Programming Uncertain <T>hings

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Diman Zad Tootaghaj	University of Pittsburgh

24 mph

runtastic

Home Map Split

Jake Van Damme

GPS

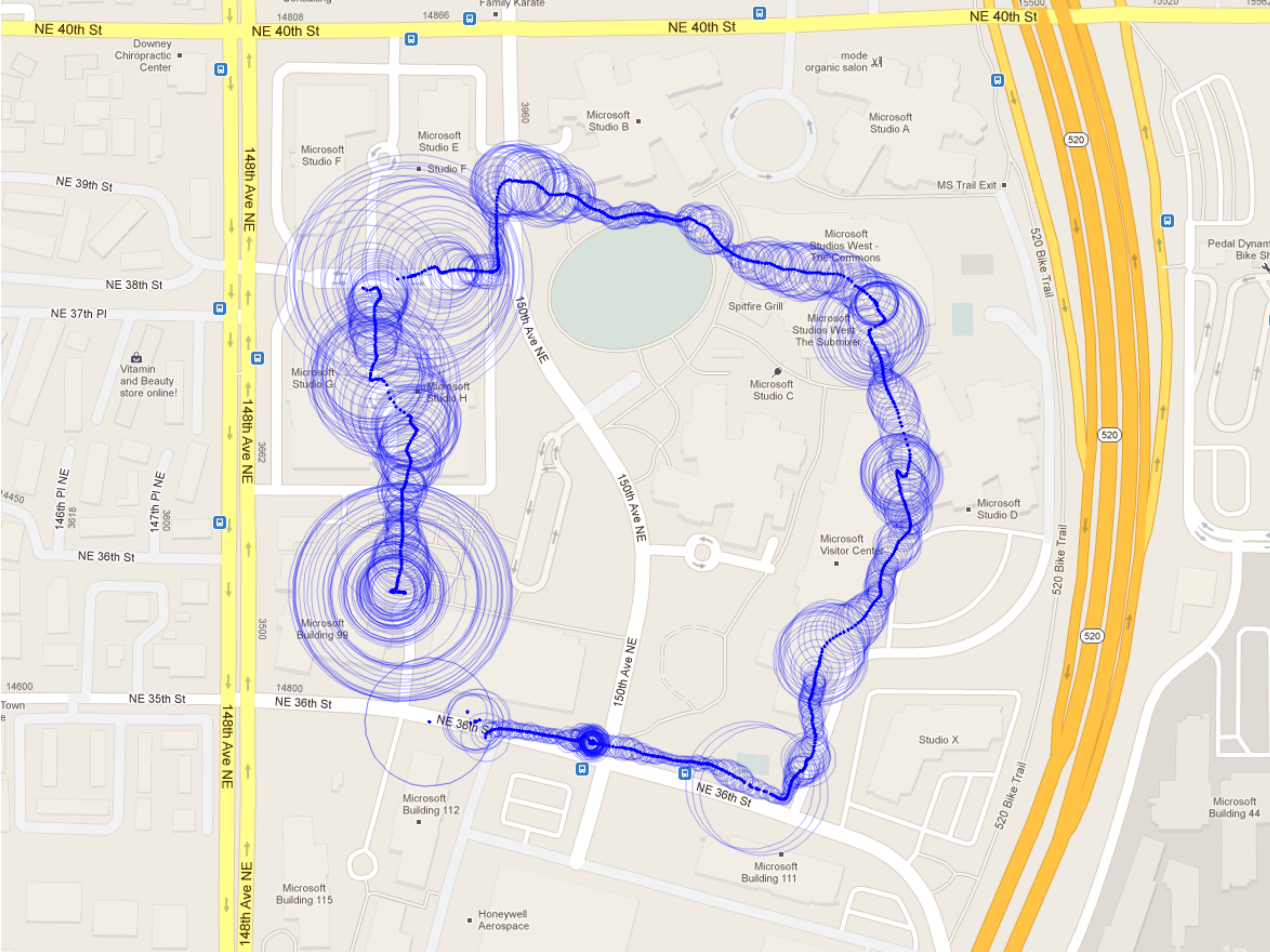
DURATION	DISTANCE
00:23:43	2.59
h:m:s	mi

PACE min/mi	08:53	AVG. SPEED mph	6.5
ALTITUDE ft	10	CALORIES kCal	354

Pause | Stop

59 mph

```
GeoCoordinate Location = GPS.Get();
```


NE 40th St
NE 40th St
NE 40th St
NE 40th St
14808
14866
Family Karate
15500
15520
Downey
Chiropractic
Center
mode
organic salon
Microsoft
Studio B
Microsoft
Studio A
Microsoft
Studio E
Microsoft
Studio F
Studio F
3960
MS Trail Exit
520
NE 39th St
148th Ave NE
NE 38th St
NE 37th Pl
Microsoft
Studios West -
The Commons
Spitfire Grill
Microsoft
Studios West
The Submixer
520 Bike Trail
Pedal Dynam
Bike Sh
150th Ave NE
Vitamin
and Beauty
store online!
Microsoft
Studio G
Microsoft
Studio H
Microsoft
Studio C
520
148th Ave NE
3662
150th Ave NE
14450
146th Pl NE
3618
147th Pl NE
3600
Microsoft
Studio D
NE 36th St
Microsoft
Visitor Center
3500
Microsoft
Building 99
520 Bike Trail
520
14600
NE 35th St
14800
NE 36th St
150th Ave NE
Town
NE 36th St
148th Ave NE
Studio X
NE 36th St
520 Bike Trail
Microsoft
Building 112
Microsoft
Building 111
Microsoft
Building 44
Microsoft
Building 115
148th Ave NE
Honeywell
Aerospace

```
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
double Dist =
             Distance(PrevLocn, Location);
double Speed = Dist / 5;
```

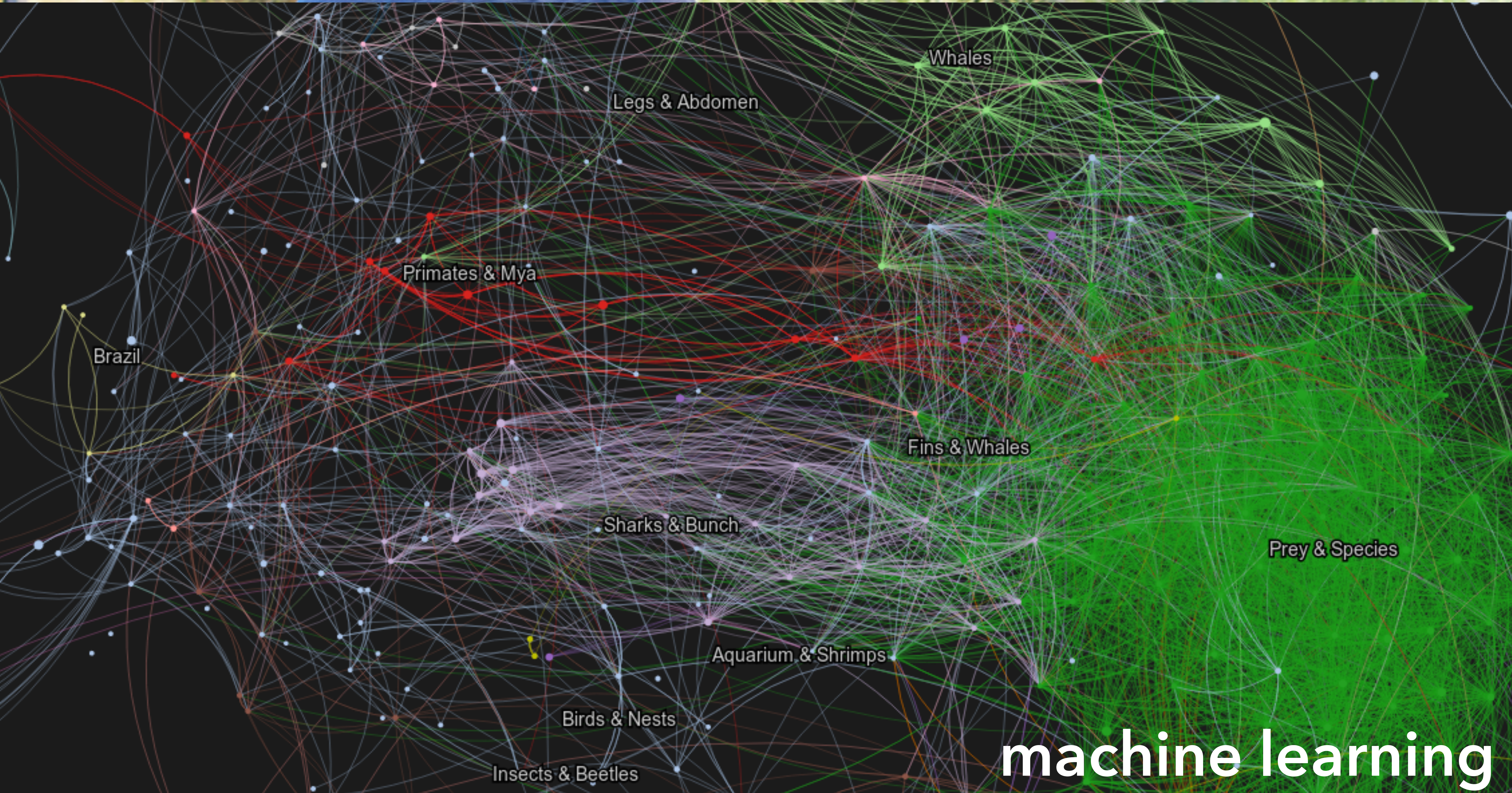
```
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
double Dist =
             Distance(PrevLocn, Location);
double Speed = Dist / 5;


Print(Speed);
```

59 mph

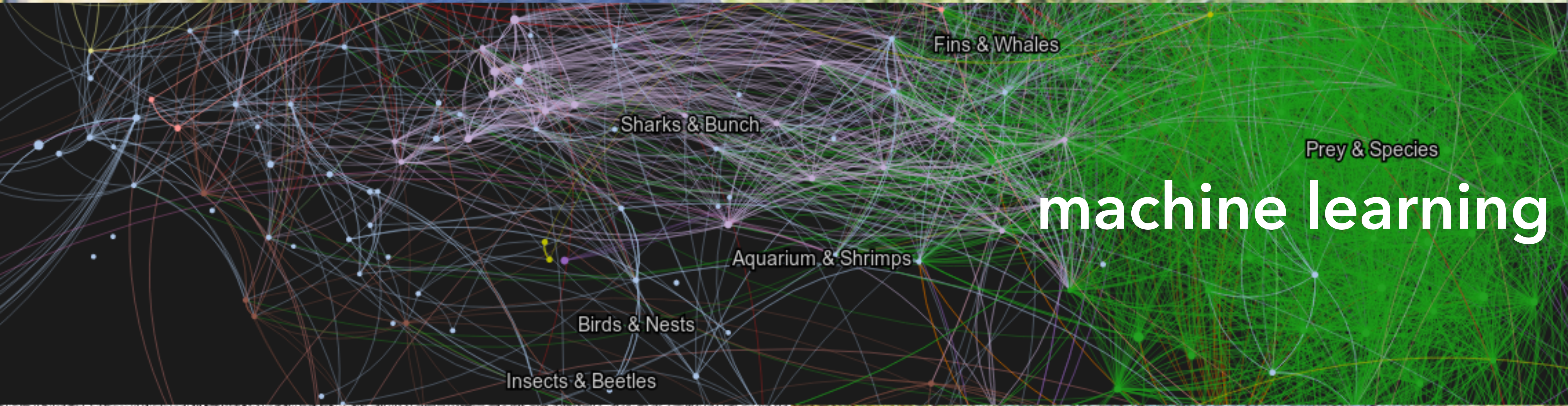
6.0mi
summary
54:36
346cals

sensors

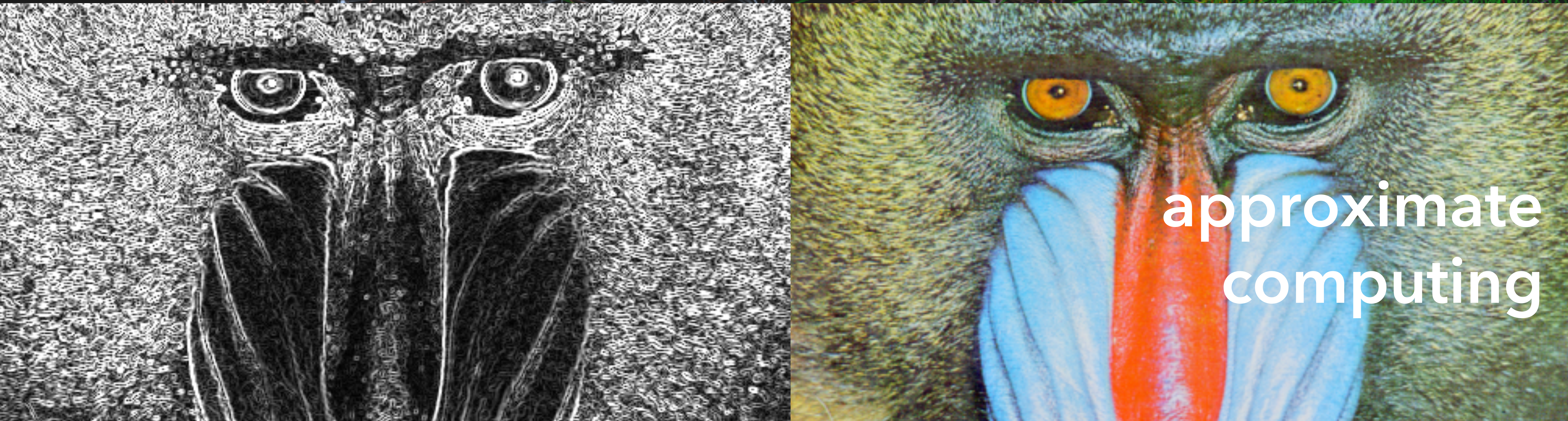


machine learning

sensors



machine learning



approximate computing

Uncertain<*T*>

an abstraction for reasoning about noise

[ASPLOS’14]

exploiting context

improving accuracy with more language & inference

[rejected so far]

what does it mean?

probabilistic assertions

[PLDI’14]

