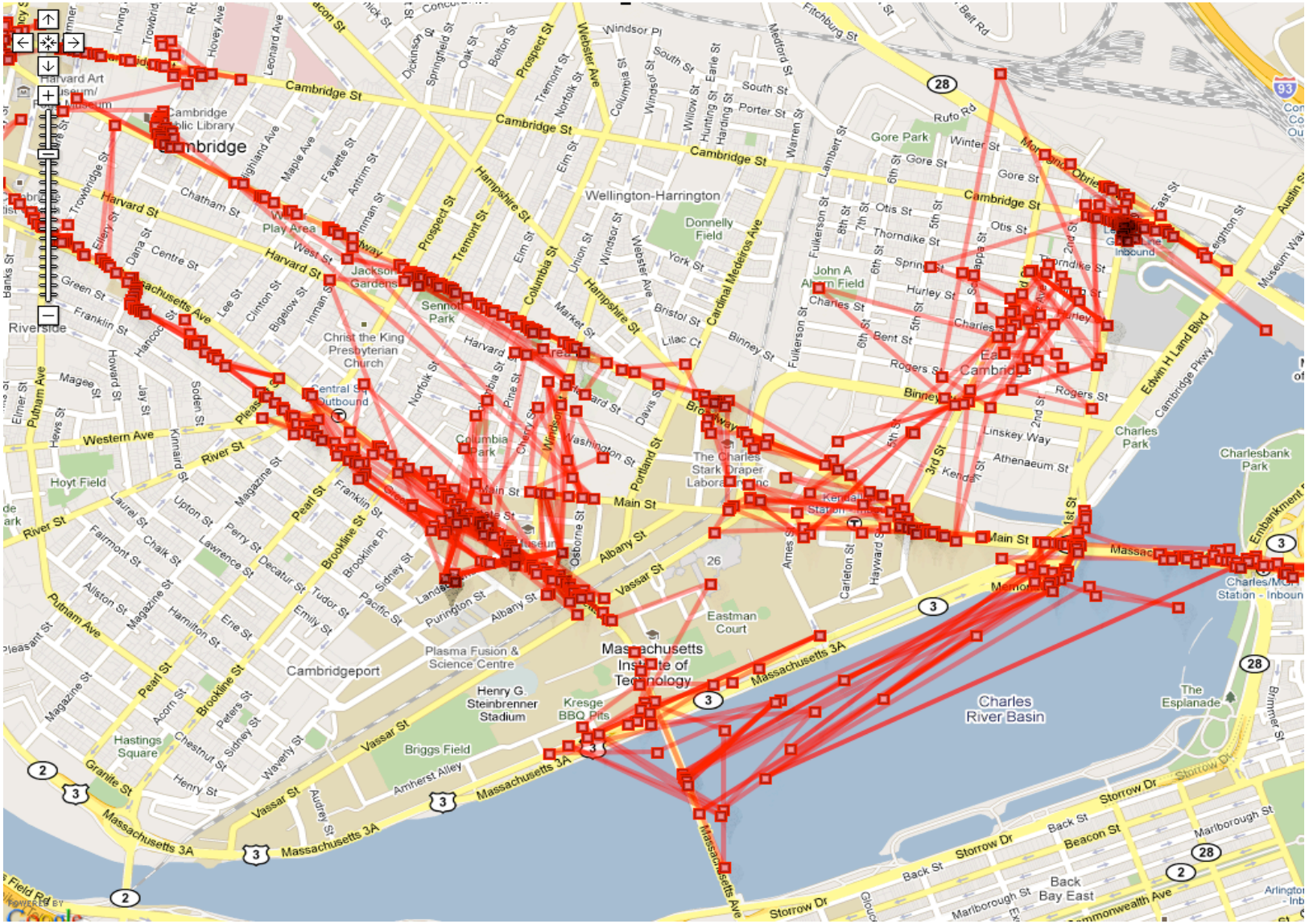
Key Insight in CTrack

- 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

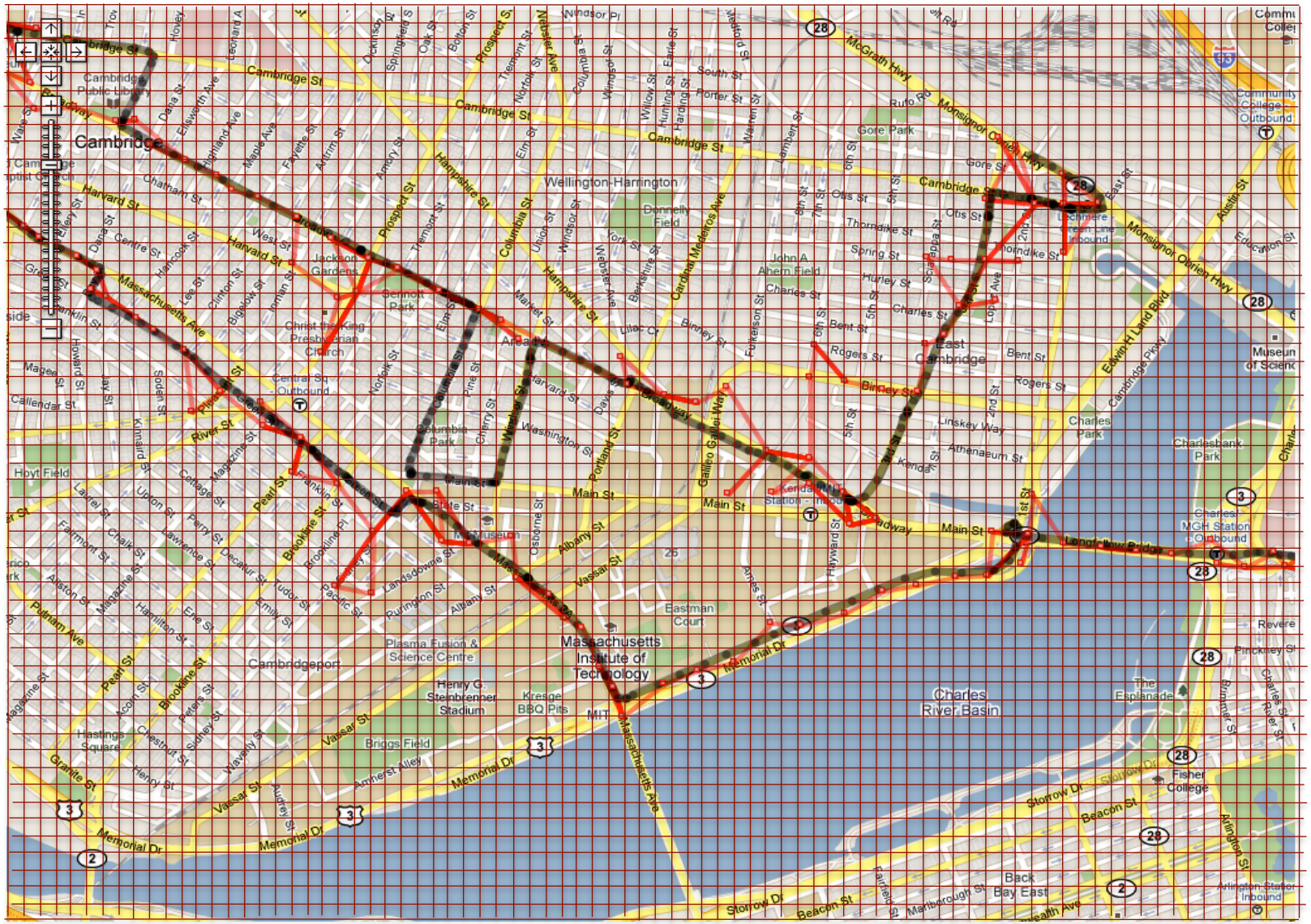
CTrack FlowChart



Raw points (Placelab)



