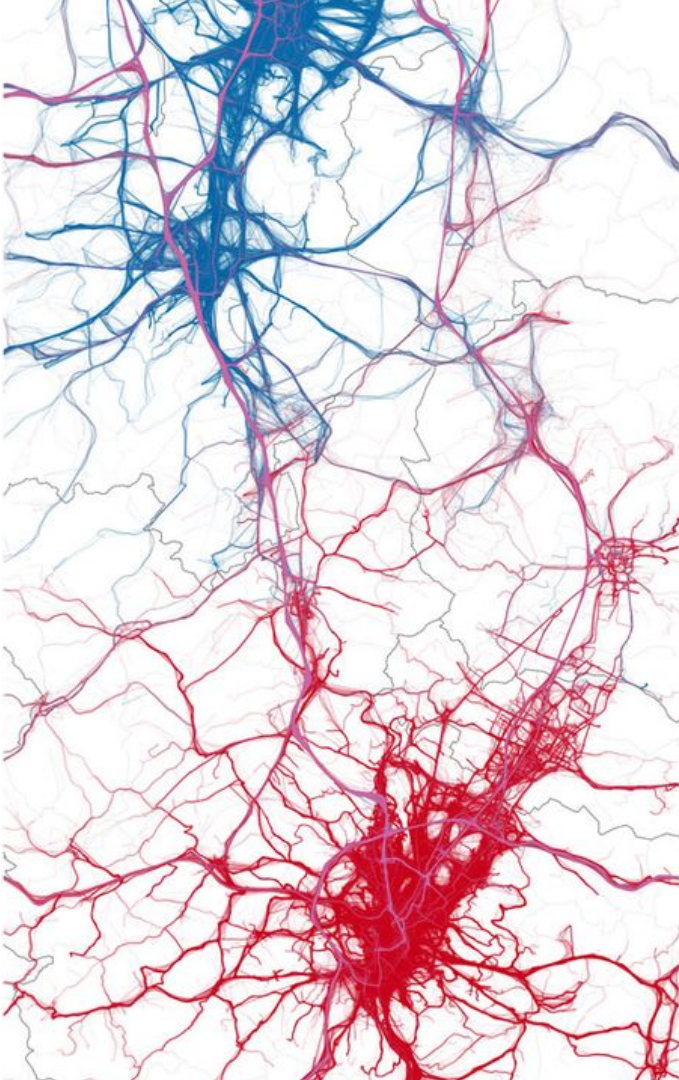




Consiglio Nazionale
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Individual mobility laws

Understanding the laws of individual human mobility

- is there a typical traveling distance?
- can we profile individuals according to their mobility behavior?
- to what extent are humans predictable?

Modelling individual human mobility

- What determines the decision to start a trip?
- What determines the choice of the destination?
- What determines the decision to come back home or to explore new locations?
- Can we generate realistic individual trajectories?

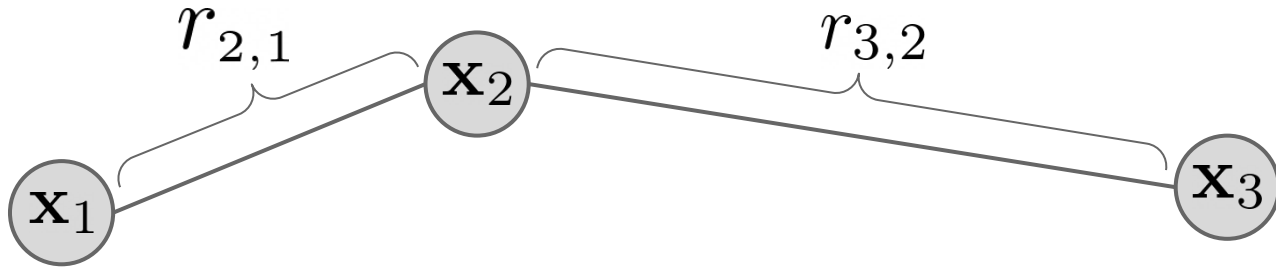
Distances

Travel distance (jump length)