Uncertain<*T*>

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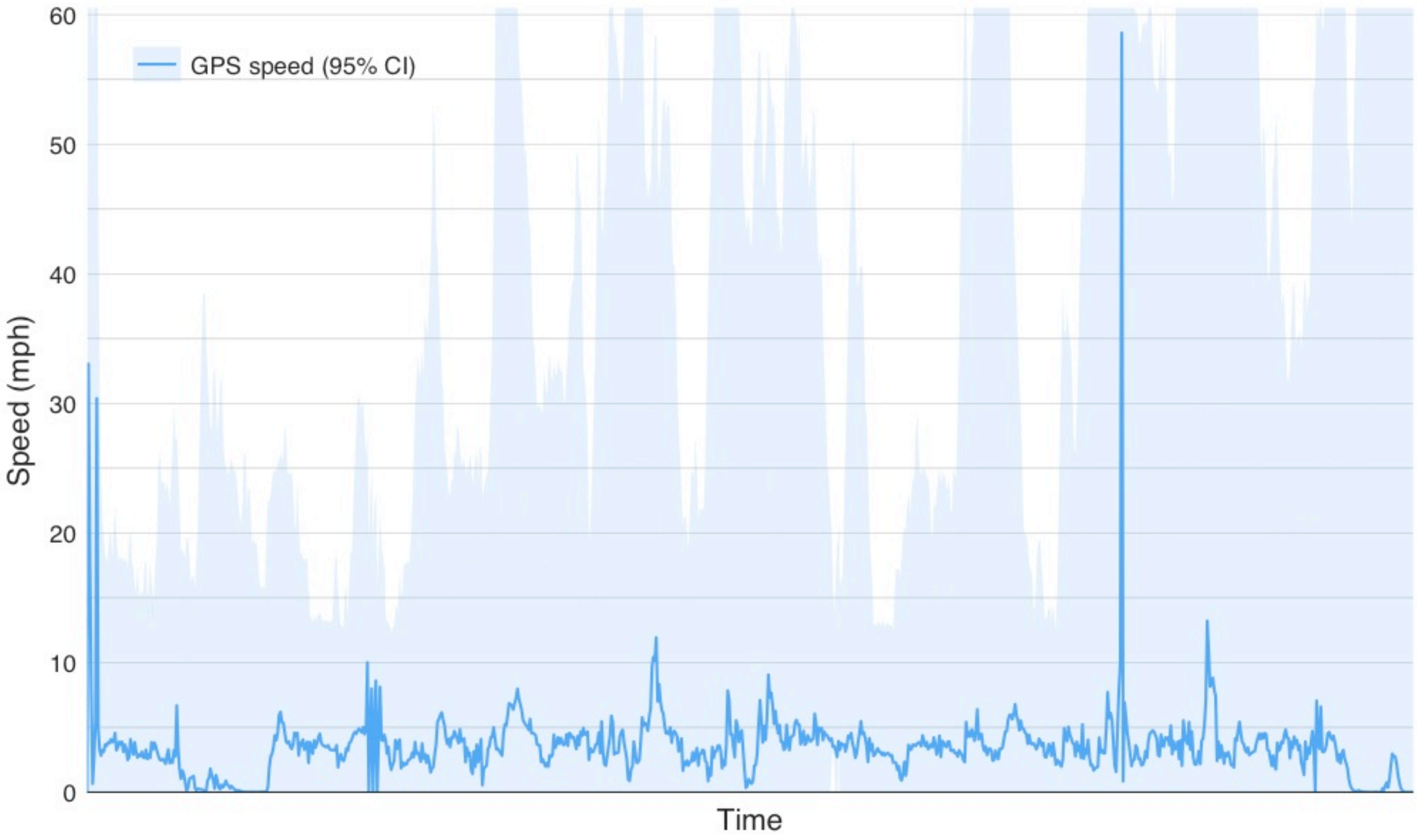
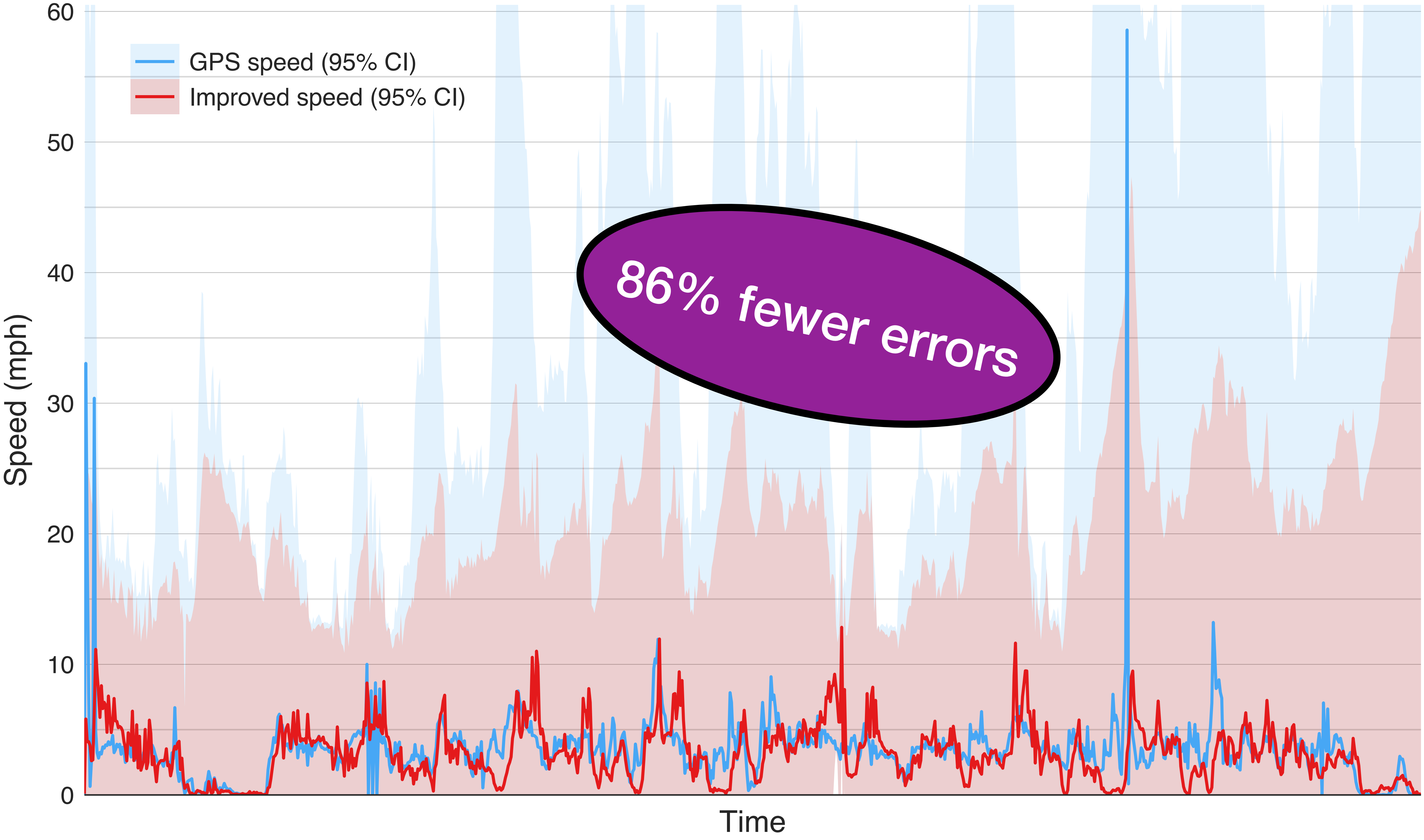
```
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
double Dist =
             Distance(PrevLocn, Location);
double Speed = Dist / 5;


Print(Speed);
```


GPS speed (95% CI)
60
50
40
30
20
10
0
Speed (mph)
Time

```
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
double Dist =
             Distance(PrevLocn, Location);
double Speed = Dist / 5;


Print(Speed);
```

```
Uncertain<GeoCoordinate> PrevLocn = Get();
Sleep(5);
Uncertain<GeoCoordinate> Location = Get();
Uncertain<double> Dist =
             Distance(PrevLocn, Location);
Uncertain<double> Speed = Dist / 5;


Print (Speed);  // Expected value at 95 CI
```



86% fewer errors

Fitness application

```
Uncertain<GeoCoordinate> PrevLocn = Get();
Sleep(5);
Uncertain<GeoCoordinate> Location = Get();
Uncertain<double> Dist =
             Distance(PrevLocn, Location);
Uncertain<double> Speed = Dist / 5;

if (Speed > 4)
    Alert(“Keep it up!”);
```

Hypothesis Test

more likely than

not Speed > 4

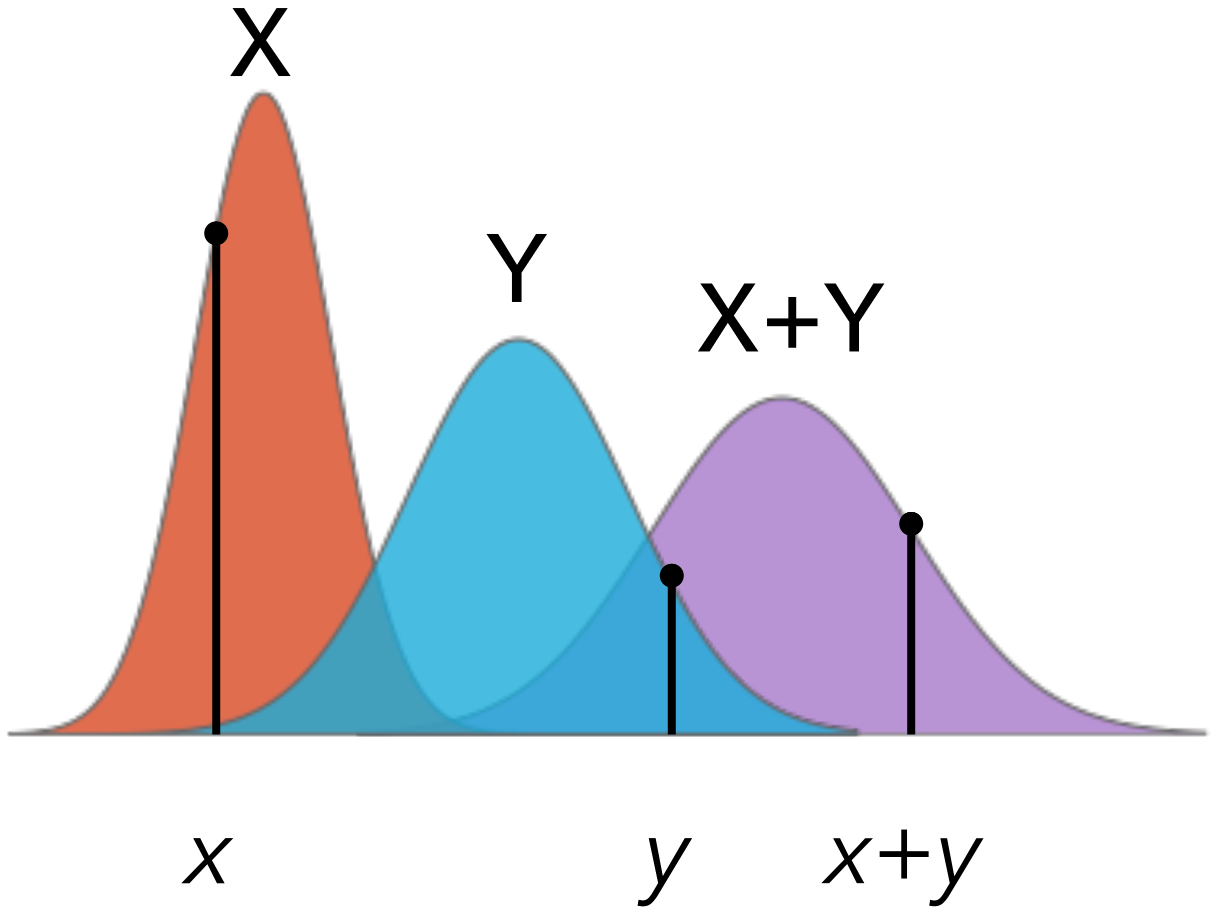
Semantics

Uncertain<T> encapsulates probability distributions and hides statistical complexity.

- Computing over random variables
- Evaluating expected value & conditionals

Computations

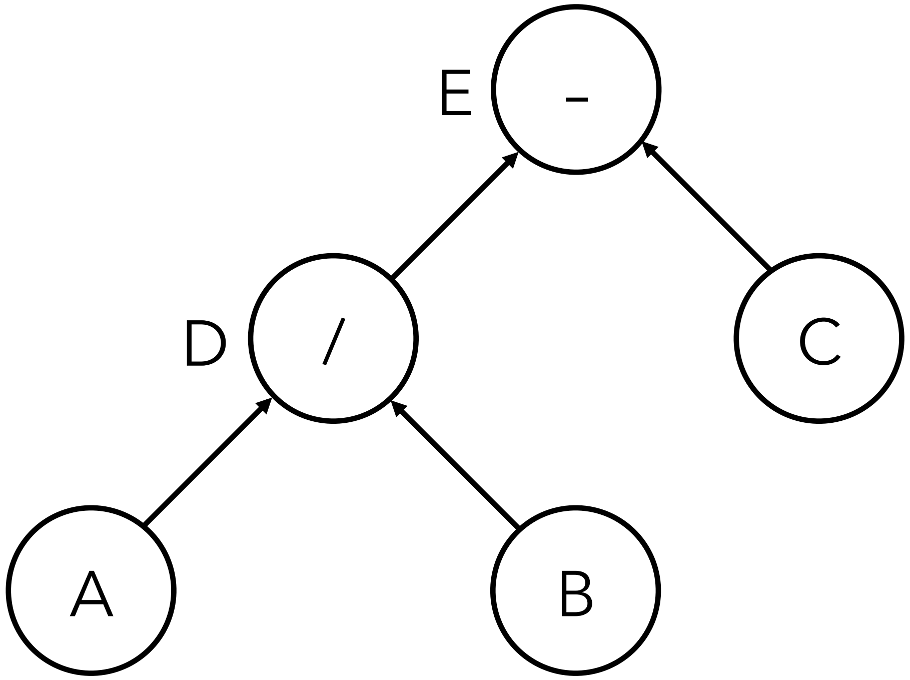
Represent distributions by random samples



Computations - lazy evaluation

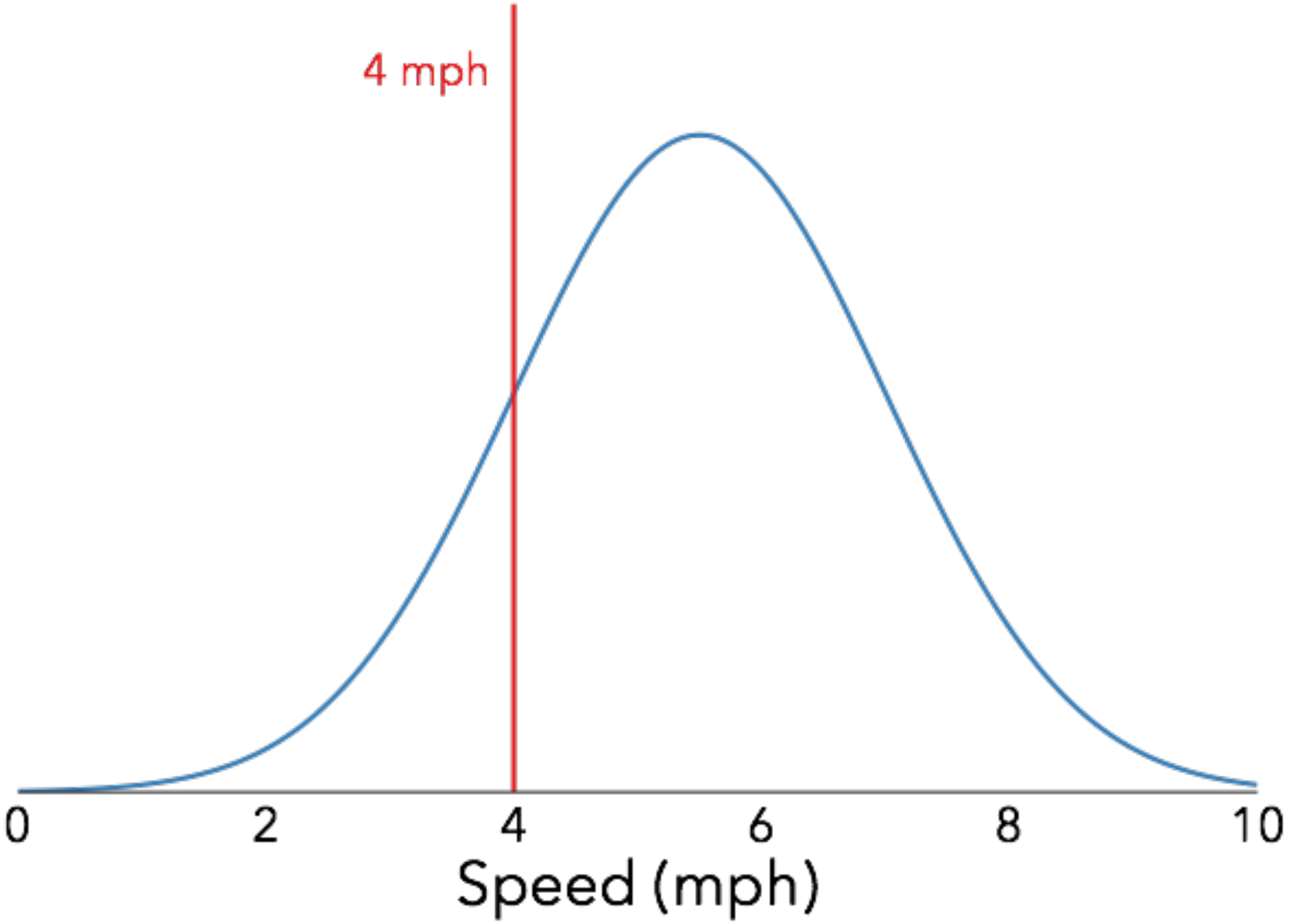
Operators build a Bayesian network rather than evaluating immediately.