Grid Sequence



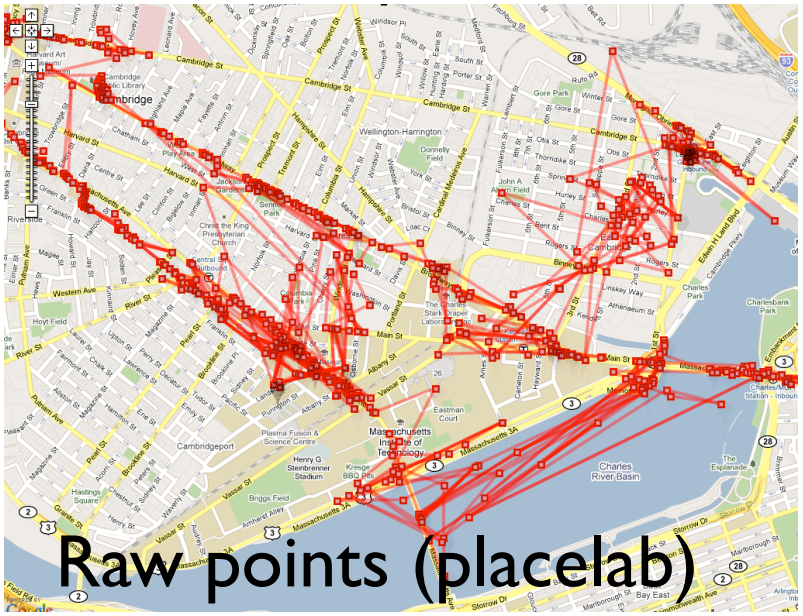
Smooth + Interpolate Grid Sequence

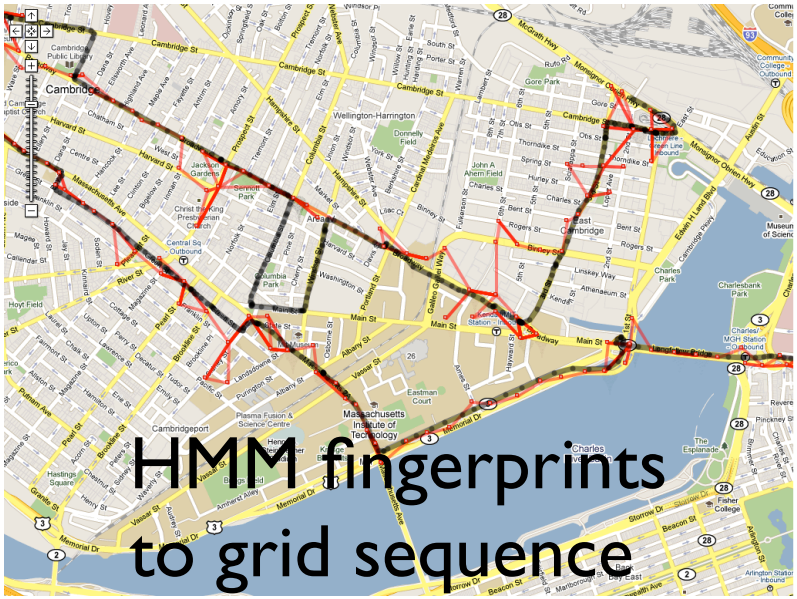


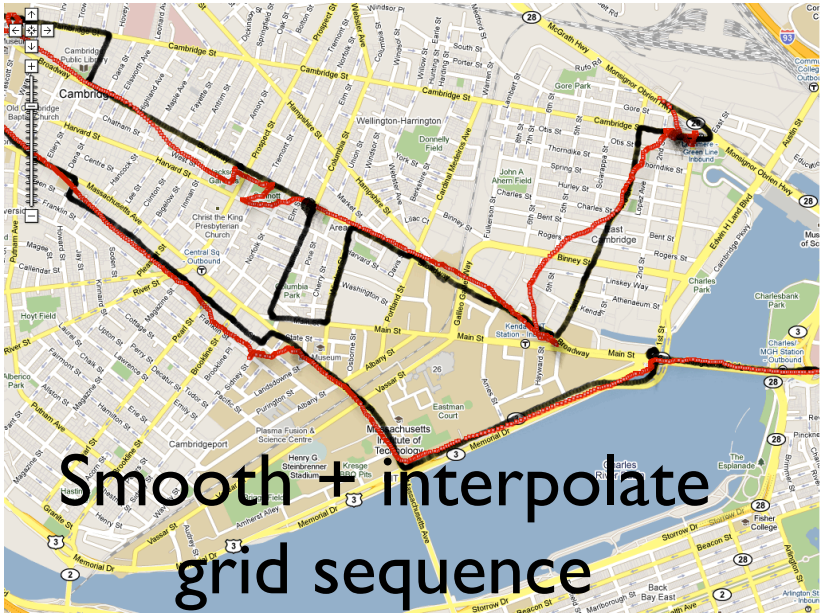
Smoothed Grid → Road Segments

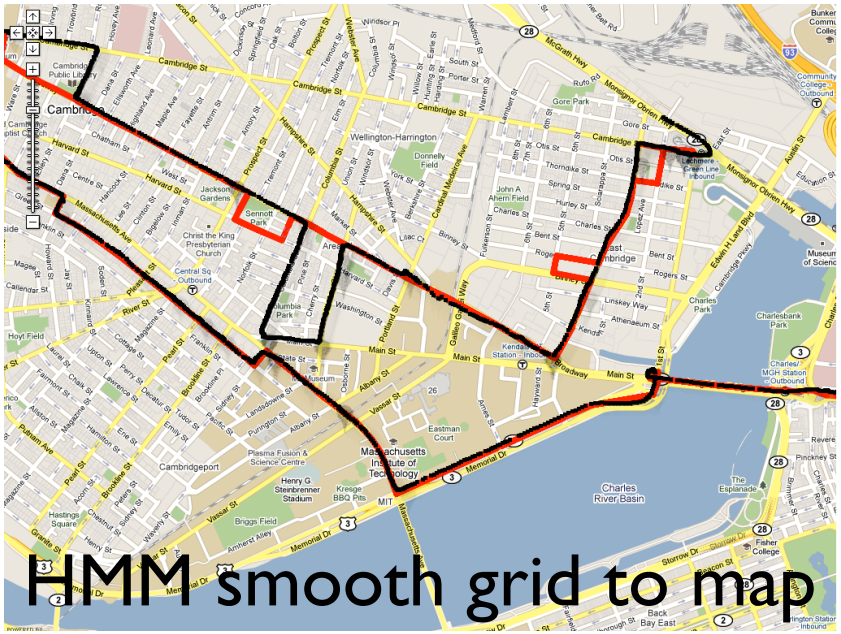


CTrack Steps





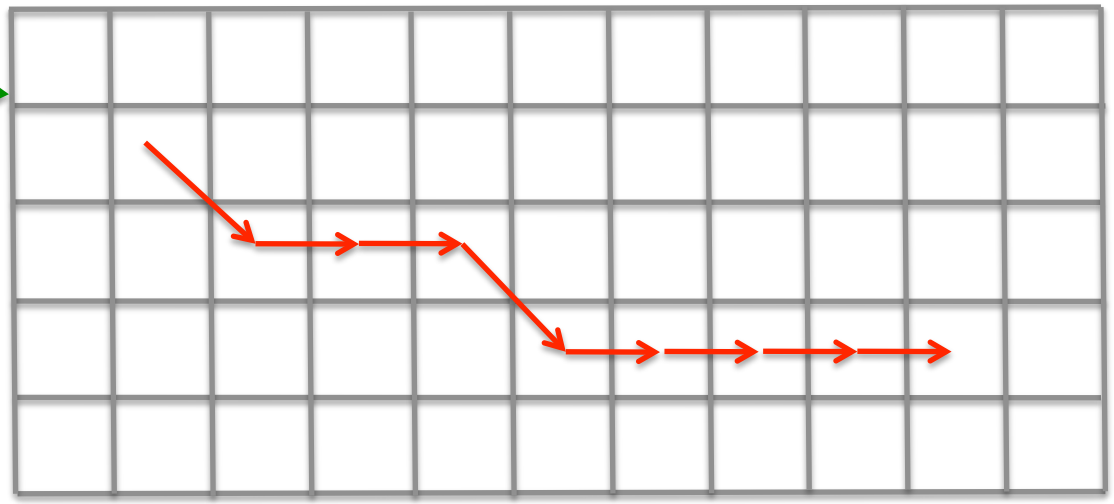




Grid Sequencing

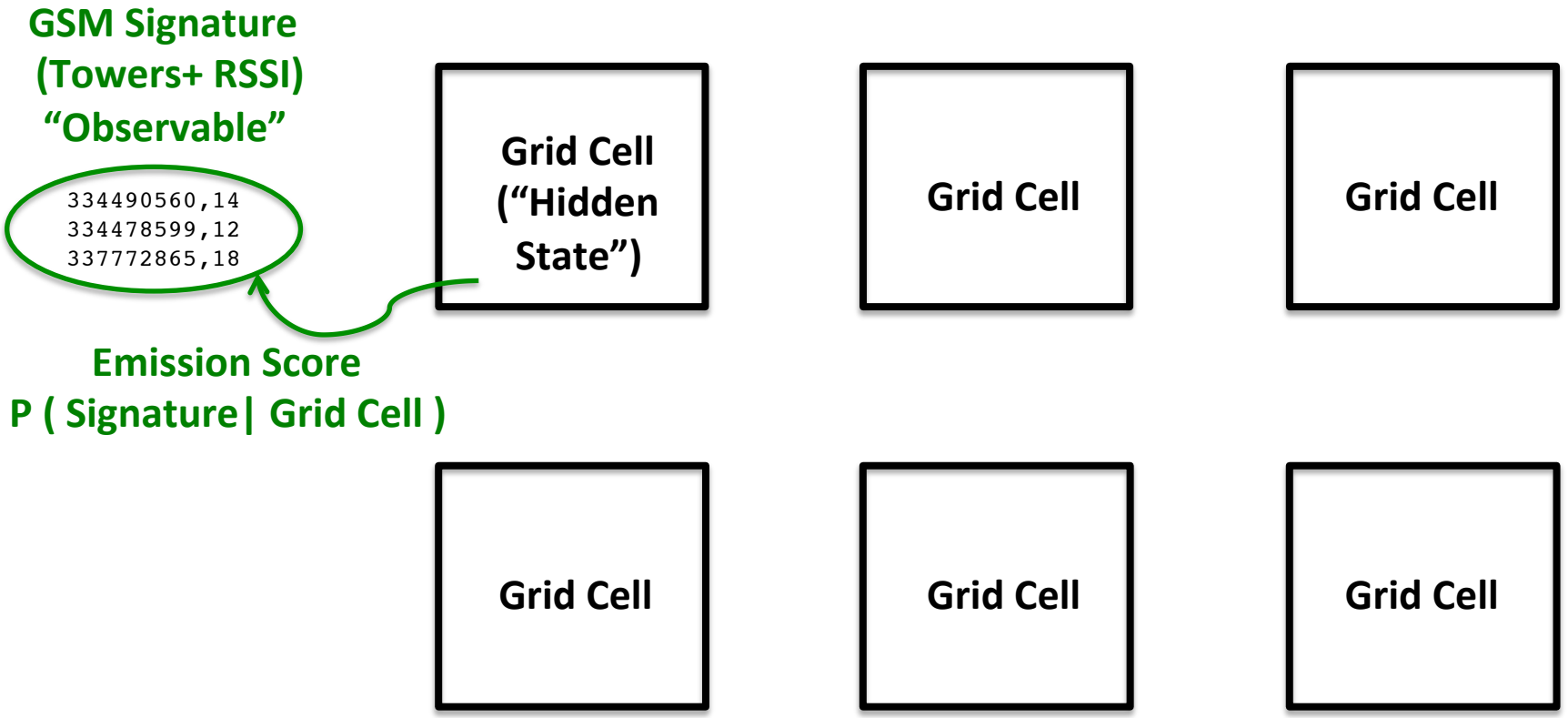
Time	TowerId	RSSI
18.03	334490560	14
	334478599	12
	337772865	18
	334478600	14
	334470539	12
	334490699	12
19.01	.	.

Size of grid = 125 meters
Why?

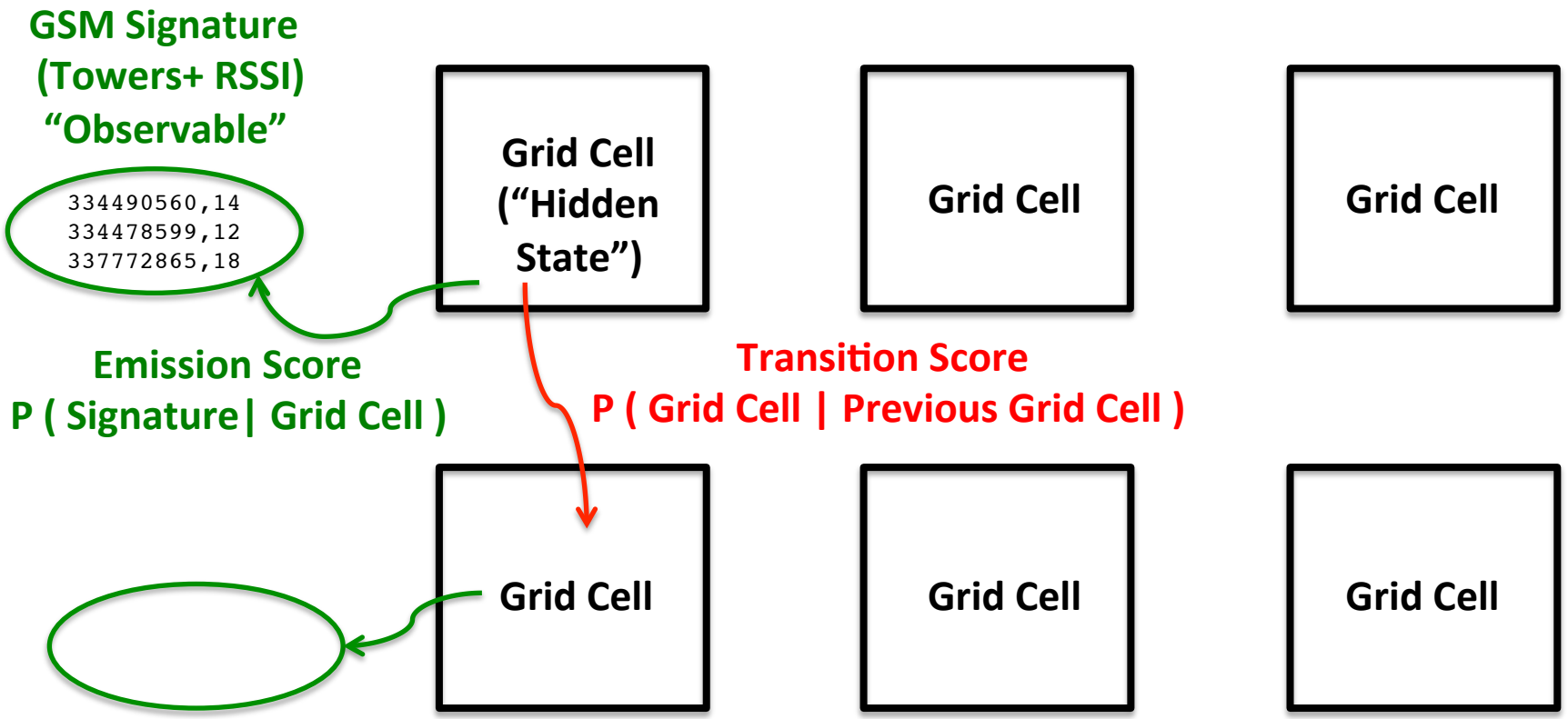


Given a sequence of GSM fingerprints (TowerID, RSSI), what is the most likely sequence of grid cells?