Distance between
two consecutive locations
visited by a moving object

$$r = \left| \mathbf{x}_2 - \mathbf{x}_1 \right|$$

Earth distance





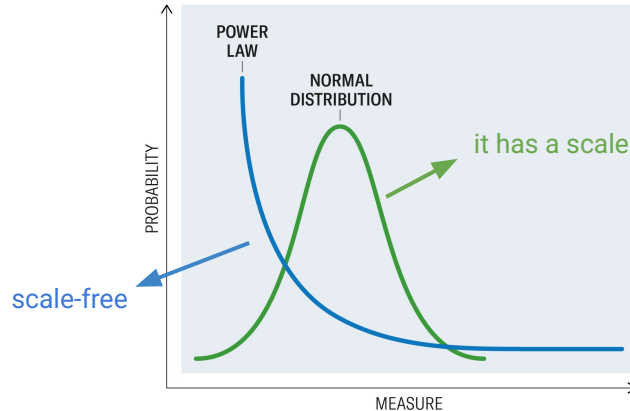
Travel distance probability

$P(r)$ = probability of finding a trip of length r

A Pareto Distribution vs. a Gaussian Curve

A normal distribution (i.e., a Gaussian curve) is bell-shaped, whereas a Pareto distribution (i.e., power law) is shaped like a hockey stick with long tails.

What's the shape of this distribution?





Tracking of dollar bills

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Welcome to Where's George?

To get started tracking your bills, please select below

I found a Where's George? bill, and I want to see where it has been

[click here](#)

I want to enter and track my own Where's George? dollar bills

[click here](#)

By entering this bill, you will help maintain the tracking of the journey this bill has made. Additionally, you will get back a list of all the cities, states, and countries where your bill has been recorded, as well as travel time and distance along its journey.

You can start and enter your own bills to track! You will need to **Register** before entering your own bills so you can be notified when your bills are found next.

[Show Me an Example of a Bill Tracking Report](#)

Portions U.S. Patent #8,682,917

309,182,332 Total Bills Entered

\$1,662,473,399 Total Dollar Value

1,117 Bills Entered Today

118 Hits Today

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CURRENCY TRACKING PROJECT

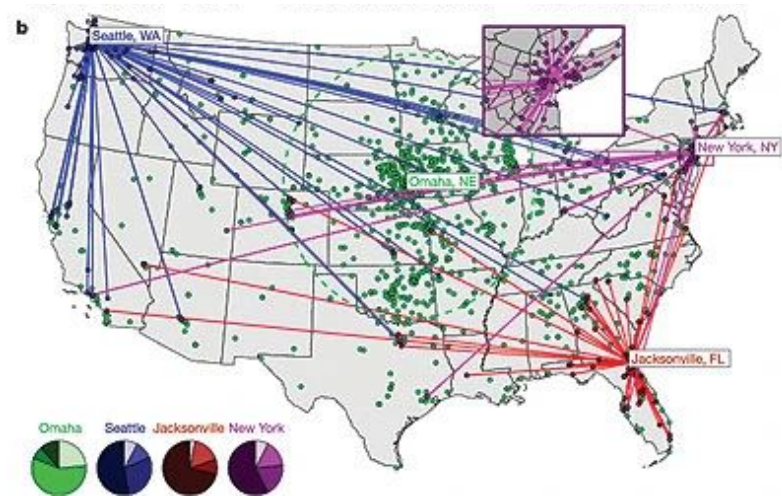


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UNITED STATES CURRENCY TRACKING PROJECT

Tracking of dollar bills

Brockmann et al., 2006:

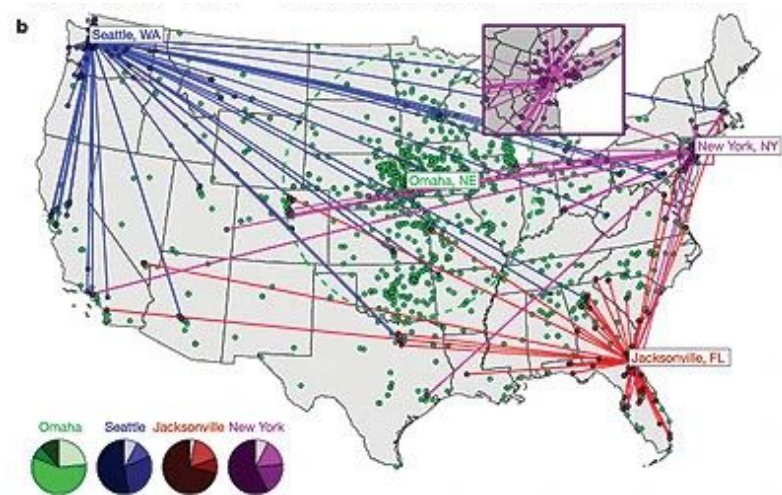
- Dollar bills: 464,670
- Records: 1,033,095
- Area: US
(excluding Alaska and Hawaii)



Trajectories of bank notes originating from four different places with travelling time $T < 14$ days.