D = A / B
E = D - C



Evaluating conditionals

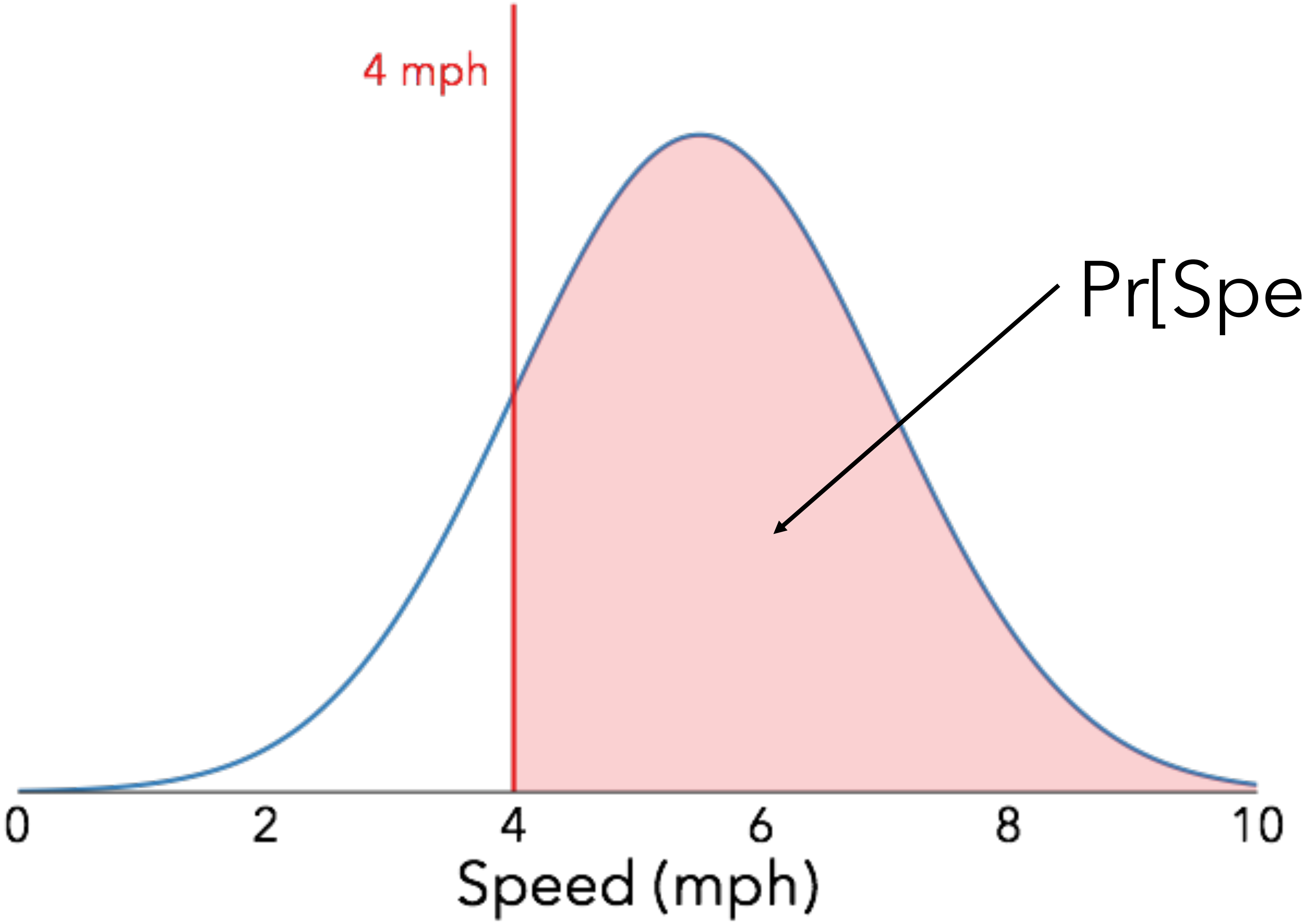
```
if (Speed > 4)
    Alert("Keep it up!");
```



Evaluating conditionals

```
if (Speed > 4)
    Alert("Keep it up!");
```

More likely than not that Speed > 4?

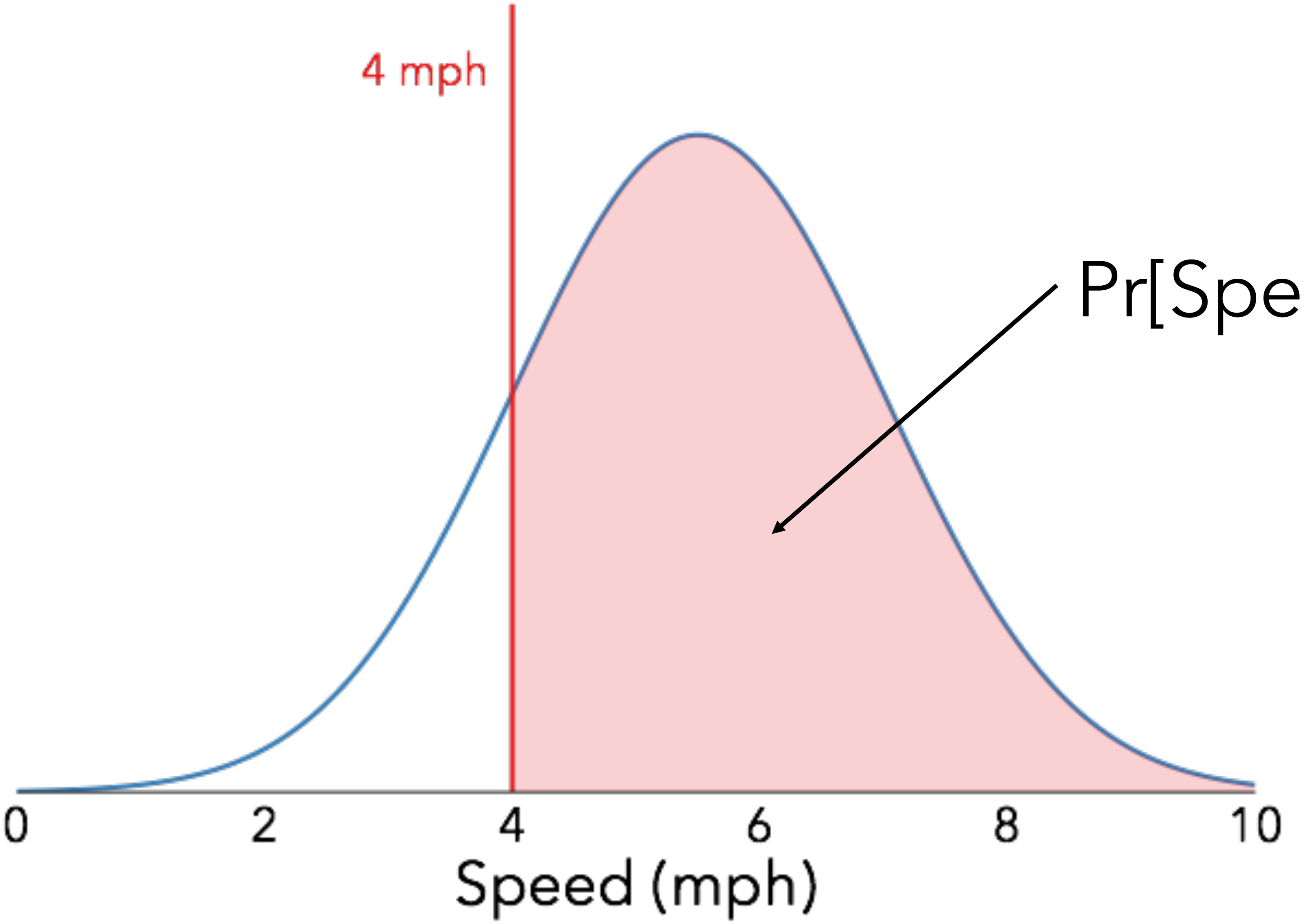


Pr[Speed > 4]

Evaluating conditionals

```
if ((Speed > 4).Pr(0.9))
    Alert("Keep it up!");
```

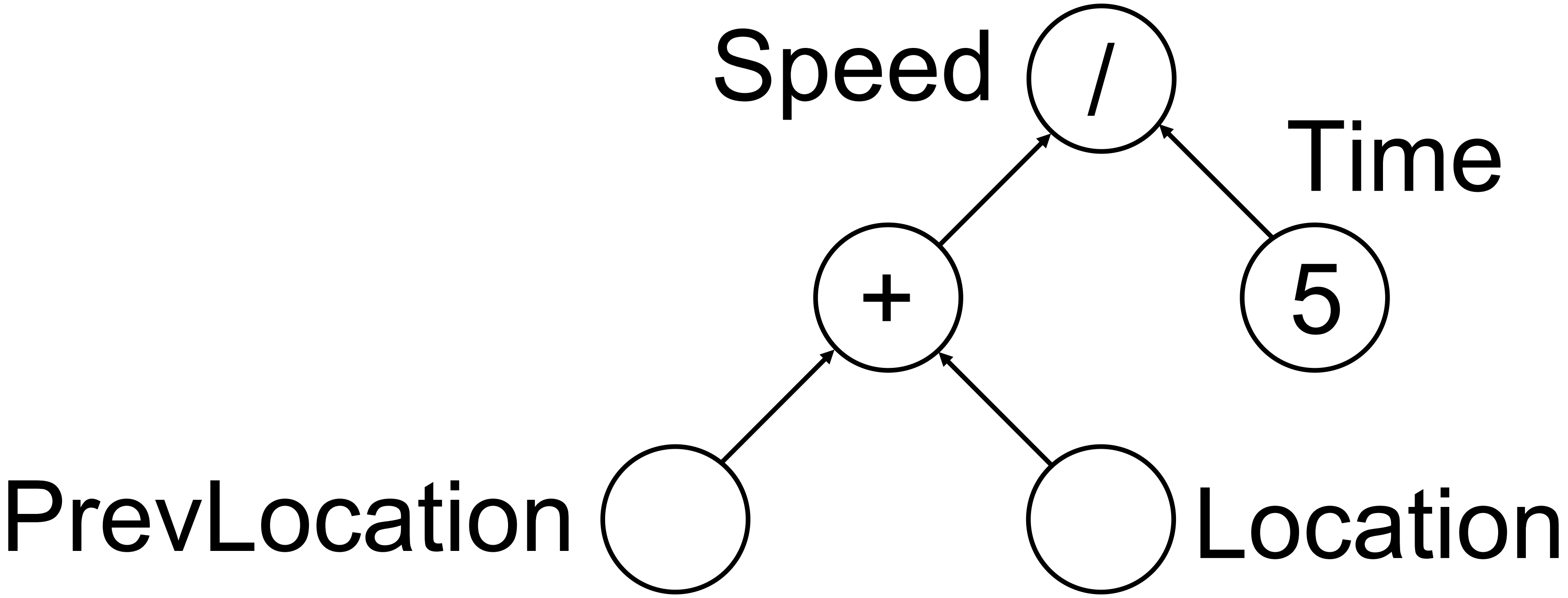
At least 90% likely that Speed > 4?



Pr[Speed > 4]

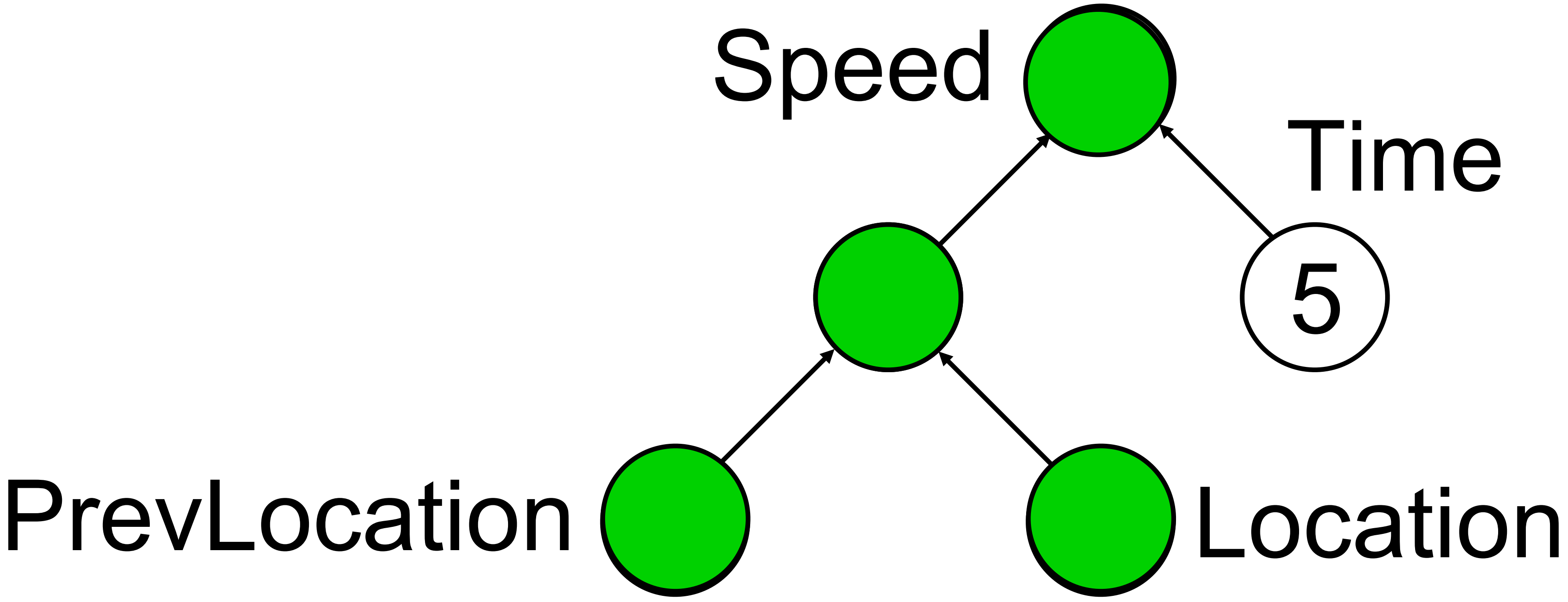
Sampling at runtime

```
if (Speed > 4)
    Alert("Keep it up!");
```