HMM For Grid Sequencing



HMM For Grid Sequencing

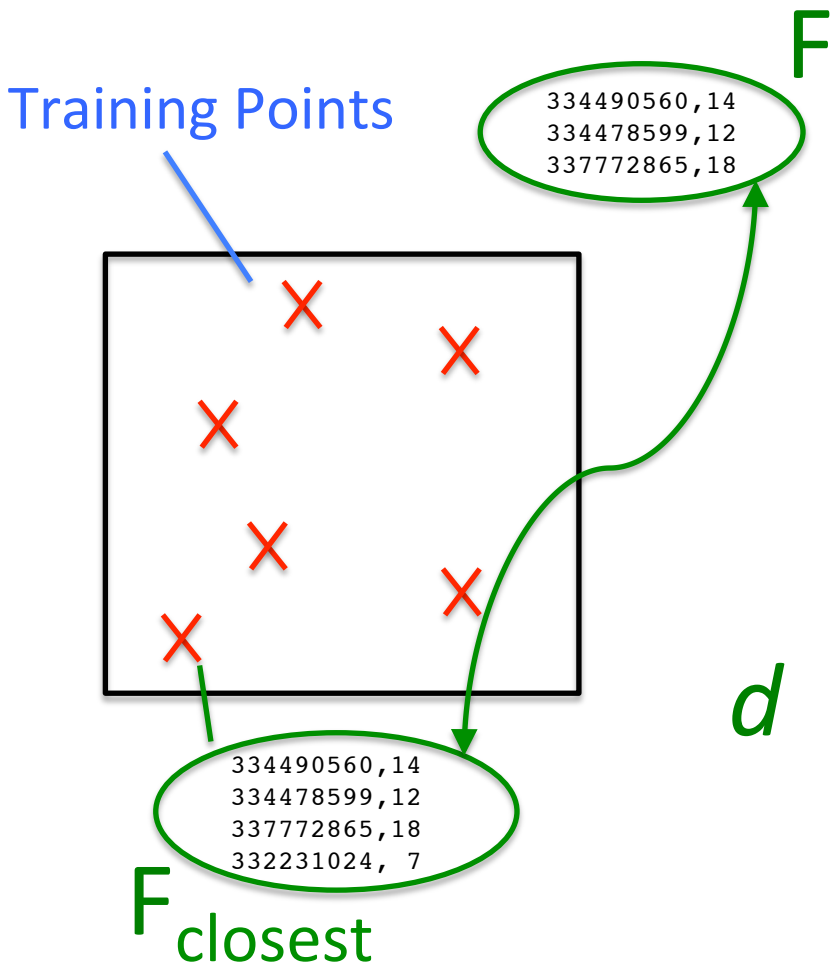


Dynamic Programming Finds Best Grid Sequence (cf. Viterbi)

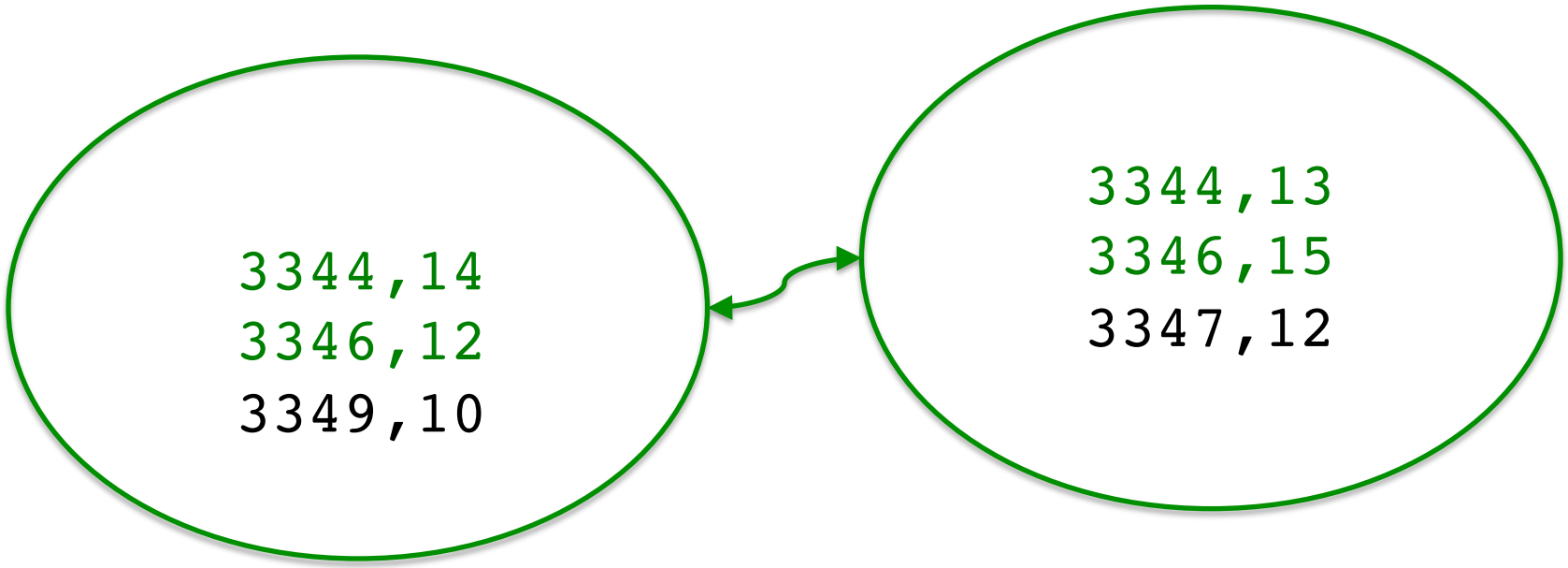
"Best" => Max (Emission Score * Transition Score)