Tracking of dollar bills

- Most bank notes are reported close the initial entry, $r \leq 10km$
 - Seattle 53%, NYC 58%, Jacksonville 71%
- A small but **considerable** fraction is reported at large distances, $r > 800km$
 - Seattle 8%, NYC 7%, Jacksonville 3%



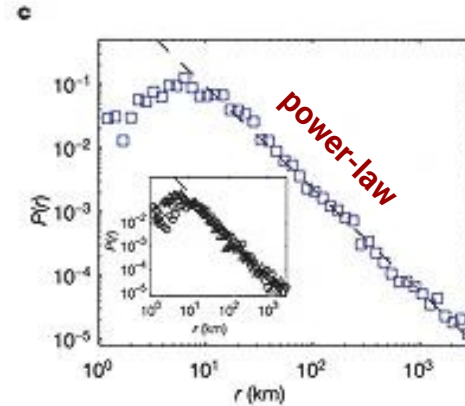
Trajectories of bank notes originating from four different places with travelling time $T < 14$ days.

Tracking of dollar bills

- Probability of traversing a distance in 1-4 days (20,540 bills)

$$P(r) \sim r^{-(1+\beta)}$$

$$\beta = 0.59 \pm 0.02$$



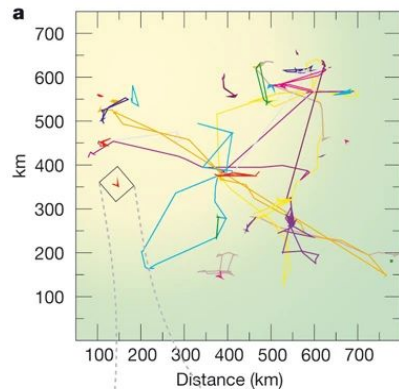
Measured $P(r)$ of traversing a distance in less than $T = 4$ days. The inset shows $P(r)$ for metropolitan areas, cities of intermediate size, small towns.



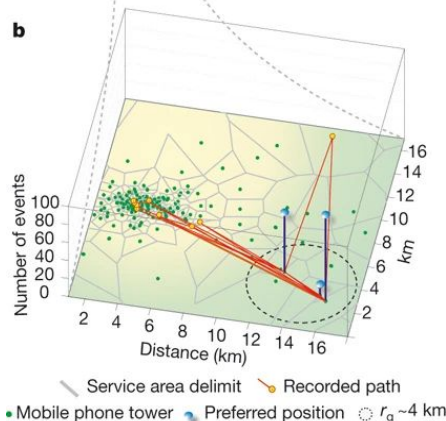
Mobile Phone Records

González et al., 2008:

- Dataset D1 (CDRs):
 - Users: 100,000
 - Records: 16,264,308
- Dataset D2 (CPRs):
 - Users: 206
 - Records: 10,407



Week-long trajectory of 40 mobile phone users

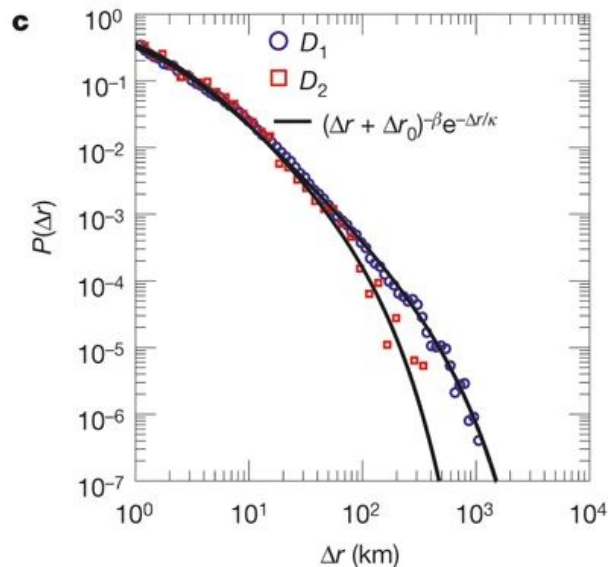


Detailed trajectory of a single user

- 186 two-hourly reports
- 12 locations.

The circle represents the radius of gyration centred in the user's centre of mass.