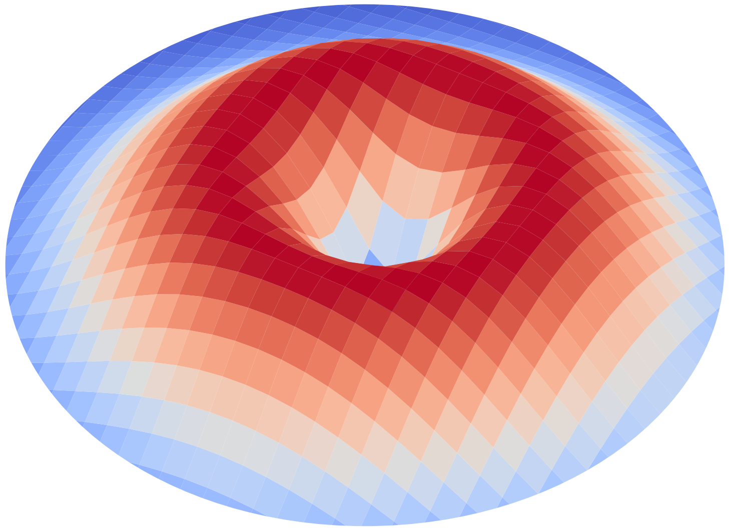
Sampling at runtime

```
if (Speed > 4)
    Alert("Keep it up!");
```



Sampling functions

Data source responsible for describing errors in estimate



3 D Raleigh Distribution
GPS error

Arbitrary
non-continuous functions

Sampling functions

Data source responsible for describing errors in estimate

```
GeoCoordinate Sample (GeoCoordinate location,
  double accuracy) {

  return SampleRayleigh(location, accuracy);

}
```

Identifying absurd data

```
GeoCoordinate PrevLocn = Get();
Sleep(5);
GeoCoordinate Location = Get();
double Dist =
             Distance(PrevLocn, Location);
double Speed = Dist / 5;

if (Speed > 4)
    Alert("That’s crazy!");
```

Naïve 30 false positives

Identifying absurd data

```
Uncertain<GeoCoordinate> PrevLocn = Get();
Sleep(5);
Uncertain<GeoCoordinate> Location = Get();
Uncertain<double> Dist =
             Distance(PrevLocn, Location);
Uncertain<double> Speed = Dist / 5;

if (Speed > 4)
    Alert("That’s crazy!");
```

Naïve 30 false positives

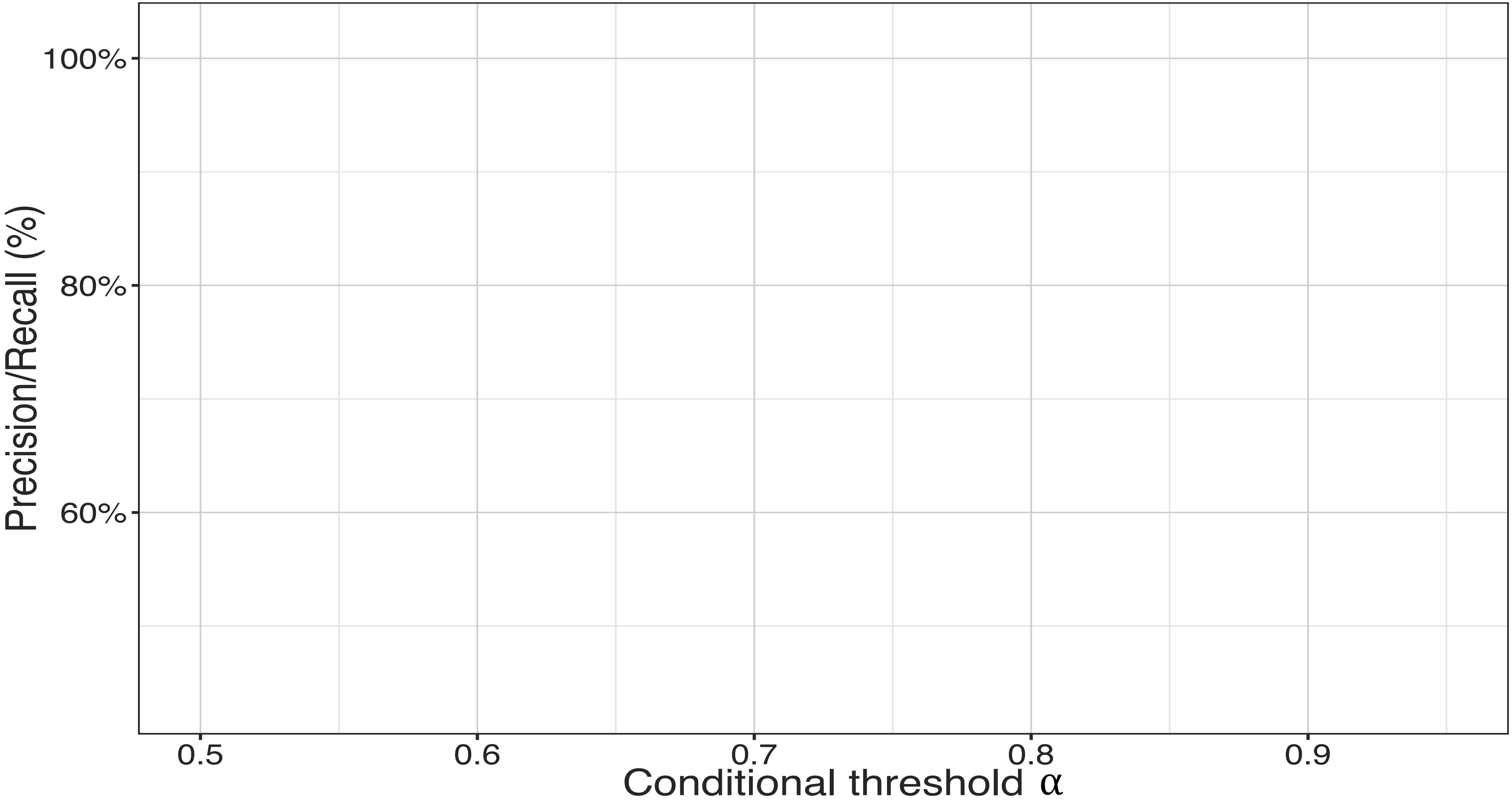
50% 4 false positives

Identifying absurd data

```
Uncertain<GeoCoordinate> PrevLocn = Get();
Sleep(5);
Uncertain<GeoCoordinate> Location = Get();
Uncertain<double> Dist =
             Distance(LastLocn, Location);
Uncertain<double> Speed = Dist / 5;

if ((Speed > 4).Pr(0.9))
    Alert("That’s crazy!");
```

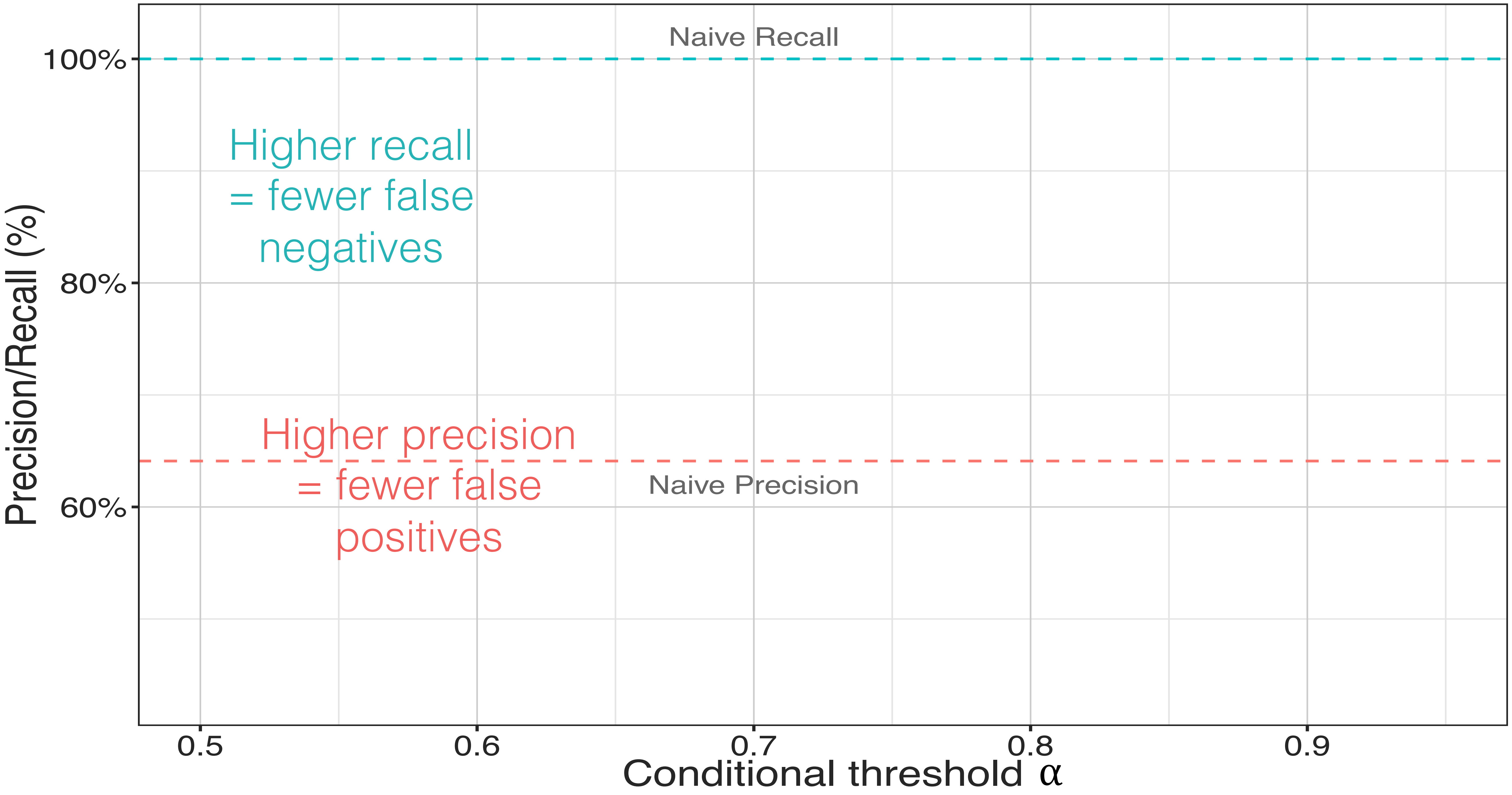
Naïve	**30 false positives**
50%	**4 false positives**
90%	**none**

Edge Detection



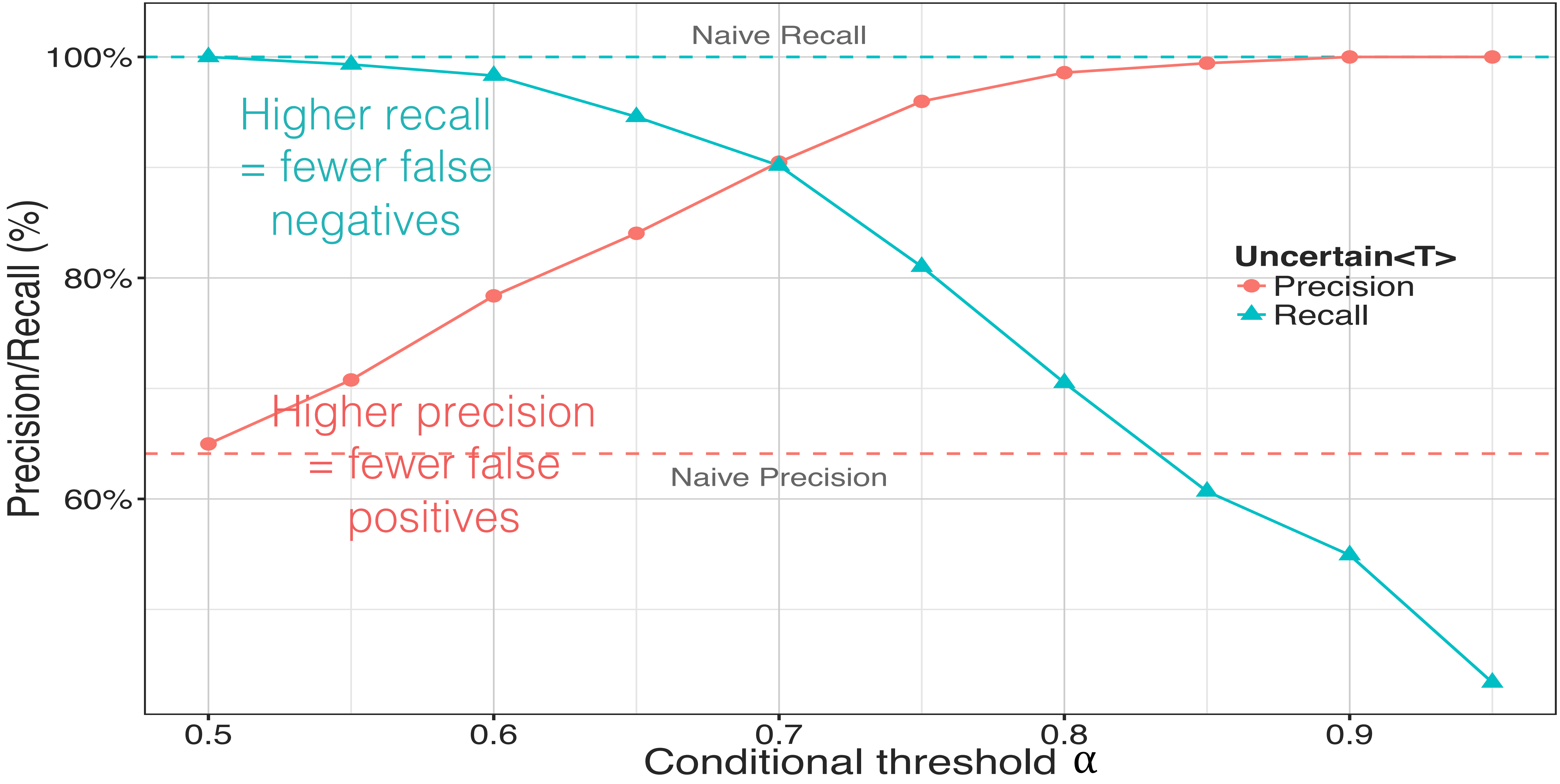
Pr[Sobel(p) > 0.1] > α

Edge Detection



$\Pr[\text{Sobel}(p) > 0.1] > \alpha$

Edge Detection



Higher recall = fewer false negatives

Higher precision = fewer false positives

$\Pr[\text{Sobel}(p) > 0.1] > \alpha$

Uncertain<*T*>

an abstraction for reasoning about noise

[ASPLOS’14]