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



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

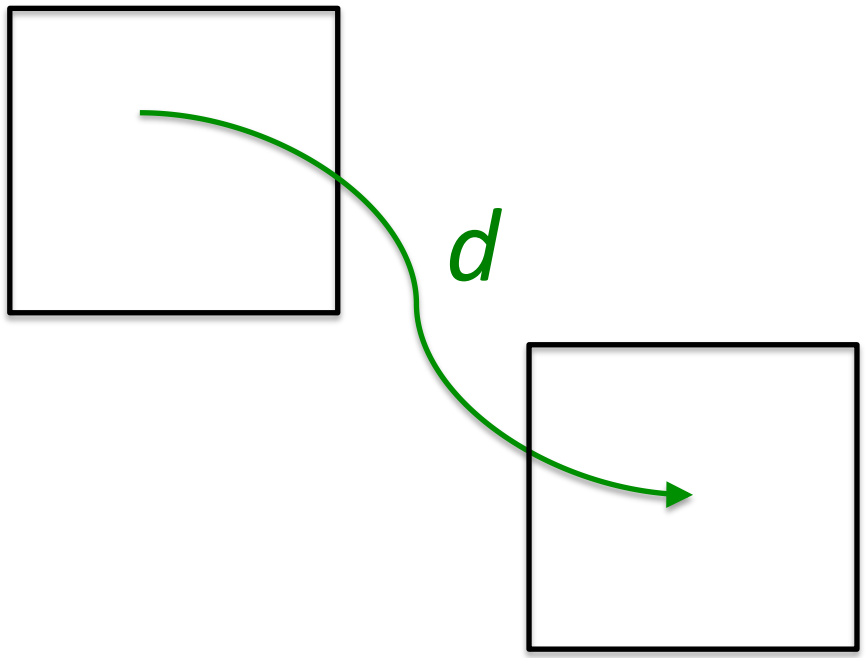
With $\lambda=3$ and $d_{max}= 32$,

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

Normalize this to (0,1] range

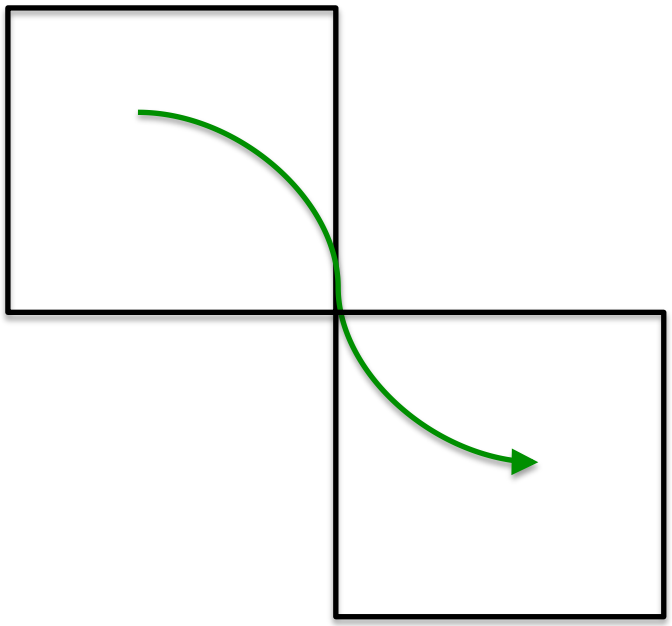
Tolerant Transition Score

- 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

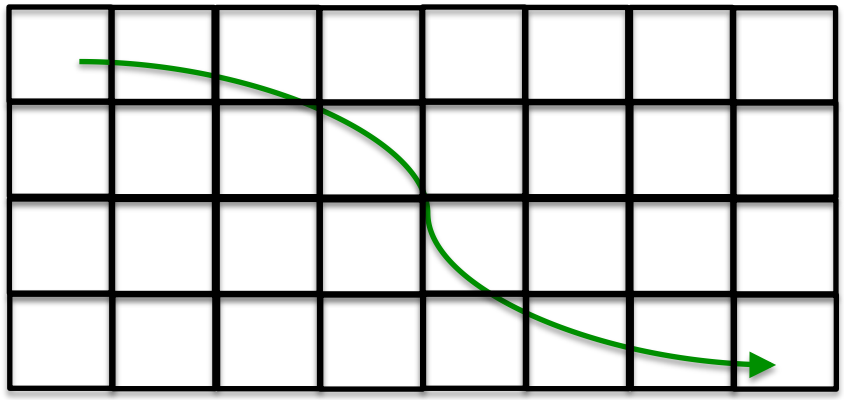


Score = 1/d

Example



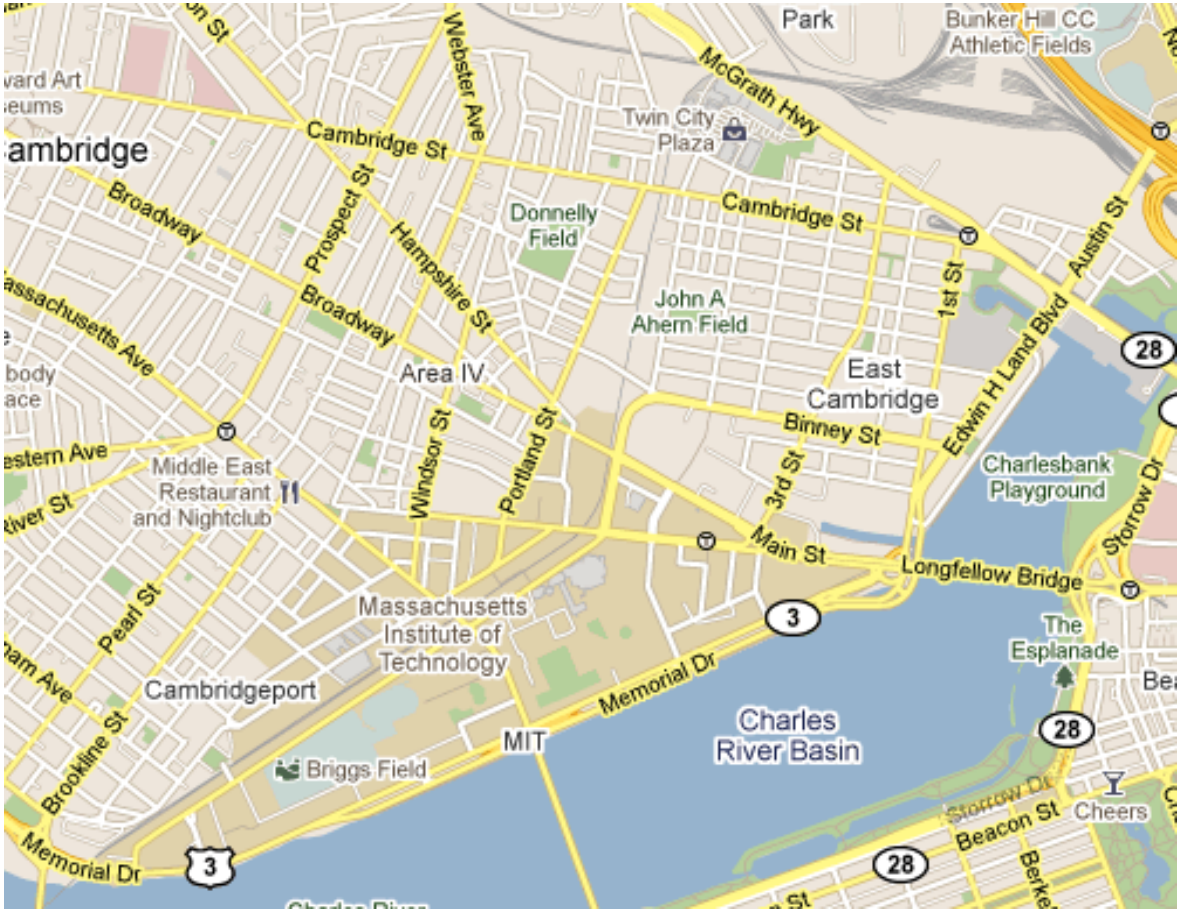
Transition Score = 1



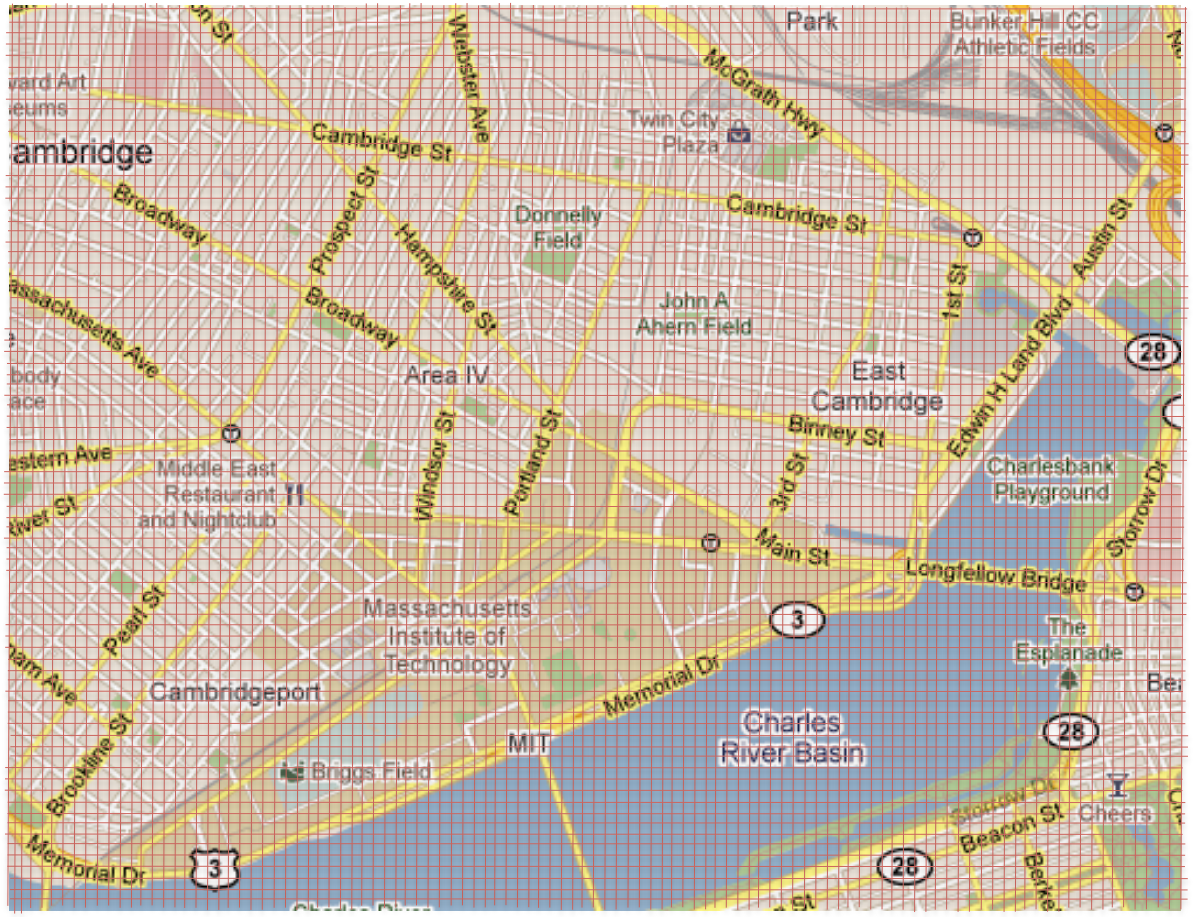
d = 7

Transition Score = 1/7

Grid Sequencing In Action

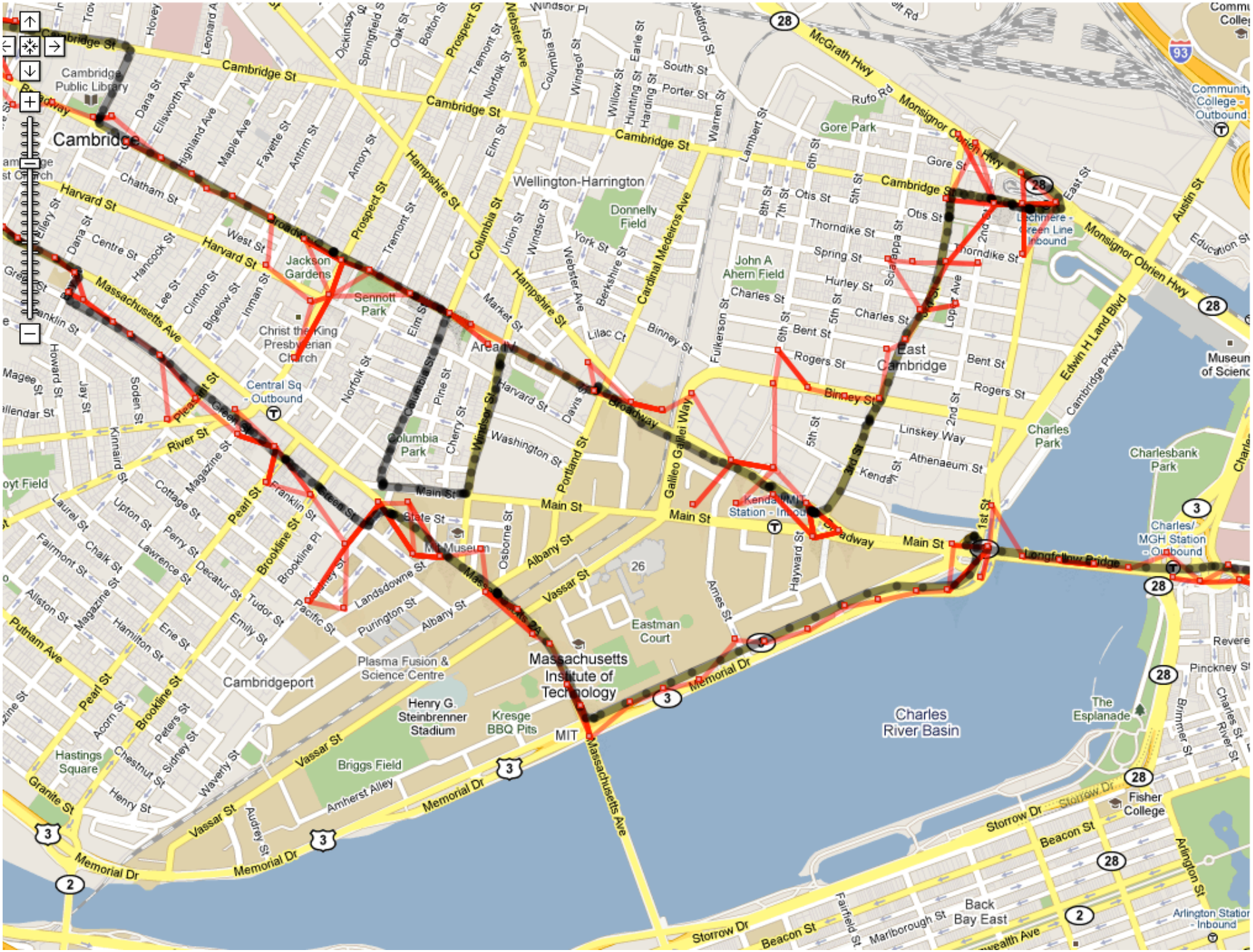


Grid Sequencing In Action



Grid Sequencing In Action

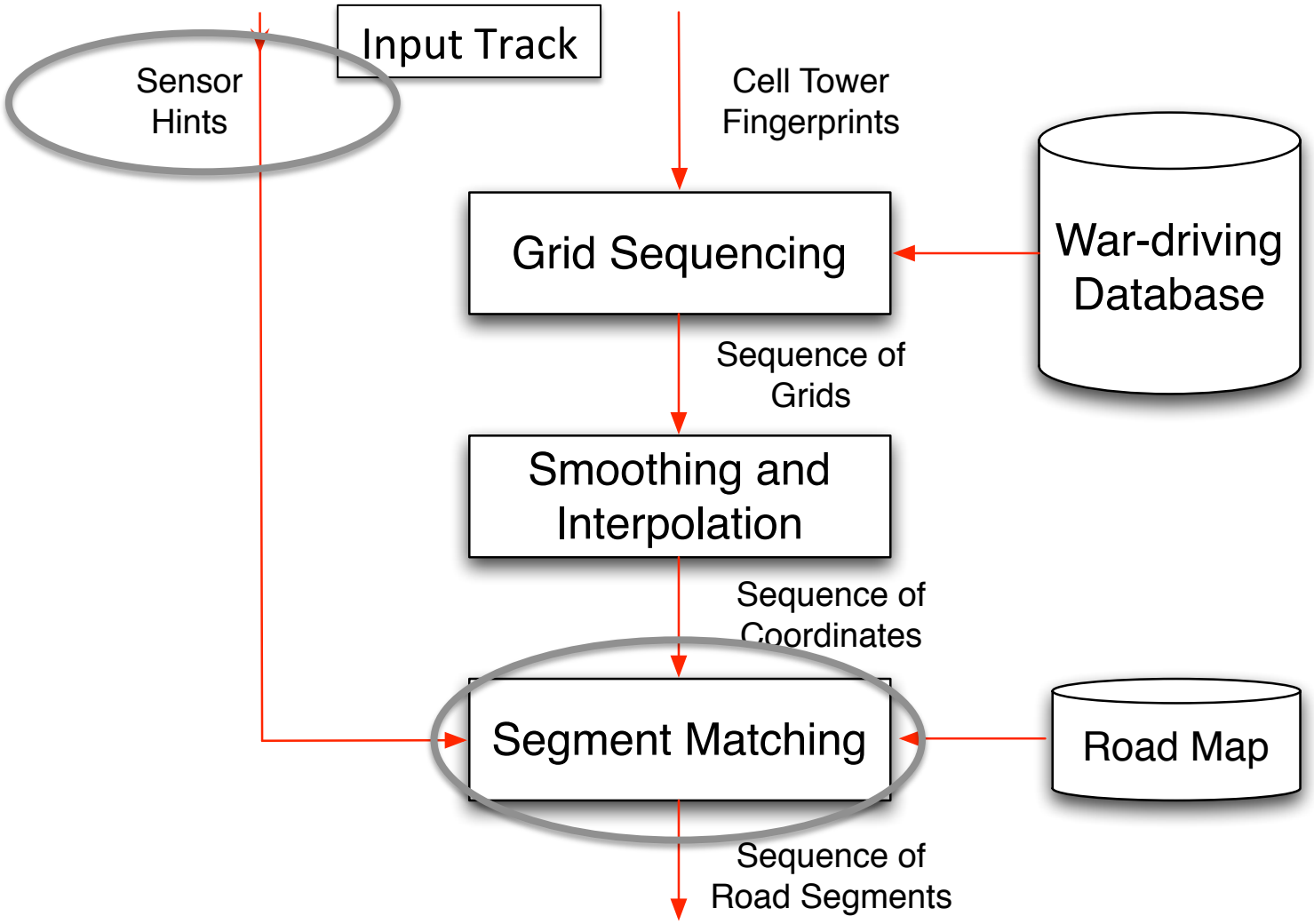



Cambridge
Cambridge Public Library
Cambridge St
Harvard St
Massachusetts Ave
Broadway
Prospect St
Hampshire St
Columbia St
Main St
Memorial Dr
Vassar St
Albany St
Portland St
Galileo Galilei Way
Binney St
Charles St
McGrath Hwy
Monsignor Obrien Hwy
Longfellow Bridge
Wellington-Harrington
Donnelly Field
Jackson Gardens
Sennott Park
Christ the King Presbyterian Church
Central Sq - Outbound
Columbia Park
Area 4
John A Ahern Field
East Cambridge
Gore Park
Kendall/MIT Station - Inbound
Charles/MGH Station - Outbound
Charles Park
Charlesbank Park
Eastman Court
Massachusetts Institute of Technology
MIT
Mit Museum
Plasma Fusion & Science Centre
Henry G. Steinbrenner Stadium
Kresge BBQ Pits
Briggs Field
Cambridgeport
Hastings Square
Charles River Basin
The Esplanade
Back Bay East
Fisher College
Storrow Dr
Beacon St
Arlington Station - Inbound
Community College - Outbound
Lechmere - Green Line Inbound
Museum of Science