Mobile Phone Records



$$P(r) = (r + r_0)^{-\beta} \exp(-r/\kappa)$$

$$\beta = 1.75 \pm 0.15$$

$$r_0 = 1.5km$$

$$\kappa_{D_1} = 400km$$

$$\kappa_{D_2} = 80km$$

Measured $P(r)$ of travel distances obtained for D_1 and D_2 . The solid line indicates a truncated power law.

Radius of gyration

Characteristic distance
of an individual

$$r_g(u) = \sqrt{\frac{1}{n_u} \sum_{i=1}^{n_u} (\mathbf{r}_i - \mathbf{r}_{cm})^2}$$

Center of mass

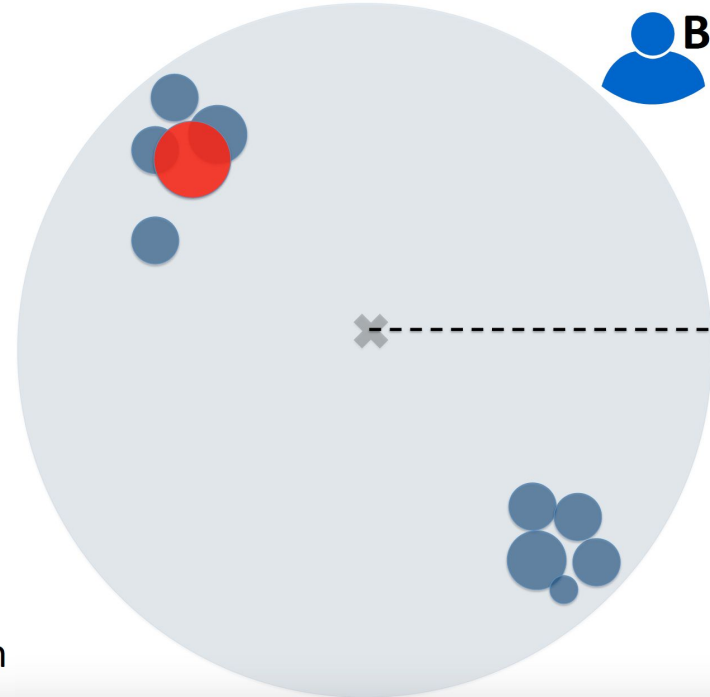
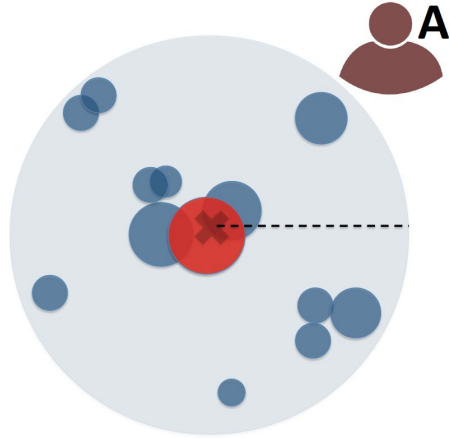
$$\mathbf{r}_{cm} = \frac{1}{n_u} \sum_{i=1}^{n_u} \mathbf{r}_i$$