exploiting context

improving accuracy with more language & inference

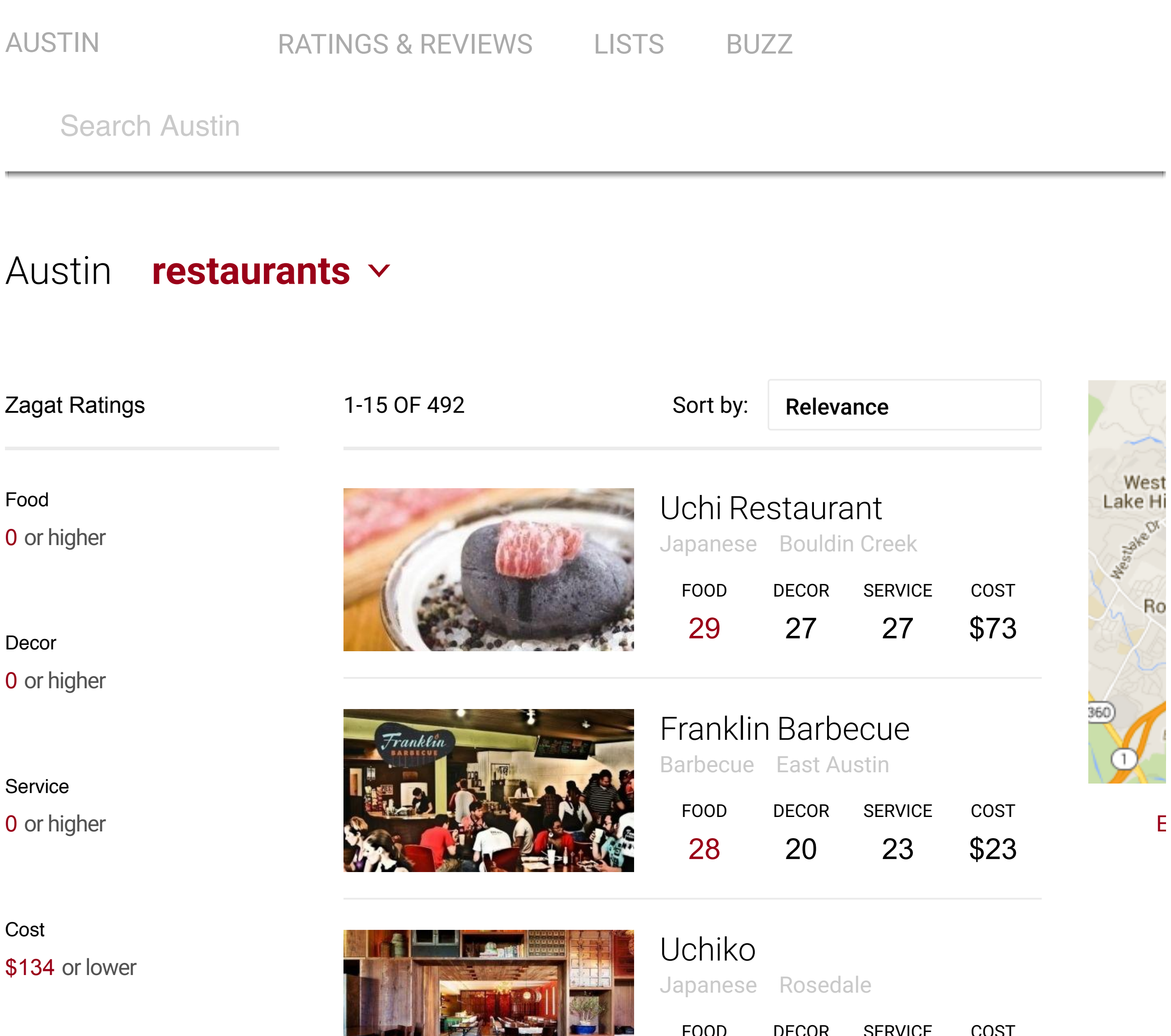
[rejected so far]

what does it mean?

probabilistic assertions

[PLDI’14]

Context



Ab

AUSTIN RATINGS & REVIEWS LISTS BUZZ

Search Austin

Austin **restaurants**

Zagat Ratings

Food
0 or higher

Decor
0 or higher

Service
0 or higher

Cost
$134 or lower

1-15 OF 492 Sort by: **Relevance**

Uchi Restaurant
Japanese Bouldin Creek

FOOD	DECOR	SERVICE	COST
29	27	27	$73

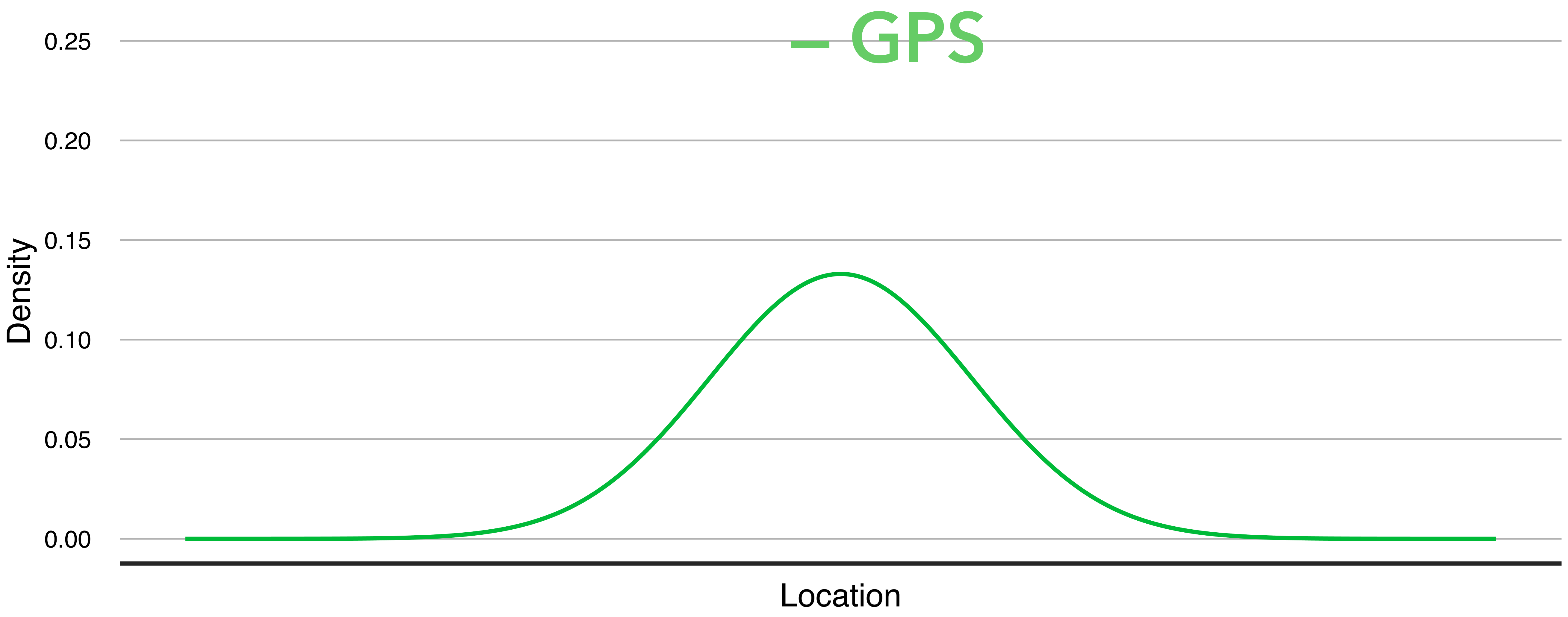
Franklin Barbecue
Barbecue East Austin

FOOD	DECOR	SERVICE	COST
28	20	23	$23

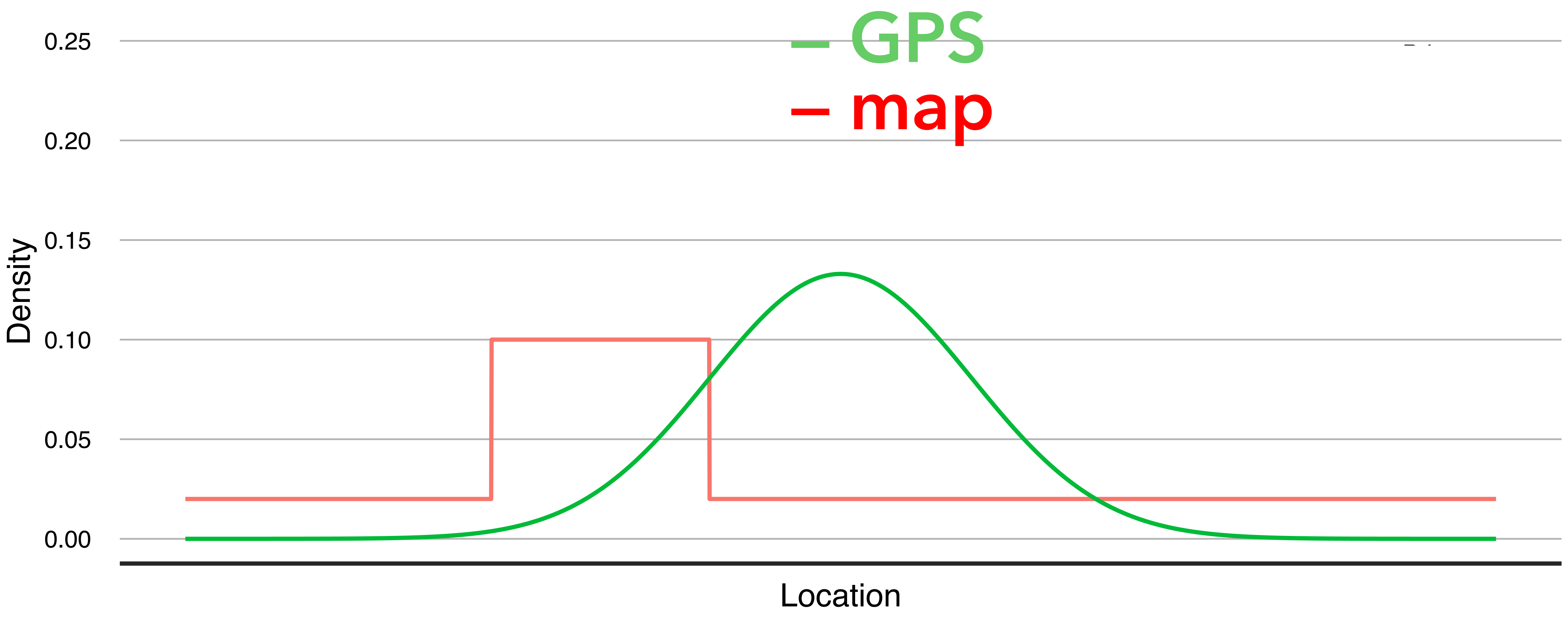
Uchiko
Japanese Rosedale

FOOD DECOR SERVICE COST

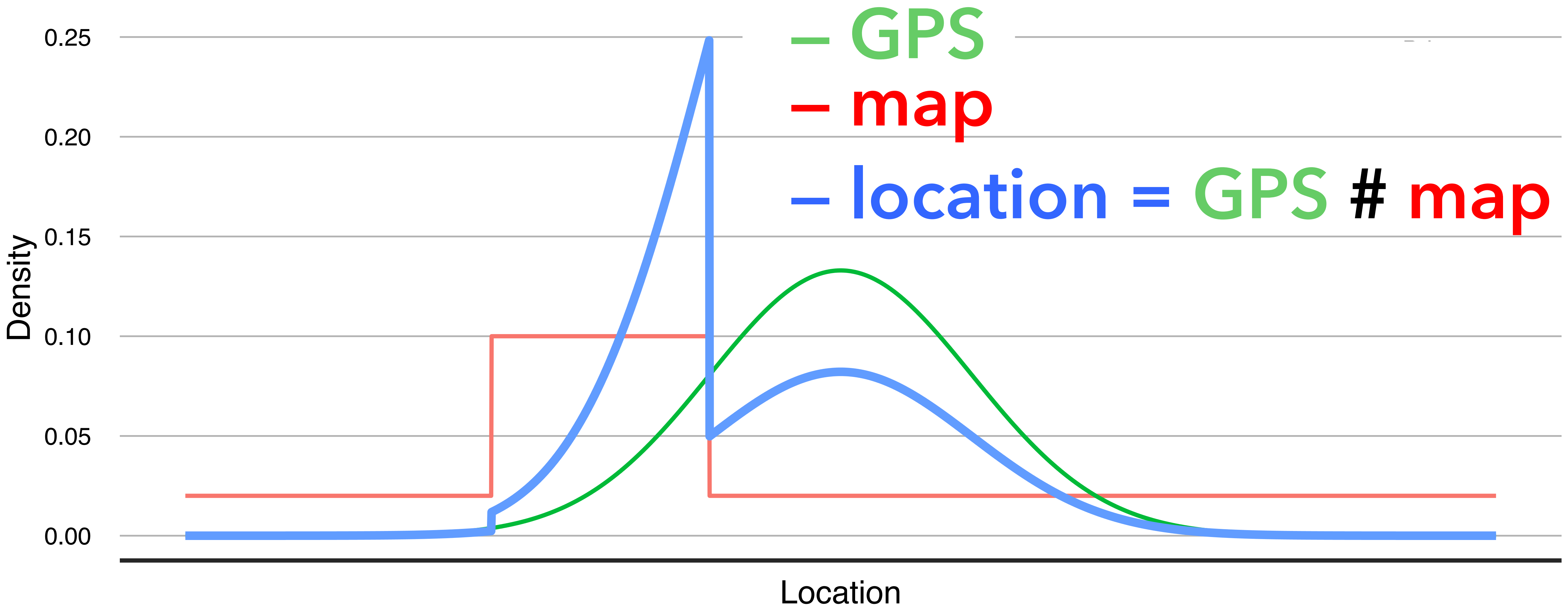
Adding domain knowledge



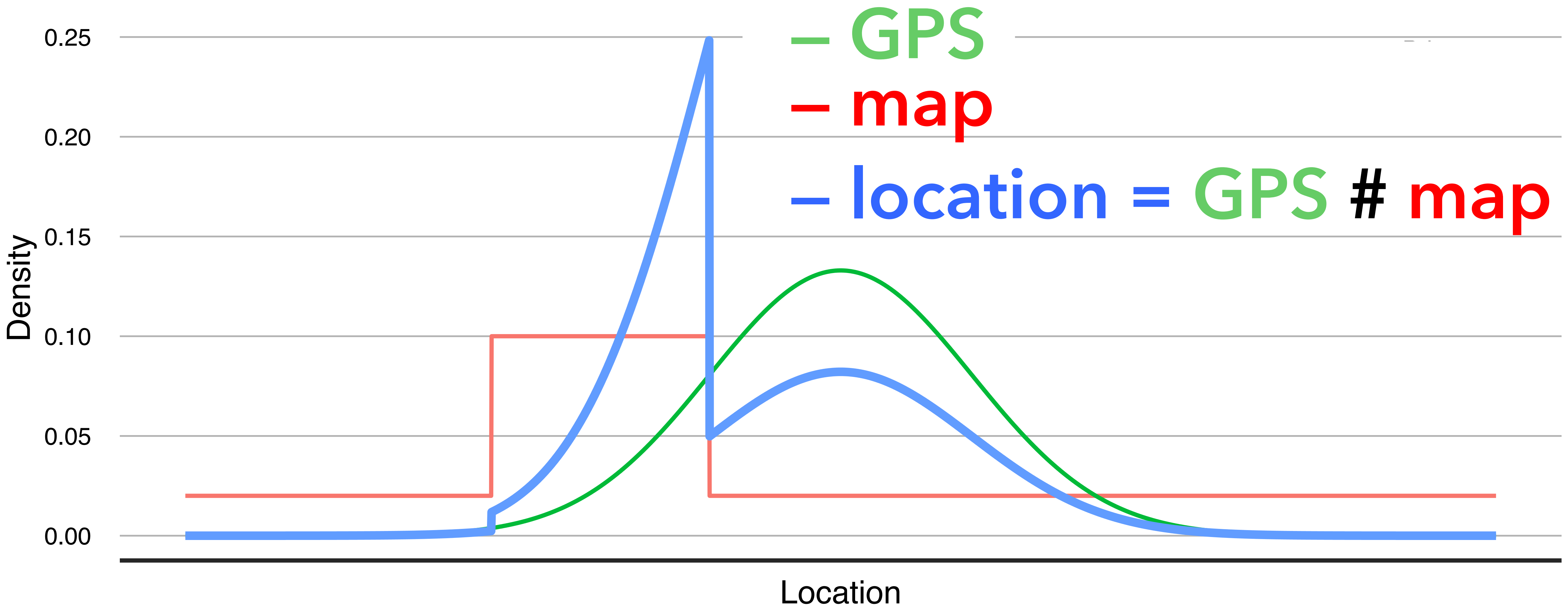
Adding domain knowledge



Adding domain knowledge



Adding domain knowledge



Bayes Rule

posterior likelihood prior

$$\mathbf{Pr}\,[H|E] = \mathbf{Pr}\,[E|H]\;\mathbf{Pr}\,[H] \,/\, \mathbf{Pr}\,[E]$$