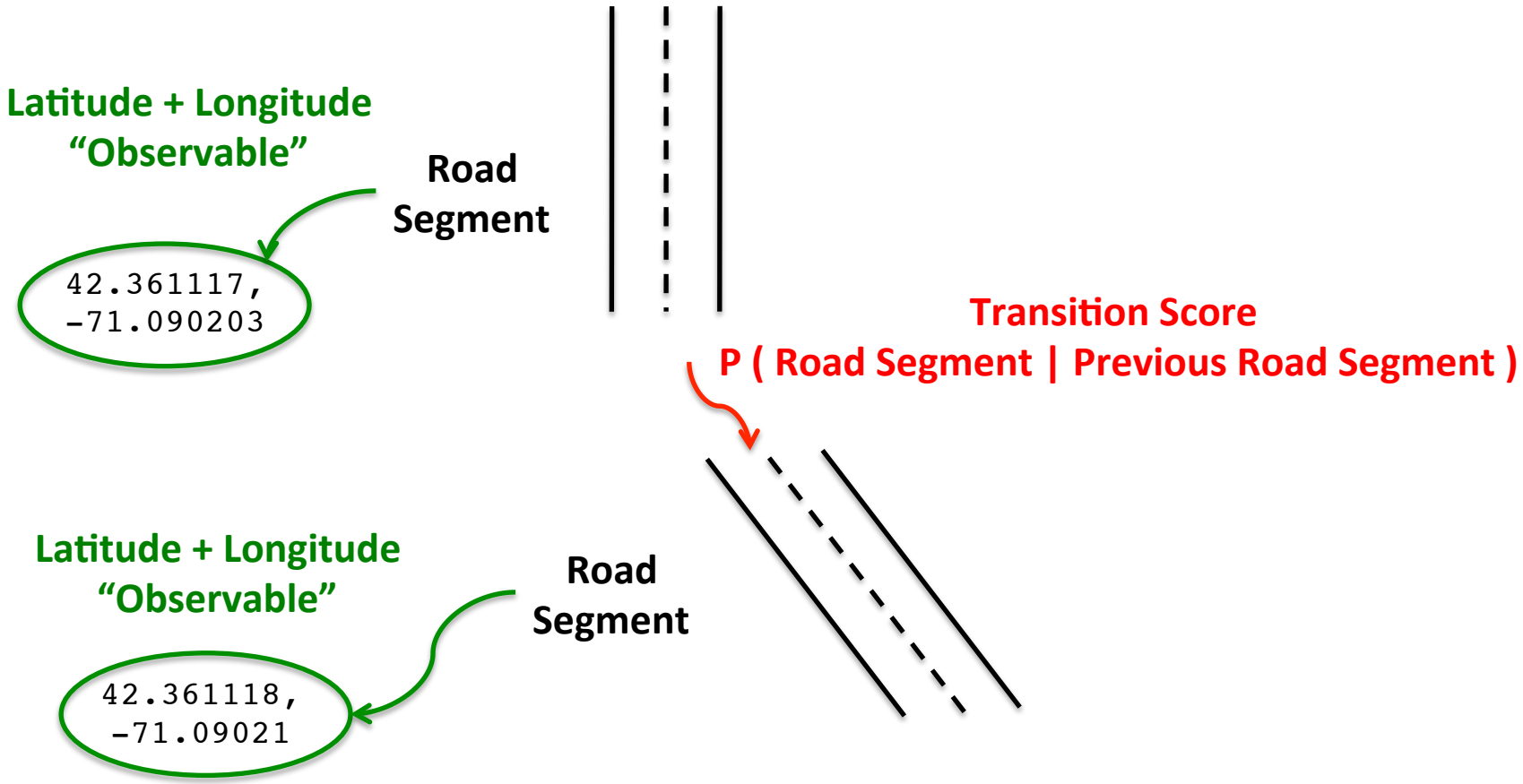
Smoothing & Interpolation



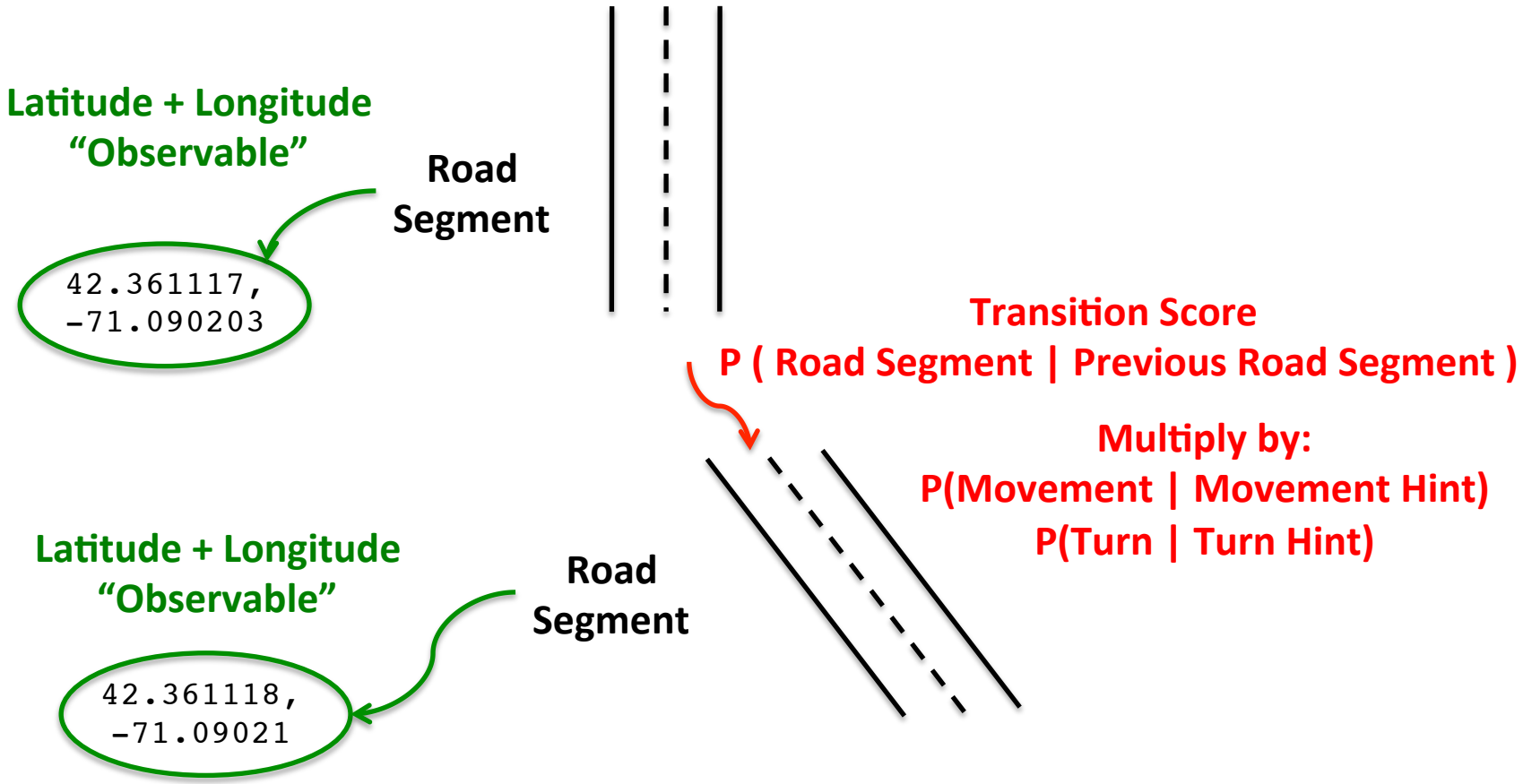
CTrack FlowChart



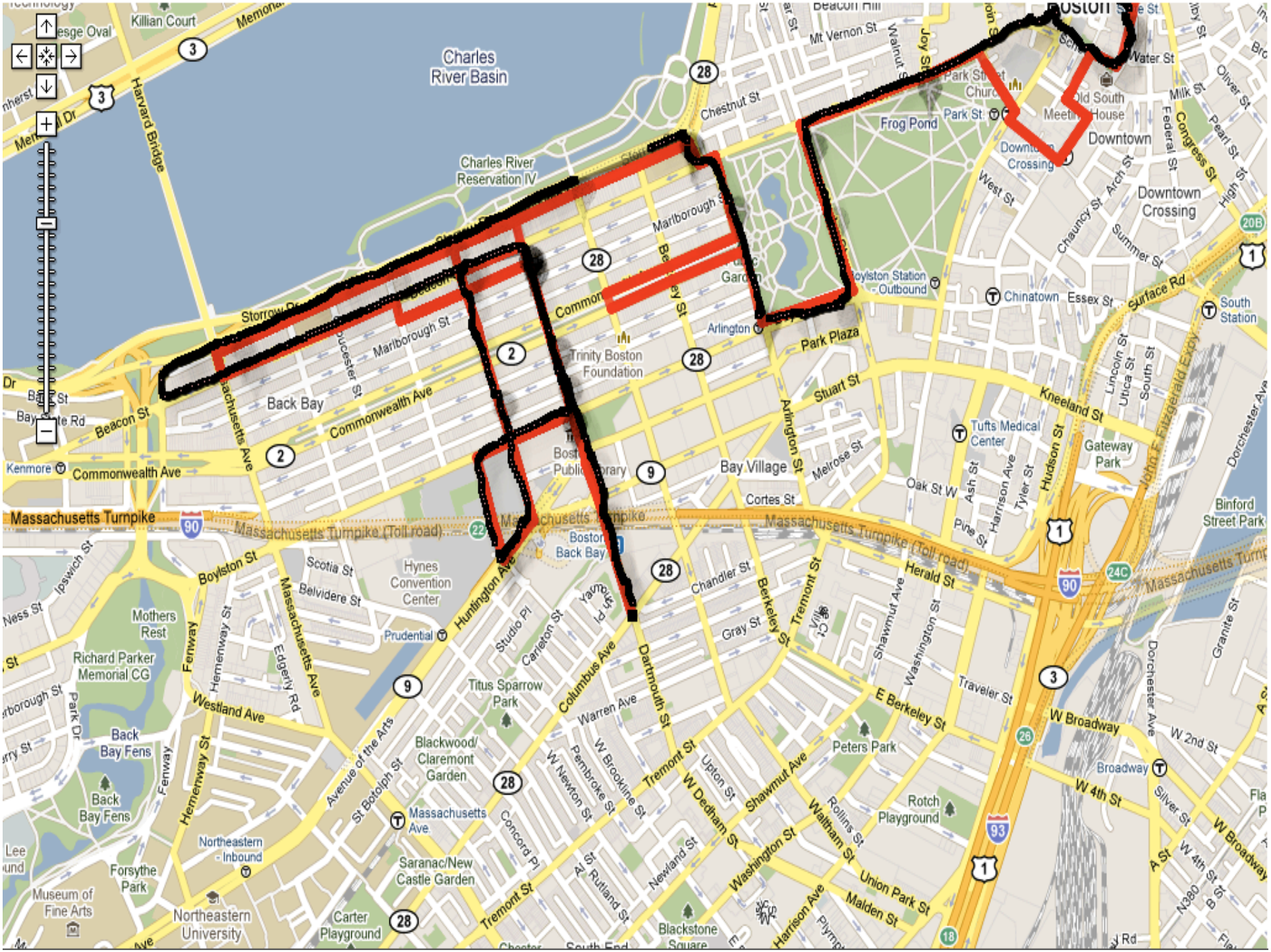
Matching (Lat, Lon) To Segments

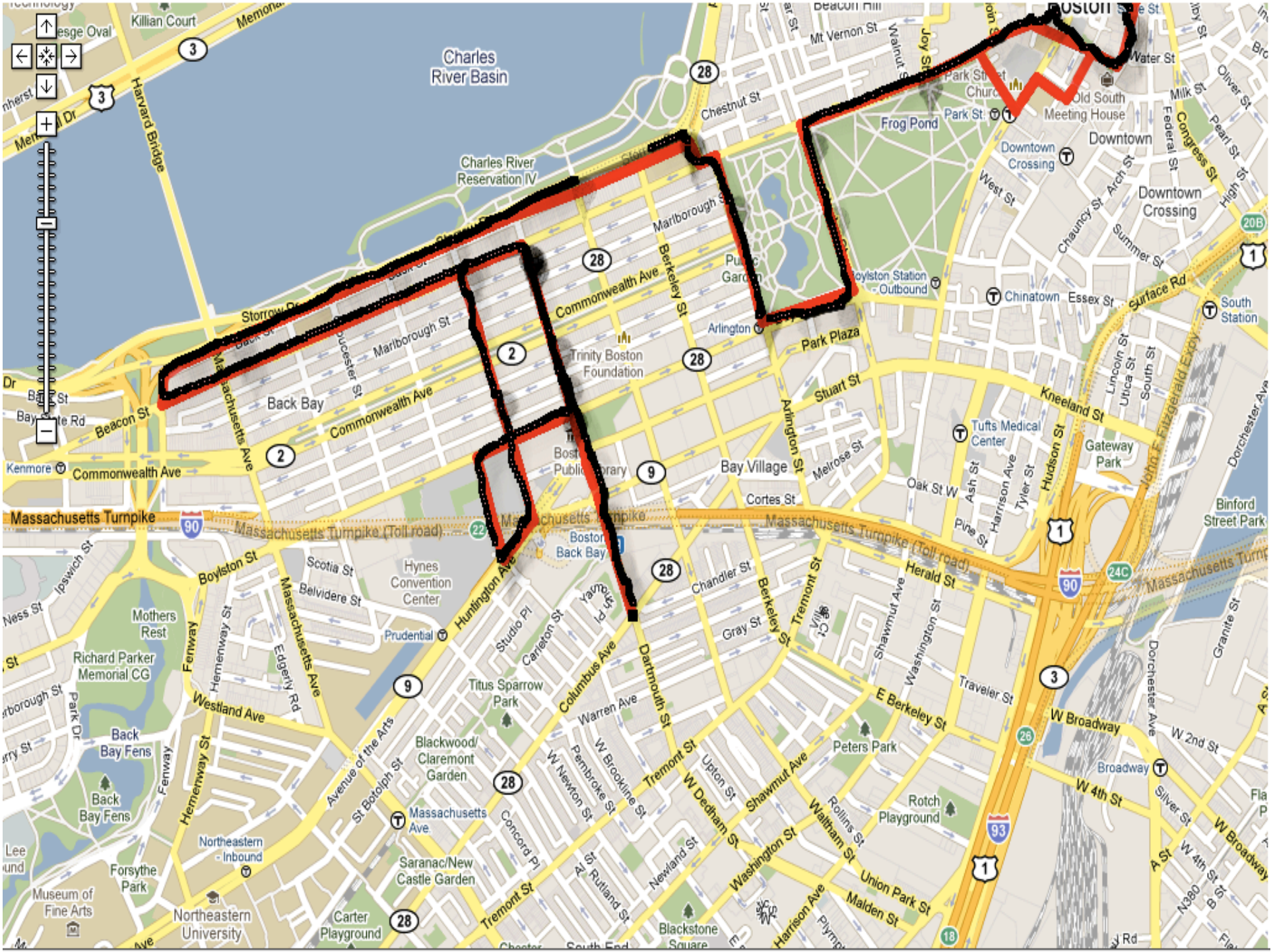


Matching (Lat, Lon) To Segments



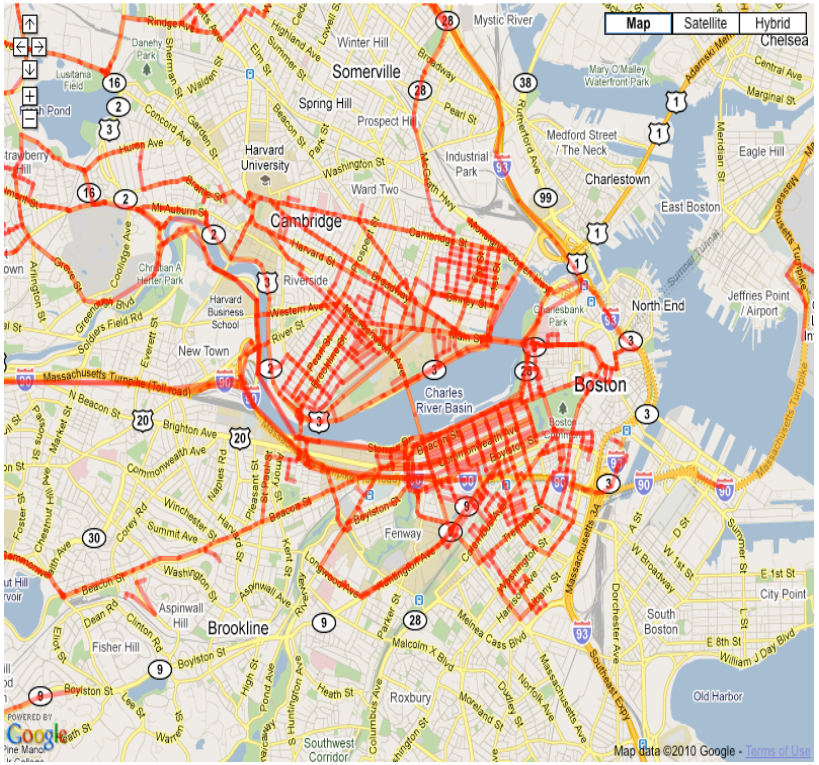
Extract 0/1 (Binary) Movement and Turn Hints For Each Time Slot