n_u	number of records
$\mathbf{r}_i$	position

Radius of gyration

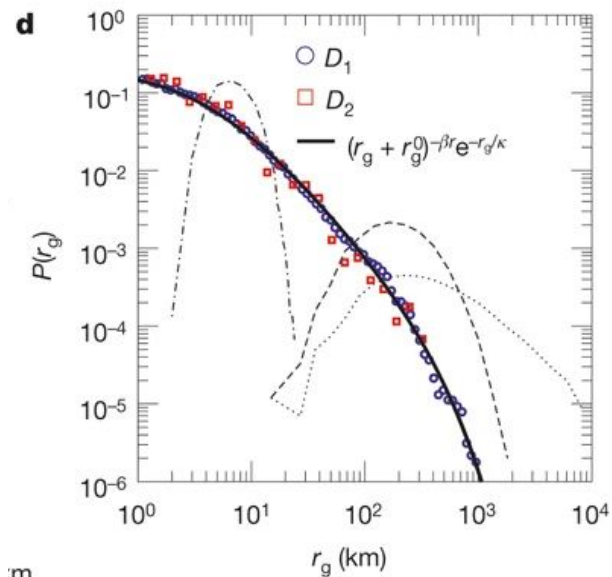
● home location

✕ center of mass



---- radius of gyration

Radius of gyration



$$P(r_g) = (r_g + r_g^0)^{-\beta_r} \exp(-r_g/\kappa)$$

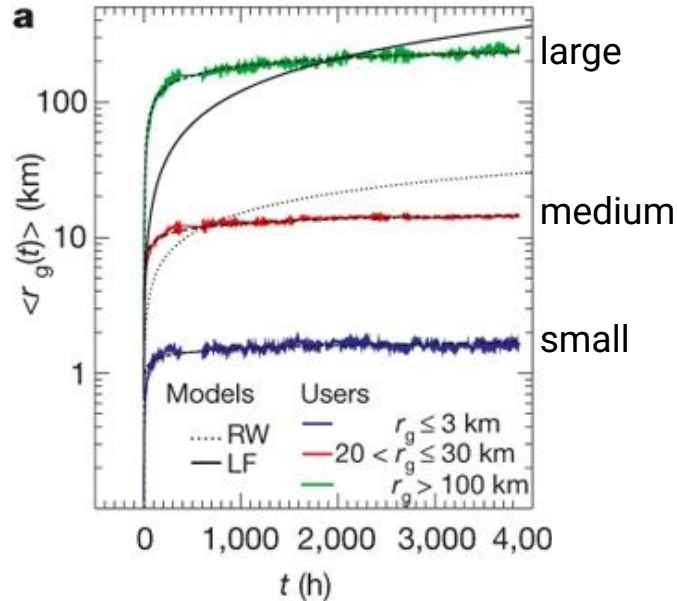
$$r_g^0 = 5.8 km$$

$$\beta_r = 1.65 \pm 0.15$$

$$\kappa = 350 km$$

Measured $P(r_g)$ on datasets D1 and D2. The dotted, dashed and dot-dashed curves show $P(r_g)$ obtained from null models

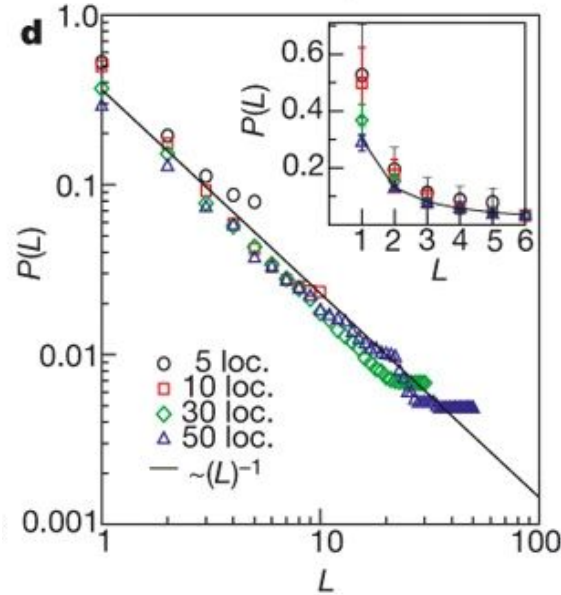
Radius of gyration - time evolution



- Radius increases logarithmically with time
 - Indicating a saturation process

Radius of gyration versus time for users of three groups. The black curves correspond to the analytical predictions for the random walk models. The dashed curves corresponding to a logarithmic fit.

Location frequency



- Rank each location based on how many times an individual is recorded there
 - E.g., $L=3$ is the third-most-visited location for an individual

$$P(L) \sim 1/L$$

Frequency of visiting locations for users observed to visit 5, 10, 30 and 50 locations. L is the rank of the location listed in the order of the visit frequency. 40% of the time individuals are found at their first two preferred locations

People devote most of their time to a few locations, spending their time to places with diminished regularity

k-radius of gyration

Recurrent
characteristic distance
of an individual

$$r_g^{(k)} = \sqrt{\frac{1}{N_k} \sum_{i=1}^k w_i (\mathbf{r}_i - \mathbf{r}_{cm}^{(k)})^2}$$