Two constructs

<|

Building probability distributions

conditional probability

#

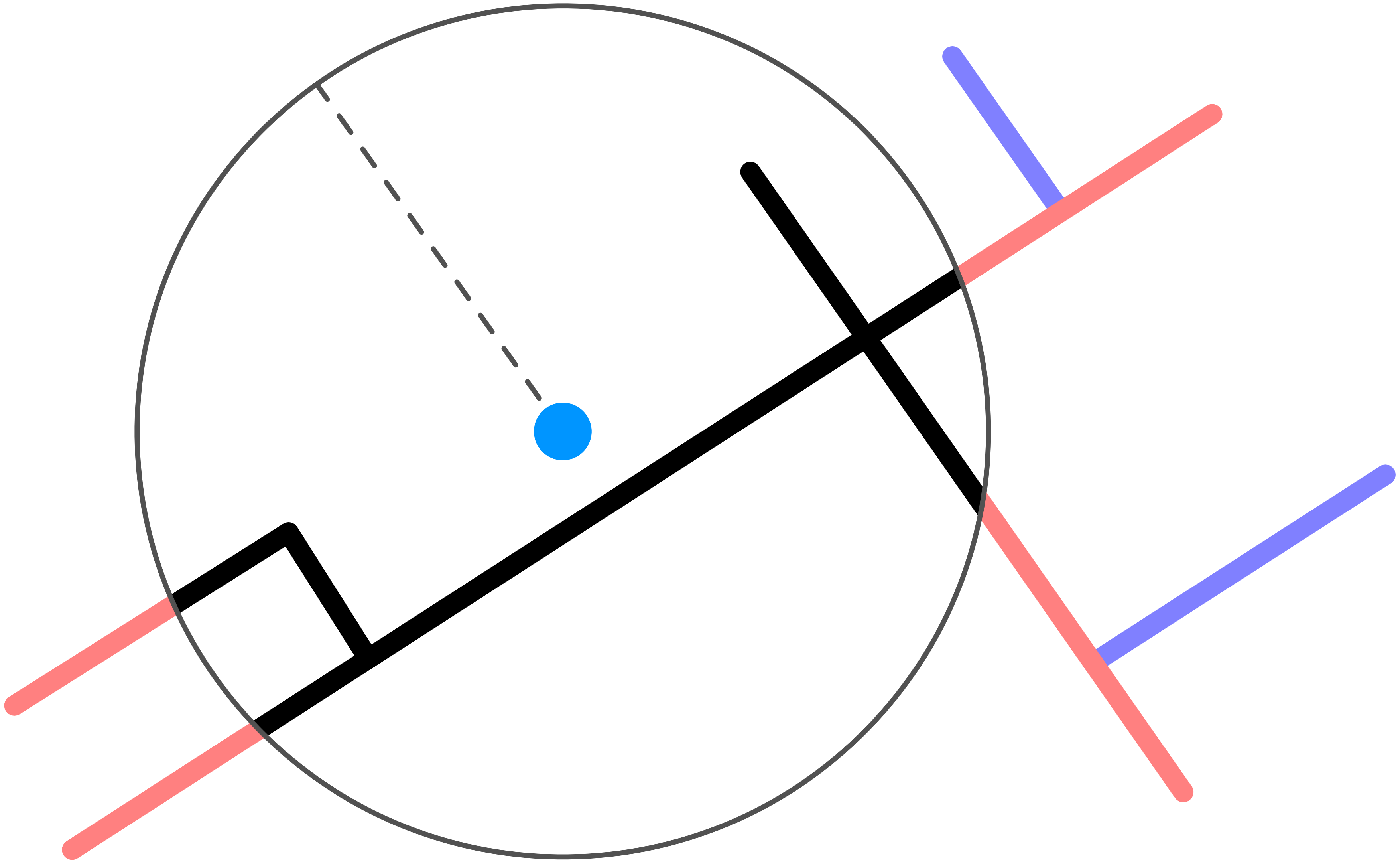
Composing context and estimates

Bayesian inference

Implementation a new *sequential likelihood reweighting* algorithm

GPS navigation – road snapping

```
// find relevant roads
Uncertain<Point> roadPrior = new uncertain<Point>(()=>
SamplePrior(location, accuracy, radiusFactor, weight))
```



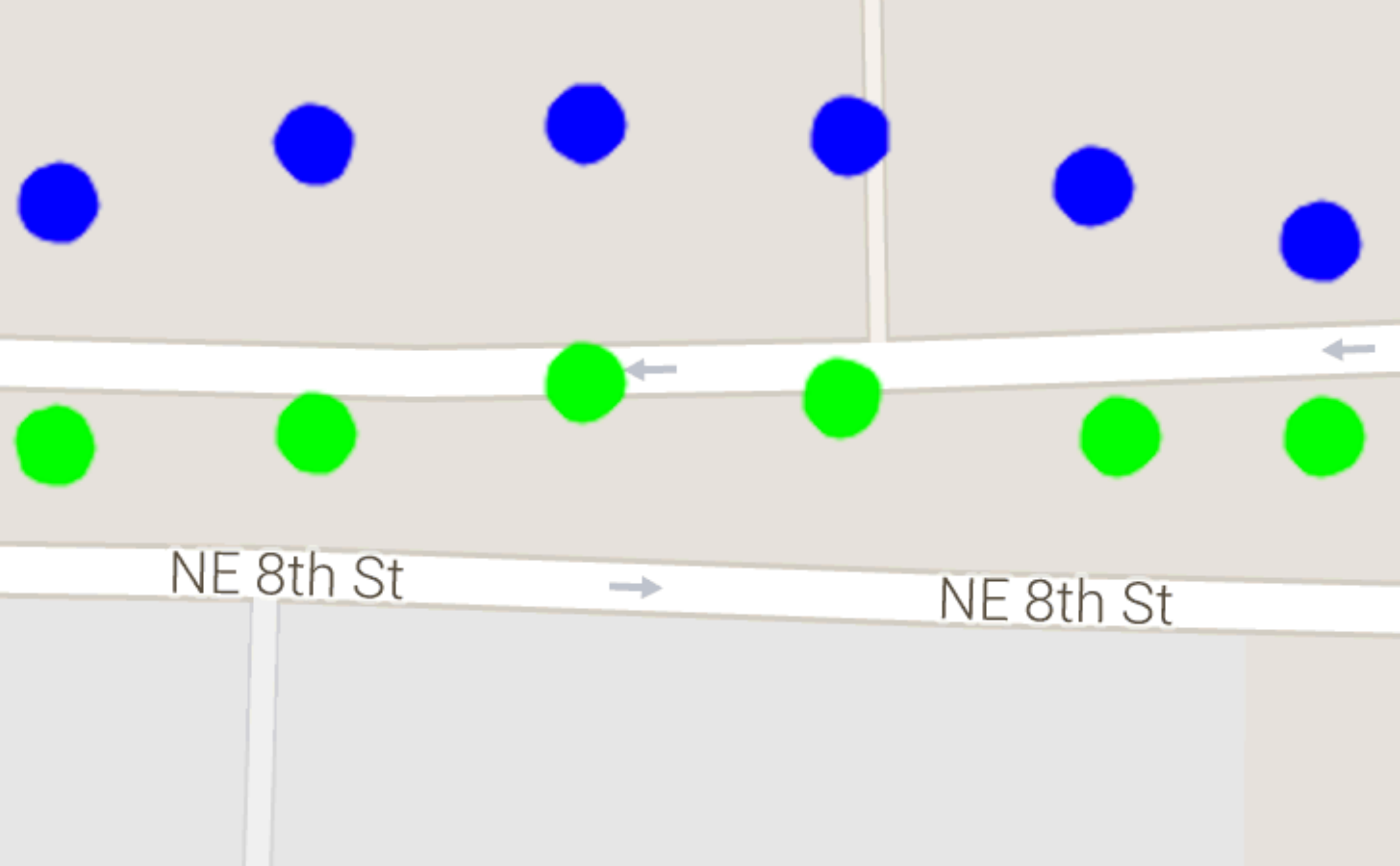
GPS navigation – road snapping

```
// find relevant roads
Uncertain<Point> roadPrior = new uncertain<Point>(()=>
SamplePrior(location, accuracy, radiusFactor, weight))

// improve location estimate
Uncertain<Point>
       NewLocation = GPSLikelihood # roadPrior
```

GPS navigation

Driver is *likely* on a road!

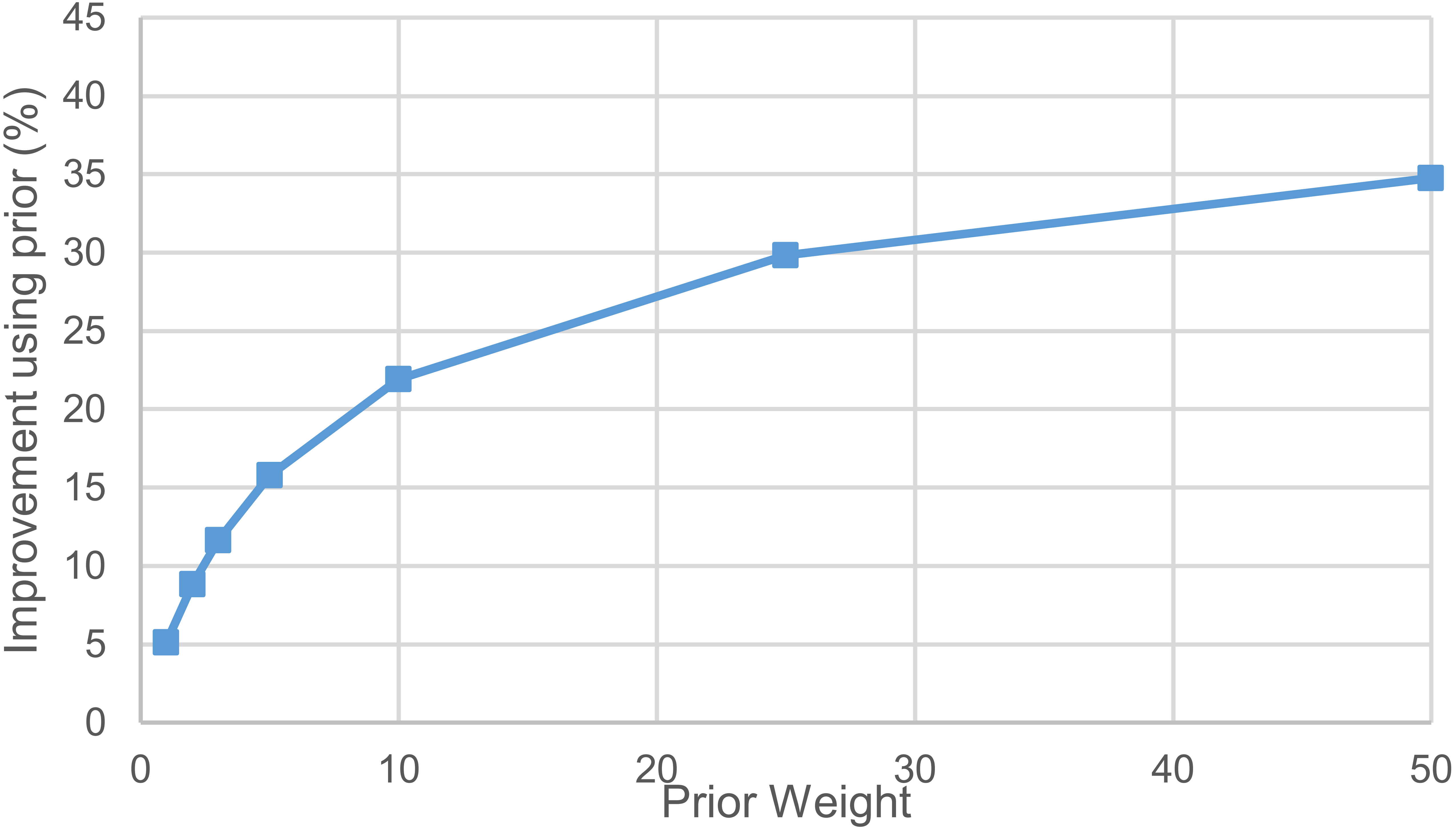
Driving on a road (or not!)