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


Charles River Basin
Charles River Reservation IV
Killian Court
Harvard Bridge
Back Bay
Commonwealth Ave
Beacon St
Massachusetts Ave
Boylston St
Arlington
Trinity Boston Foundation
Park Plaza
Stuart St
Kneeland St
Tufts Medical Center
Gateway Park
Bay Village
Cortes St
Massachusetts Turnpike
Massachusetts Turnpike (Toll road)
Hynes Convention Center
Prudential
Huntington Ave
Scotia St
Belvidere St
Mothers Rest
Richard Parker Memorial CG
Fenway
Hemenway St
Westland Ave
Back Bay Fens
Titus Sparrow Park
Blackwood/ Claremont Garden
Massachusetts Ave
Northeastern - Inbound
Saranac/New Castle Garden
Forsythe Park
Museum of Fine Arts
Northeastern University
Carter Playground
Blackstone Square
Columbus Ave
Dartmouth St
Tremont St
Berkeley St
Chandler St
Gray St
Herald St
E Berkeley St
W Broadway
Peters Park
Rotch Playground
Shawmut Ave
Washington St
Waltham St
Union Park St
Malden St
Harrison Ave
W Dedham St
Upton St
Rollins St
Newland St
Warren Ave
W Brookline St
Pembroke St
W Newton St
Concord Pl
Rutland St
St Botolph St
Avenue of the Arts
Studio Pl
Carleton St
Yarmouth Pl
Traveler St
Shawmut Ave
Washington St
Tremont St
Arlington St
Melrose St
Oak St W
Ash St
Harrison Ave
Tyler St
Hudson St
Lincoln St
Utica St
South St
John F Fitzgerald Expy
Surface Rd
Chinatown
Essex St
South Station
Downtown Crossing
Downtown
Old South Meeting House
Frog Pond
Park St
Water St
Milk St
Federal St
Congress St
Pearl St
Oliver St
High St
Summer St
Chauncy St
Arch St
West St
Boylston Station - Outbound
Public Garden
Chestnut St
Mt Vernon St
Beacon Hill
Walnut St
Joy St
Marlborough St
Berkeley St
Commonwealth Ave
Storrow Dr
Back St
Gloucester St
Kenmore
Commonwealth Ave
Bay State Rd
Ipswich St
Ness St
Park Dr
Fenway
Hemenway St
Edgerly Rd
Massachusetts Ave
Avenue of the Arts
St Botolph St
Concord Pl
Rutland St
Newland St
Warren Ave
Columbus Ave
Dartmouth St
Tremont St
Berkeley St
Chandler St
Gray St
Herald St
E Berkeley St
W Broadway
W 2nd St
W 4th St
Broadway
Silver St
A St
B St
N380
Dorchester Ave
Granite St
Binford Street Park
Dorchester Ave
Fla
Lee
Rd
Boston
Back Bay
Public Library
Trinity Boston Foundation
Arlington
Boylston Station - Outbound
Park Plaza
Stuart St
Kneeland St
Tufts Medical Center
Gateway Park
Bay Village
Cortes St
Massachusetts Turnpike
Massachusetts Turnpike (Toll road)
Hynes Convention Center
Prudential
Huntington Ave
Scotia St
Belvidere St
Mothers Rest
Richard Parker Memorial CG
Fenway
Hemenway St
Westland Ave
Back Bay Fens
Titus Sparrow Park
Blackwood/ Claremont Garden
Massachusetts Ave
Northeastern - Inbound
Saranac/New Castle Garden
Forsythe Park
Museum of Fine Arts
Northeastern University
Carter Playground
Blackstone Square
Columbus Ave
Dartmouth St
Tremont St
Berkeley St
Chandler St
Gray St
Herald St
E Berkeley St
W Broadway
Peters Park
Rotch Playground
Shawmut Ave
Washington St
Waltham St
Union Park St
Malden St
Harrison Ave
W Dedham St
Upton St
Rollins St
Newland St
Warren Ave
W Brookline St
Pembroke St
W Newton St
Concord Pl
Rutland St
St Botolph St
Avenue of the Arts
Studio Pl
Carleton St
Yarmouth Pl
Traveler St
Shawmut Ave
Washington St
Tremont St
Arlington St
Melrose St
Oak St W
Ash St
Harrison Ave
Tyler St
Hudson St
Lincoln St
Utica St
South St
John F Fitzgerald Expy
Surface Rd
Chinatown
Essex St
South Station
Downtown Crossing
Downtown
Old South Meeting House
Frog Pond
Park St
Water St
Milk St
Federal St
Congress St
Pearl St
Oliver St
High St
Summer St
Chauncy St
Arch St
West St
Public Garden
Chestnut St
Mt Vernon St
Beacon Hill
Walnut St
Joy St
Marlborough St
Berkeley St
Commonwealth Ave
Storrow Dr
Back St
Gloucester St
Kenmore
Commonwealth Ave
Bay State Rd
Ipswich St
Ness St
Park Dr
Fenway
Hemenway St
Edgerly Rd
Massachusetts Ave
Avenue of the Arts
St Botolph St
Concord Pl
Rutland St
Newland St
Warren Ave
Columbus Ave
Dartmouth St
Tremont St
Berkeley St
Chandler St
Gray St
Herald St
E Berkeley St
W Broadway
W 2nd St
W 4th St
Broadway
Silver St
A St
B St
N380
Dorchester Ave
Granite St
Binford Street Park
Dorchester Ave
Fla
Lee
Rd

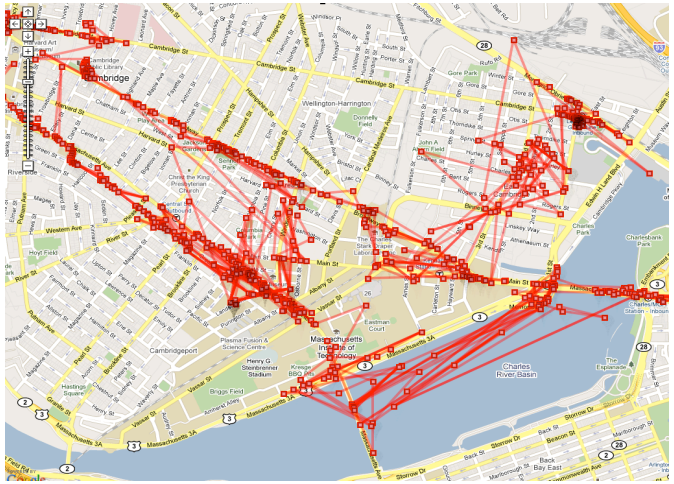
Evaluation

- 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

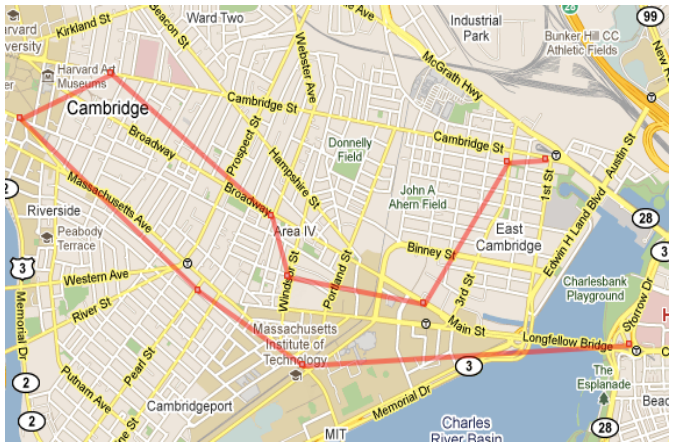


We Compared CTrack To…

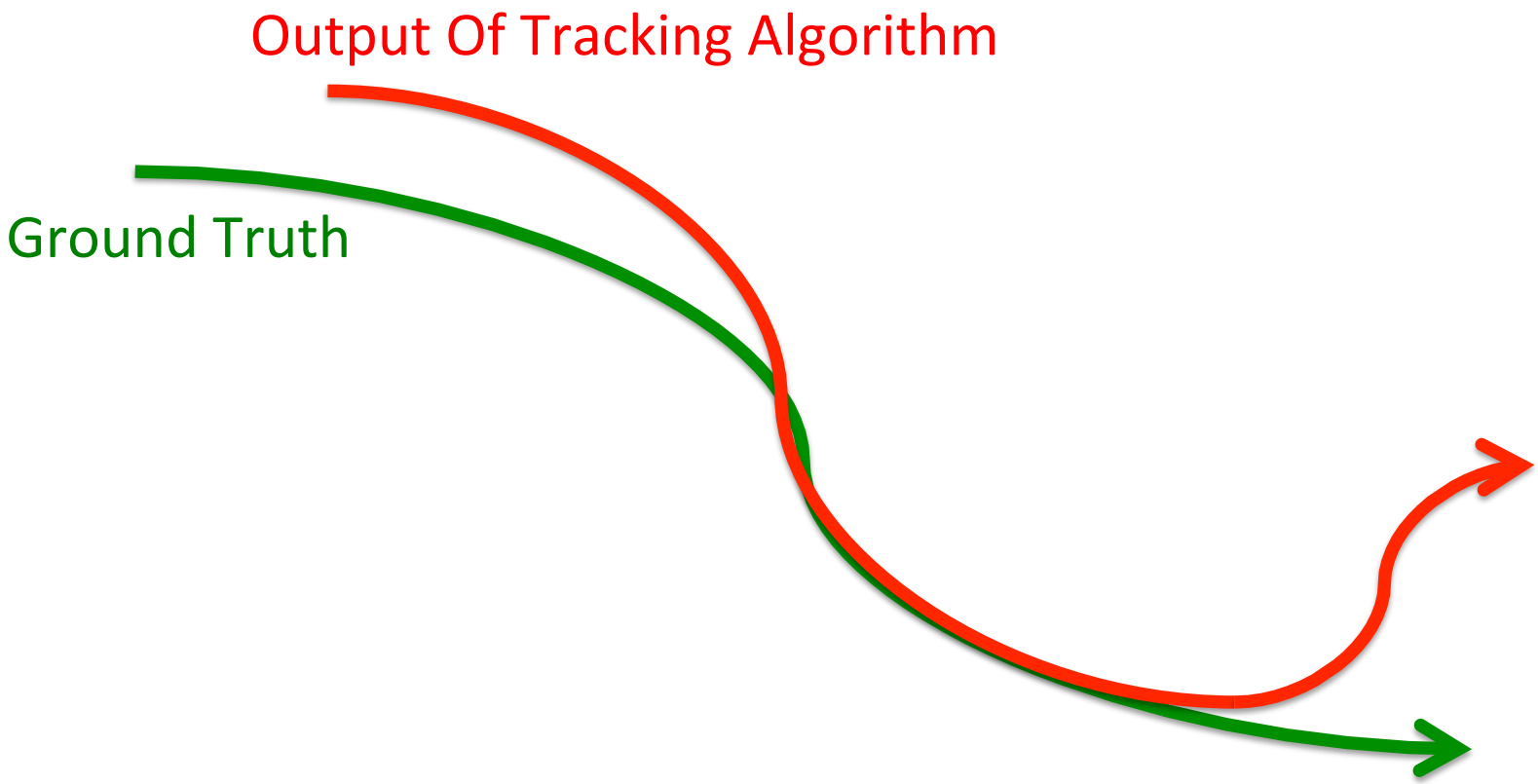
- Placelab + VTrack
  - Look up single best matching GSM fingerprint for each time
  - Match (lat, lon) using VTrack



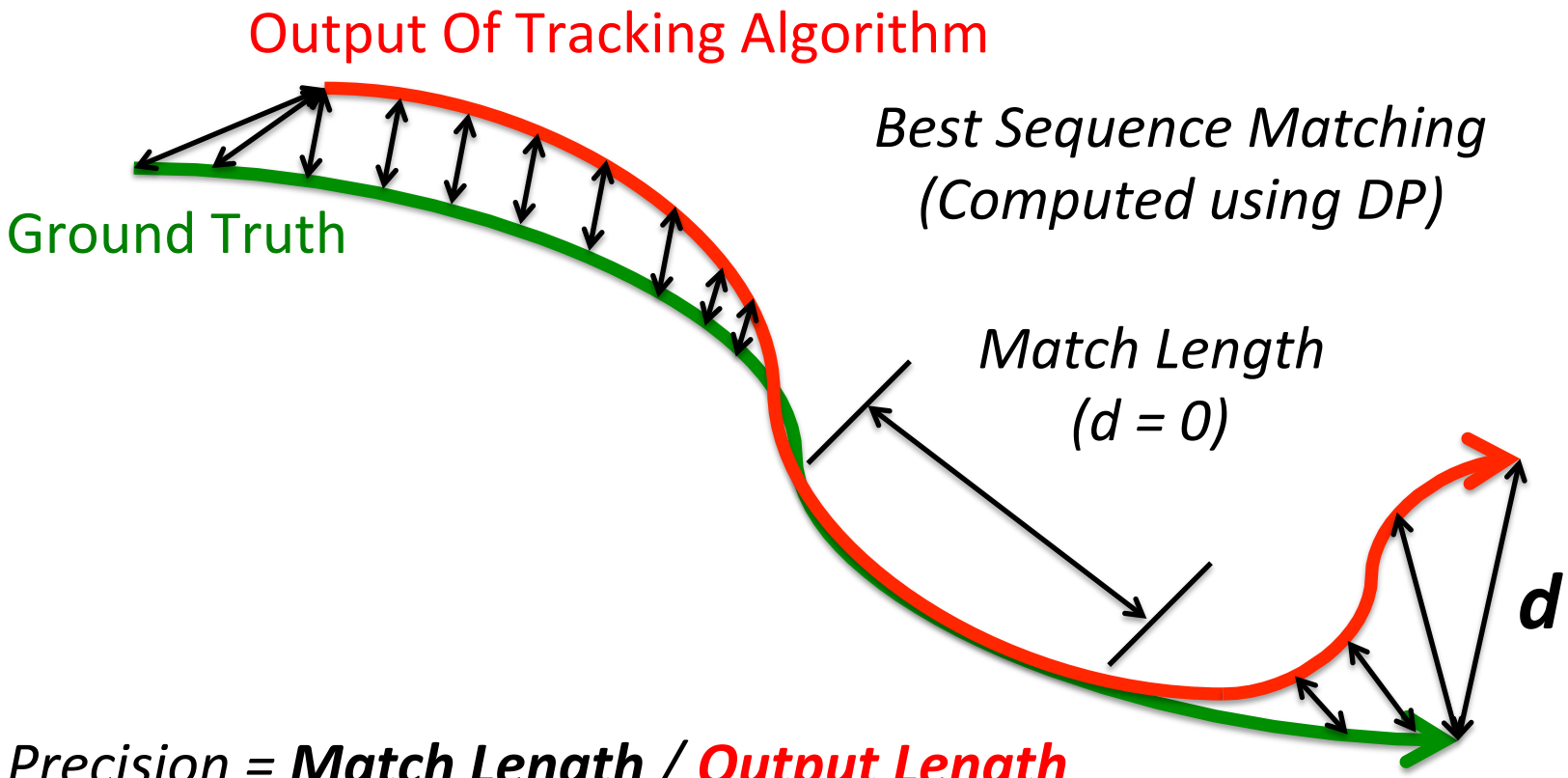
- *GPS k* + VTrack
  - Get a GPS sample every k secs
  - Match (lat, lon) using VTrack
  - k = 4 min is *energy-equivalent* to CTrack