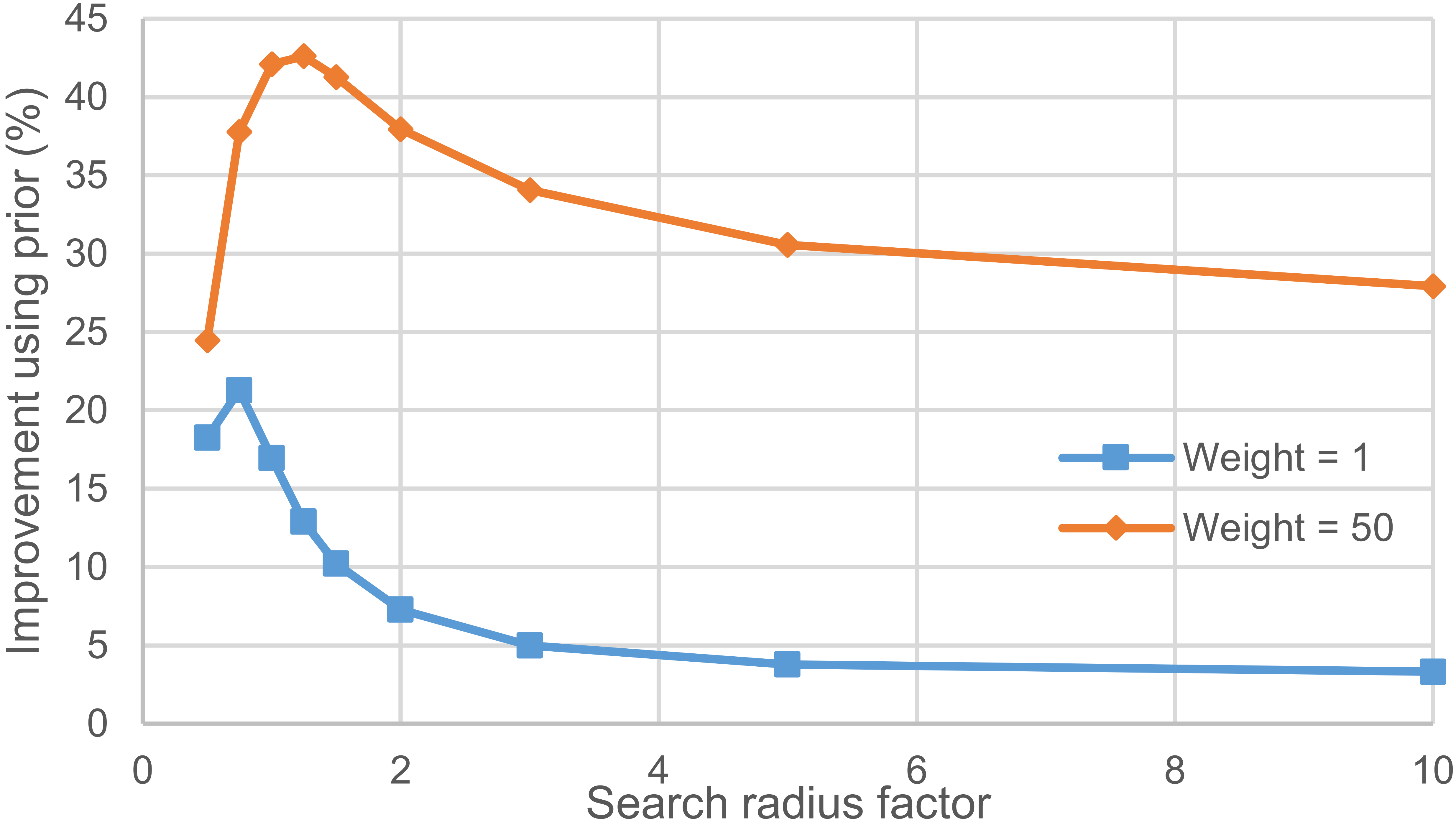
🔵 GPS

🟢 GPS + road snapping

Weighing the map prior

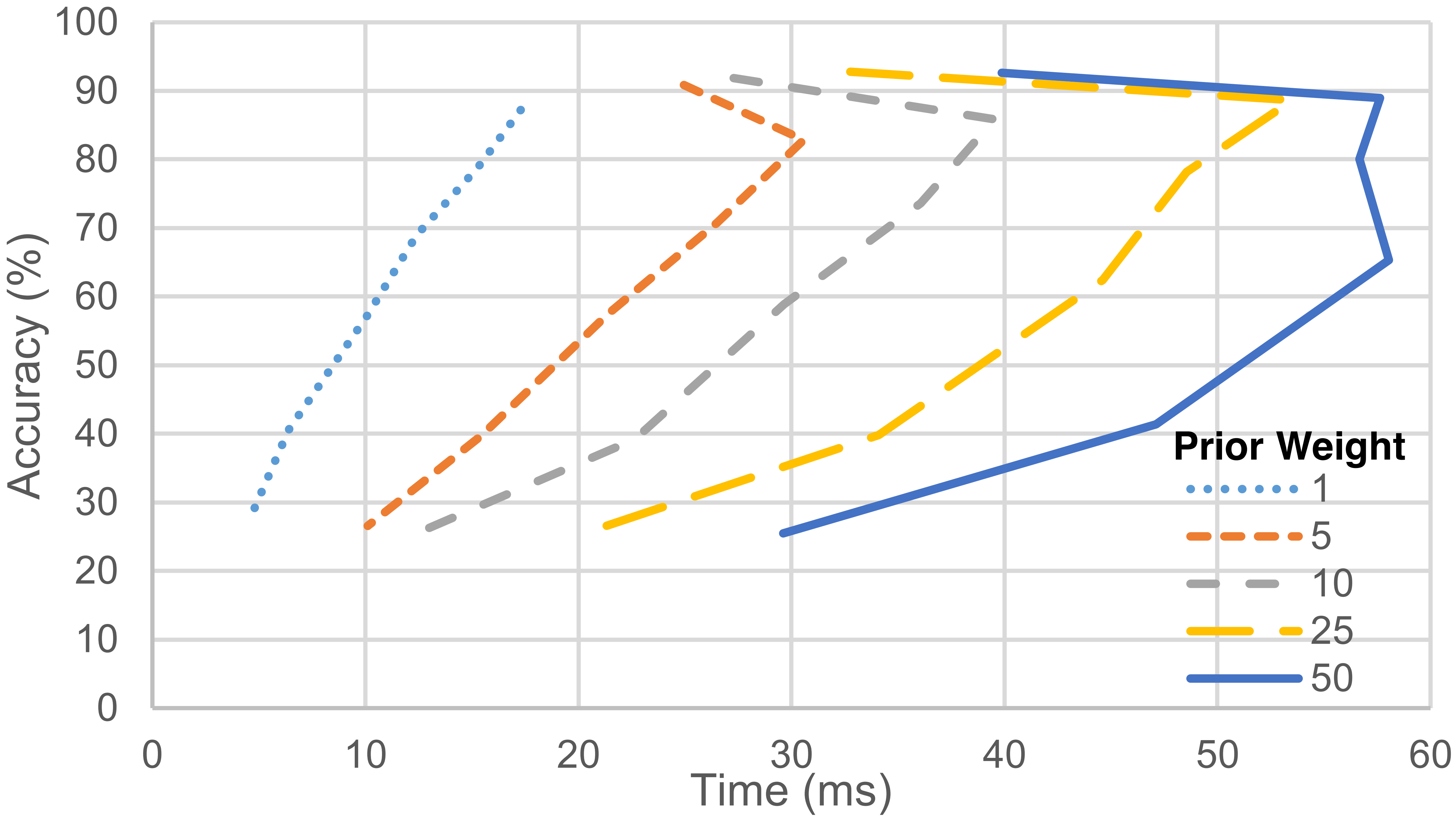


Map radius factor



Sequential likelihood reweighing

Time to sample as a function of prior strength



Uncertain<*T*>

an abstraction for reasoning about noise

[ASPLOS'14]

exploiting context

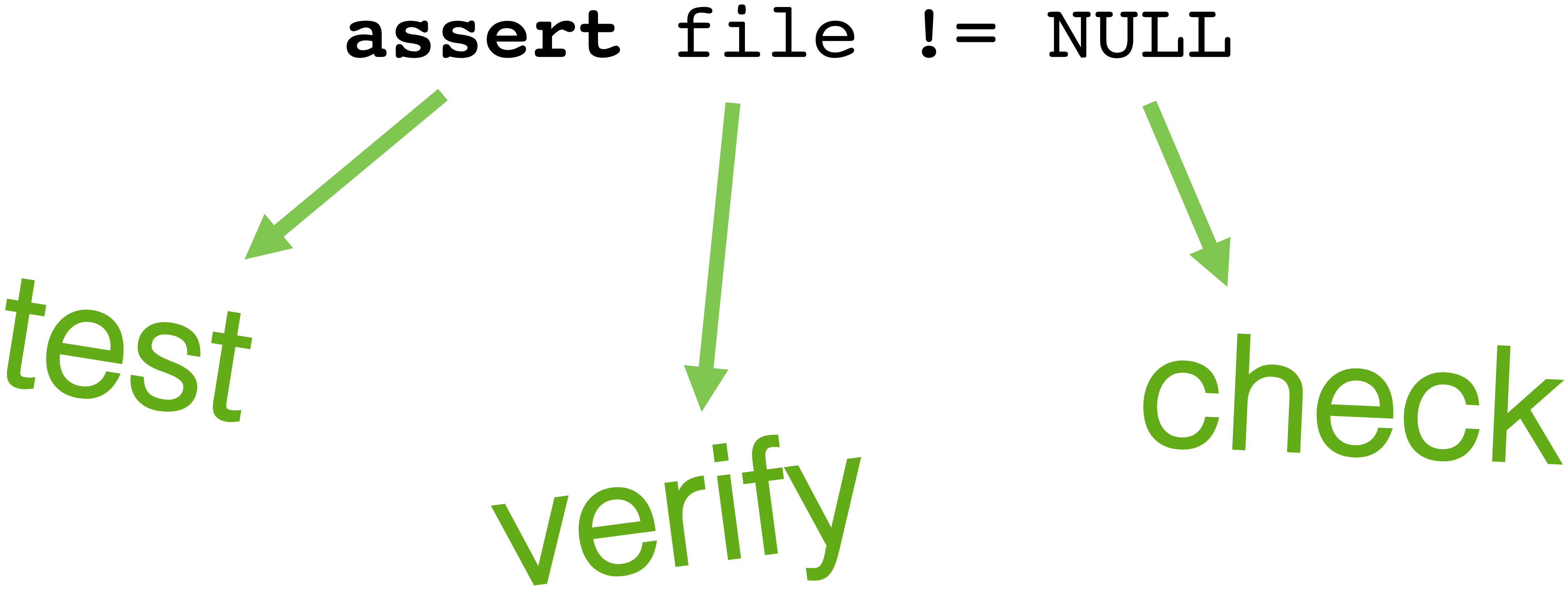
improving accuracy with more language & inference

[rejected so far]

what does it mean?

probabilistic assertions

[PLDI'14]



```
assert file != NULL
```

test

verify

check

`assert` *e*

e must hold on every execution

≈

Approximate computing

The approximate image is close to the precise version

k-means clustering is likely to converge on unreliable hardware

`assert` *e*

e must hold on **every** execution

Obfuscation for privacy

obfuscated data is still useful in aggregate

Sensing

within 5 mph of actual speed

≈

Approximate computing

The approximate image is close to the precise version

k-means clustering is likely to converge on unreliable hardware

Traditional assertions are **insufficient** for programs with **probabilistic behavior**

Obfuscation for privacy

obfuscated data is still useful in aggregate

Sensing

within 5 mph of actual speed

Assertions are insufficient for data obfuscation

```
true_avg = average(salaries)
private_avg =
  average(obfuscate(salaries))
assert true_avg - private_avg
       <= 10,000
```

Assertions are insufficient for data obfuscation

```
true_avg = average(salaries)
private_avg =
  average(obfuscate(salaries))
~~assert~~ true_avg - private_avg
       <= 10,000
```

probability distribution

Assertions

`assert` e

Probabilistic assertions

passert e, p, c

Probabilistic assertions

`passert` *e*, *p*, *c*

e must hold with probability *p*
at confidence *c*

Probabilistic assertion

```
true_avg = average(salaries)
private_avg =
  average(obfuscate(salaries))
passert (true_avg - private_avg
      <= 10,000), 90, 99
```

Verification

probabilistic program

```
float obfuscated(float n) {
  return n + gaussian(0.0, 1000.0);
}
float average_salary(float* salaries) {
  total = 0.0;
  for (int i = 0; i < COUNT; ++i)
    total += obfuscated(salaries[i]);
  avg = total / len(salaries);
  p_avg = ...;

 passert e, p, c
```

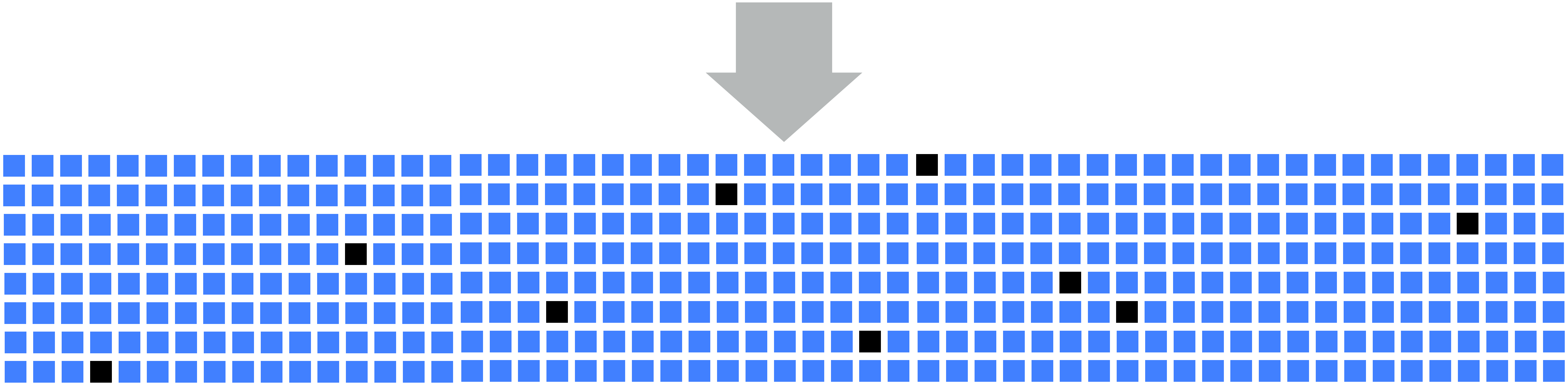
?

Naïve verification

probabilistic program

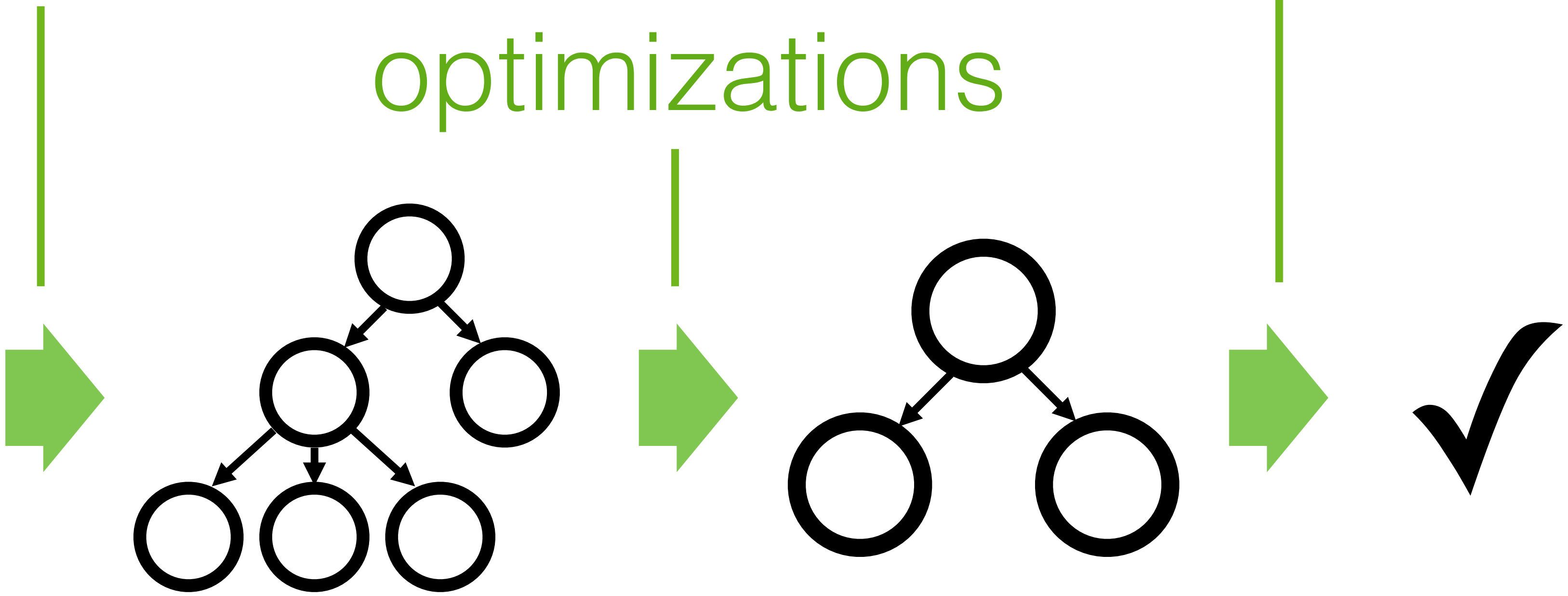
```
float obfuscated(float n) {
  return n + gaussian(0.0, 1000.0);
}
float average_salary(float* salaries) {
  total = 0.0;
  for (int i = 0; i < COUNT; ++i)
    total += obfuscated(salaries[i]);
  avg = total / len(salaries);
  p_avg = ...;

 passert e, p, c
```

?



Efficient verification

```
float obfuscated(float n) {
  return n + gaussian(0.0, 1000.0);
}
float average_salary(float* salaries) {
  total = 0.0;
  for (int i = 0; i < COUNT; ++i)
    total += obfuscated(salaries[i]);
  avg = total / len(salaries);
  p_avg = ...;
passert e, p, c
}
```



distribution extraction
via symbolic execution

statistical
optimizations

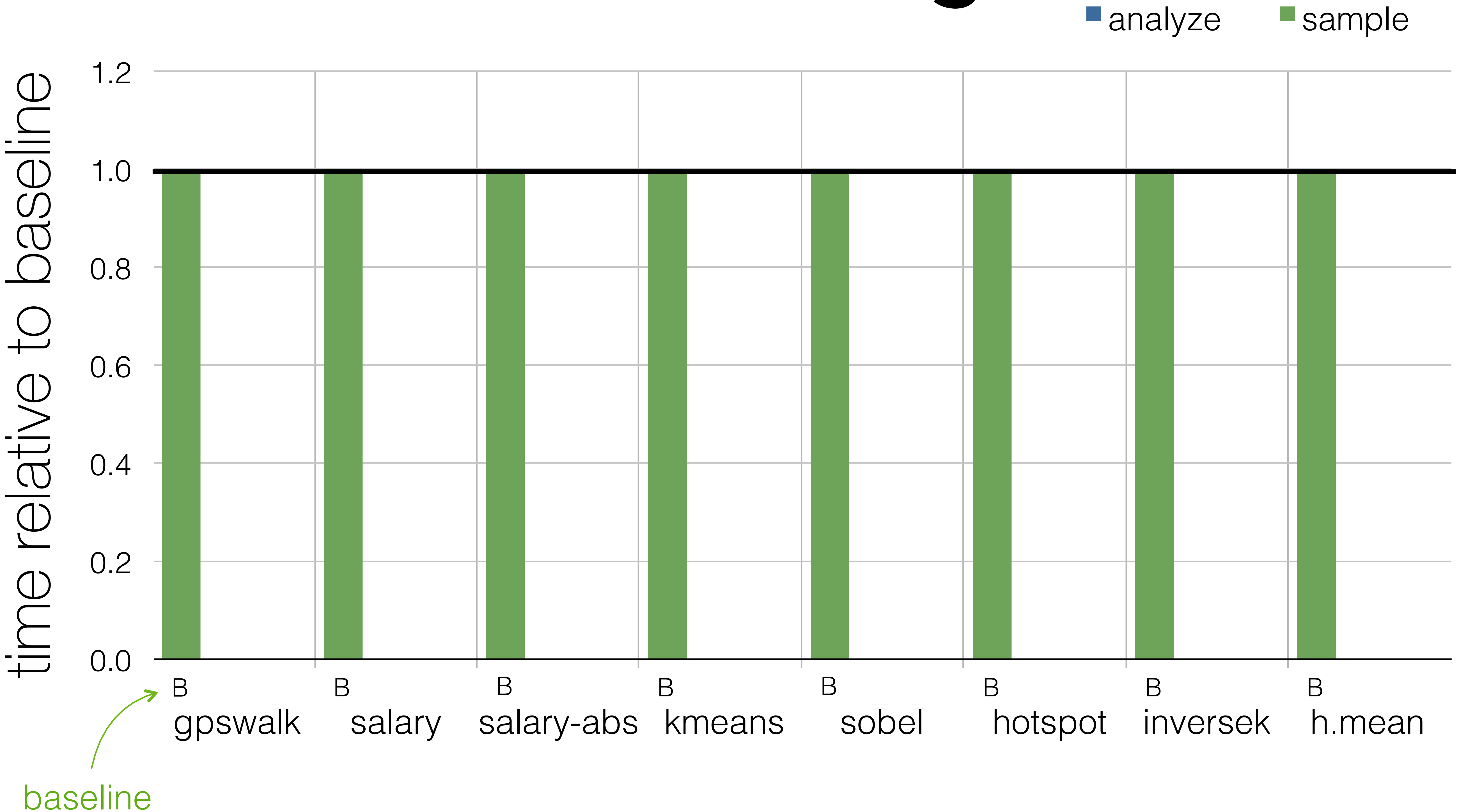
verification

Bayesian network
IR

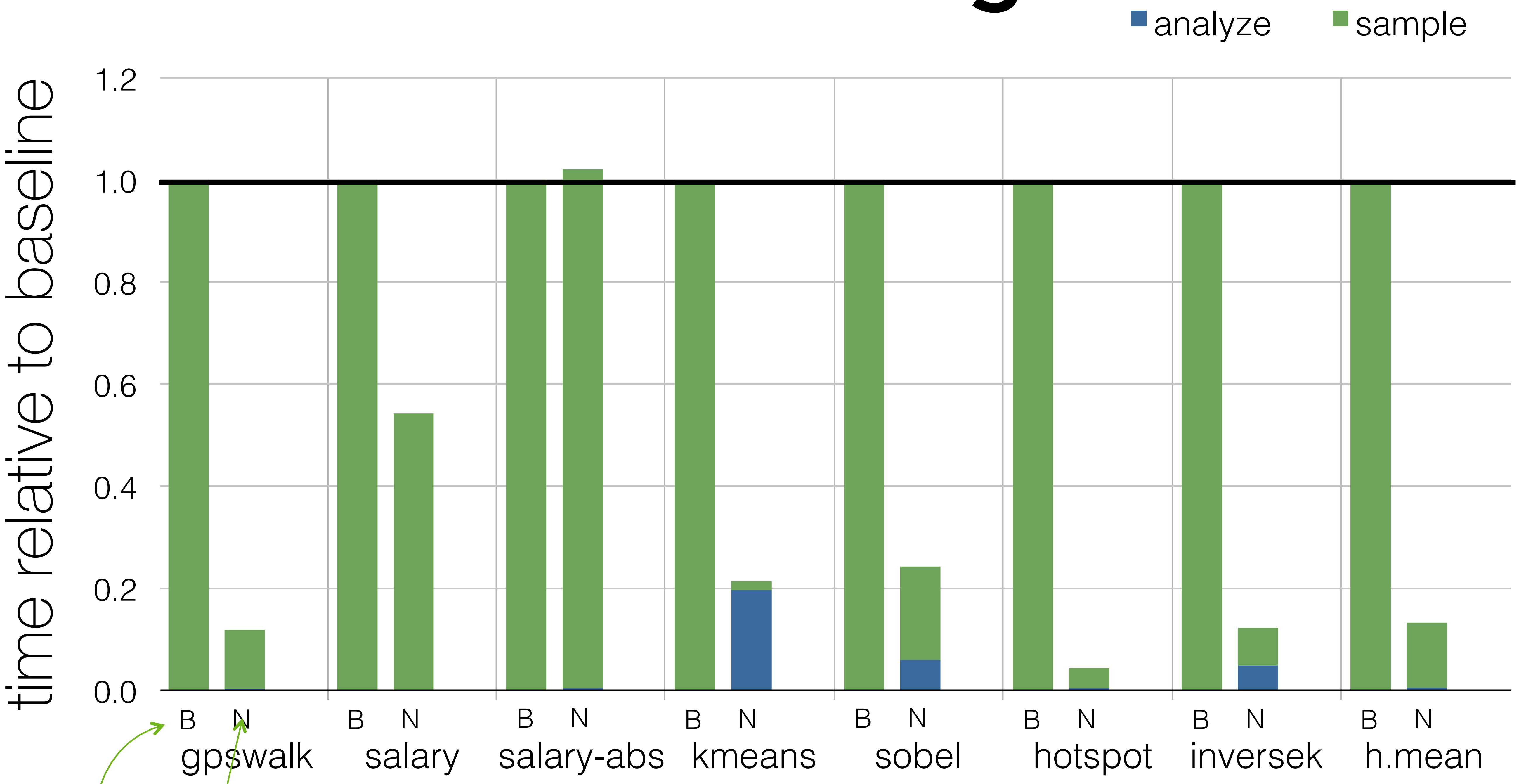
Evaluation

sensing	gpswalk
privacy	salary salary-abs
approximate computing	kmeans sobel hotspot inversek2j

Time vs Stress Testing



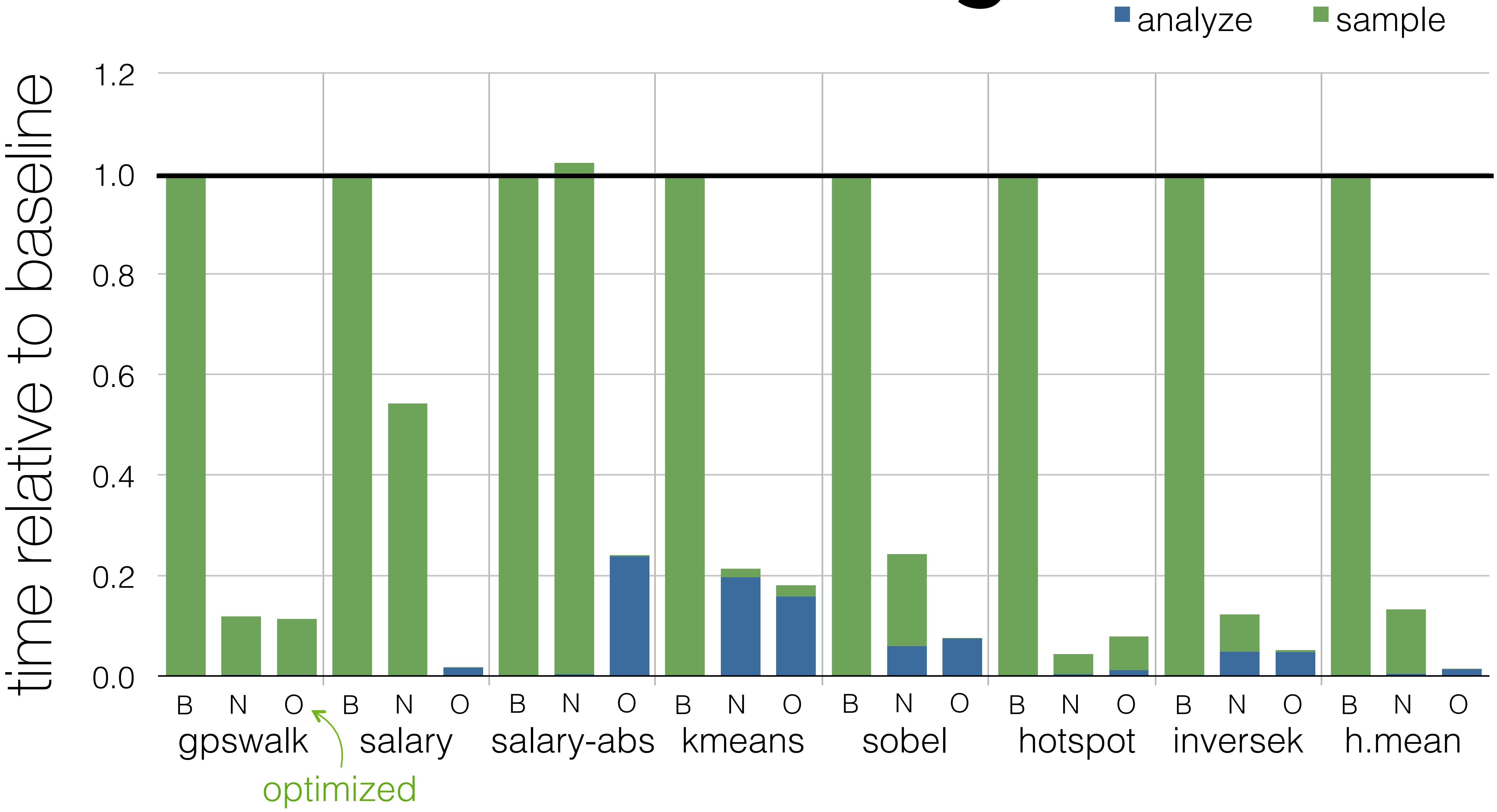
Time vs Stress Testing



baseline

no statistical optimizations

Time vs Stress Testing



- 24× faster than baseline verifier on average
- Mostly analysis time

Uncertain<*T*>

an abstraction for reasoning about noise

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[rejected so far]

what does it mean?

probabilistic assertions

[PLDI'14]

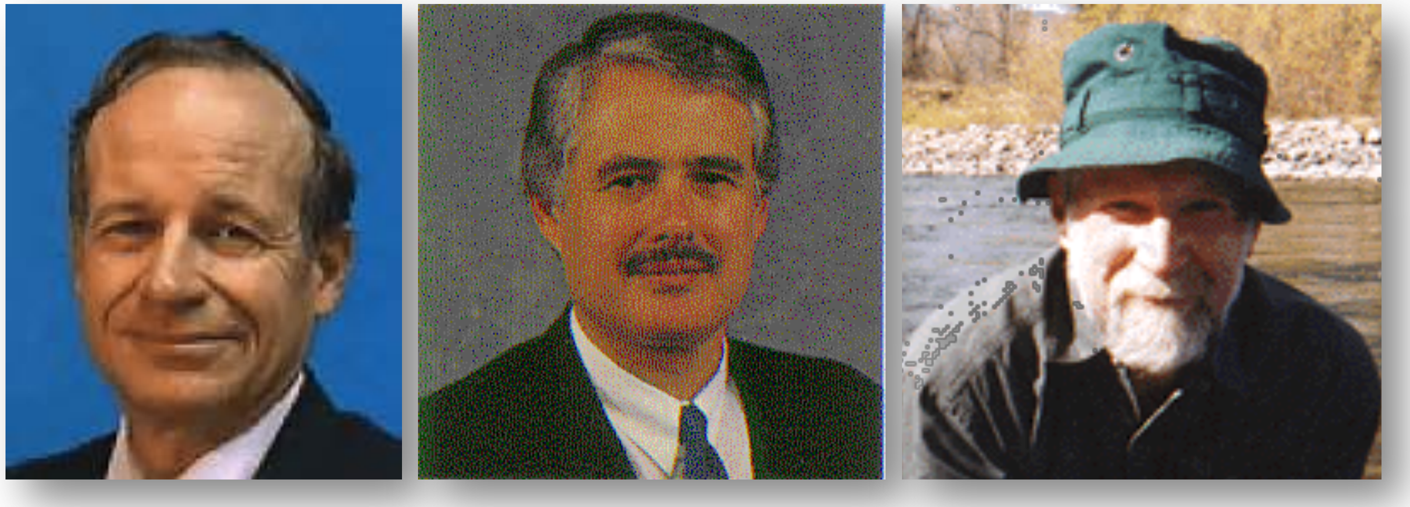
1985 IEEE floating point

Computing is at a similar point in history for estimates

Thank you!

A Byte of My Story

A Byte of My Story



Mentors

ACM Fellow

Family

Congressional Testimony

Fail, learn, succeed, repeat

- Rejected job applications
  - 1984 (all), 1993 (8 of 11), 2011 (4 of 8)
- Failed PhD qualifying exam
- Rejected first three grant applications
- Rejected 3 times one of my most cited papers
- Rejected papers, grants, papers, …