Evaluation Metrics



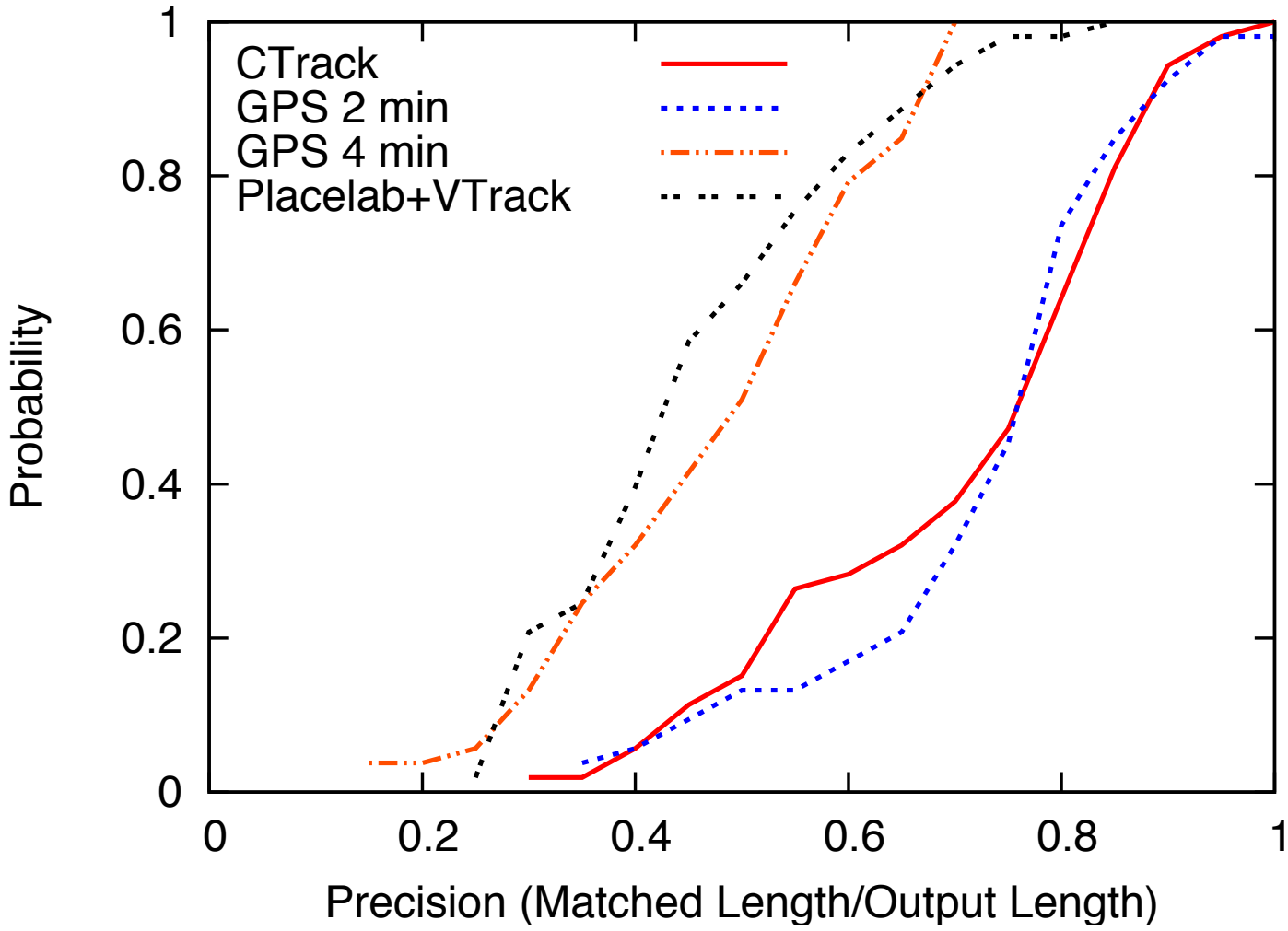
Evaluation Metrics



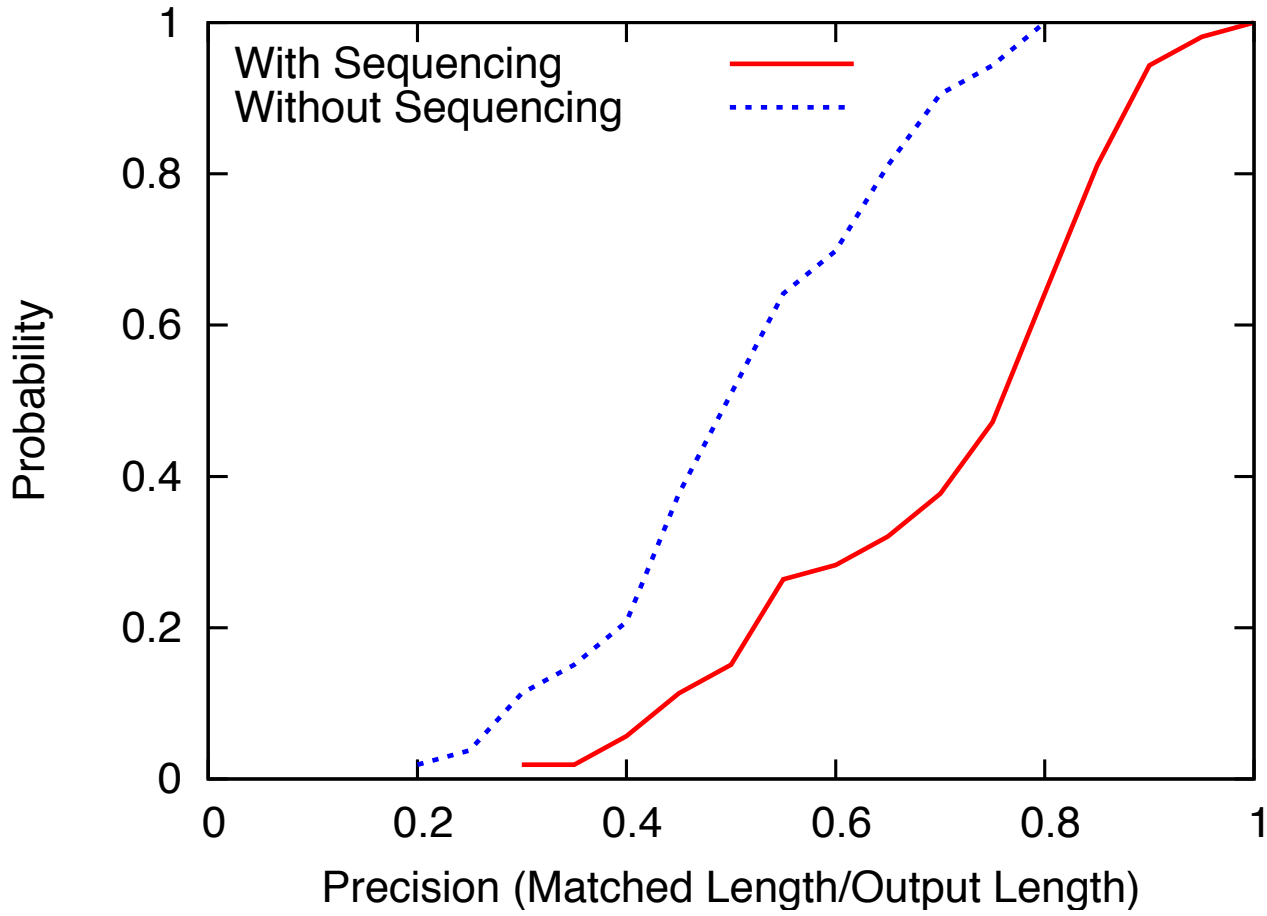
Precision = ***Match Length*** */* ***Output Length***

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

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



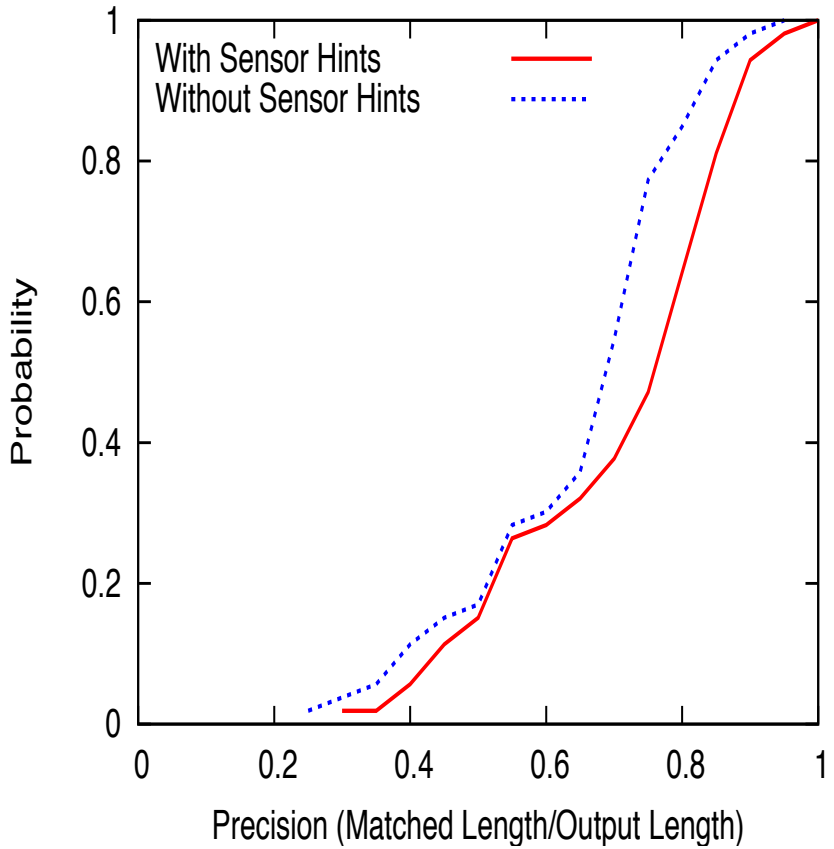
Grid Sequencing Step is Critical



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!

Conclusions

- 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 + future work:
  - Make large scale deployment of location-based apps feasible without running into energy barriers
  - Enable devices without GPS (85% of the market) to contribute to and benefit from location-based services