k-center of mass

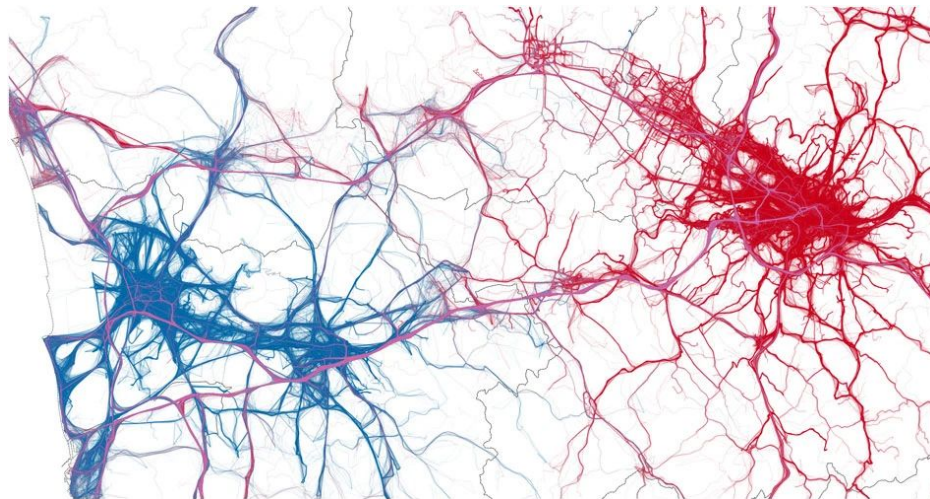
$$\mathbf{r}_{cm}^{(k)} = \frac{1}{N_k} \sum_{i=1}^k w_i \mathbf{r}_i$$

N_k number of records
in location k

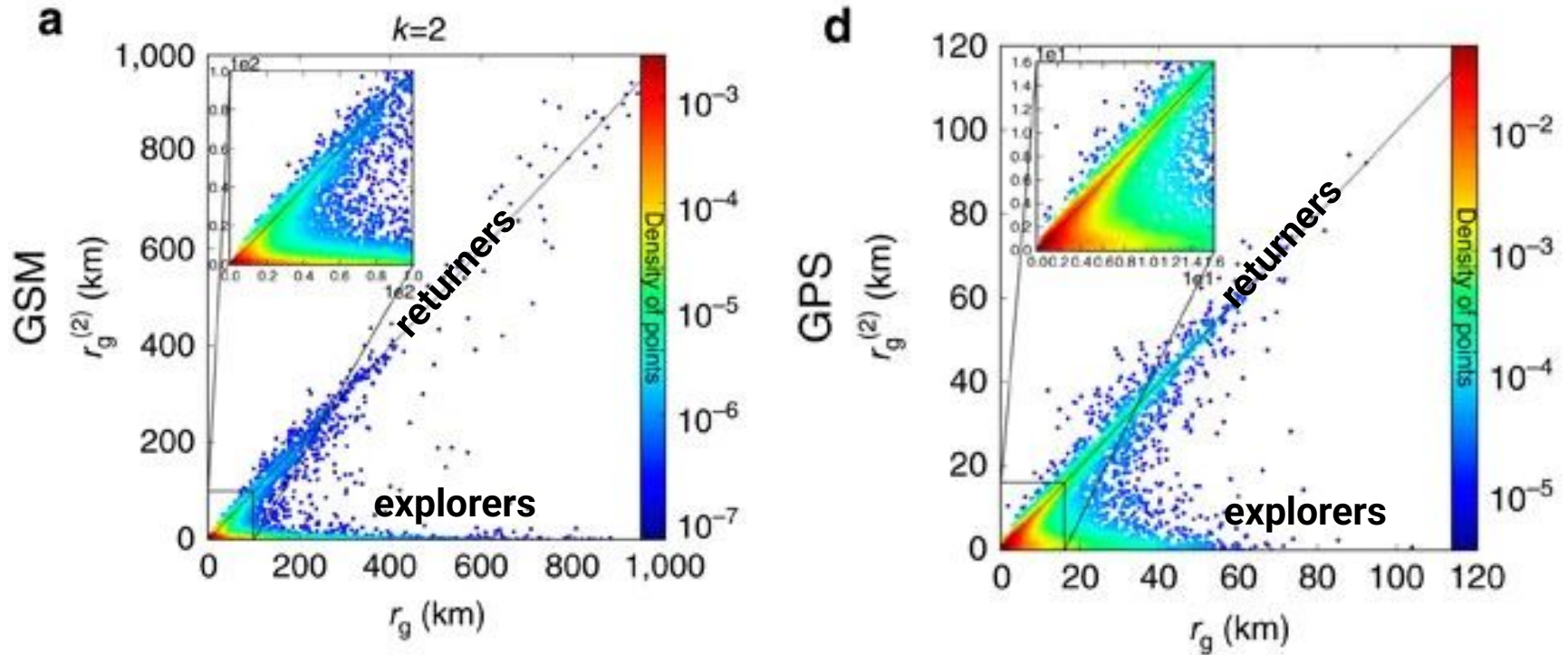
Mobile Phone Records

Pappalardo et al., 2015:

- CDRs:
 - Users: 67,000
- GPS traces:
 - Users: 46,000

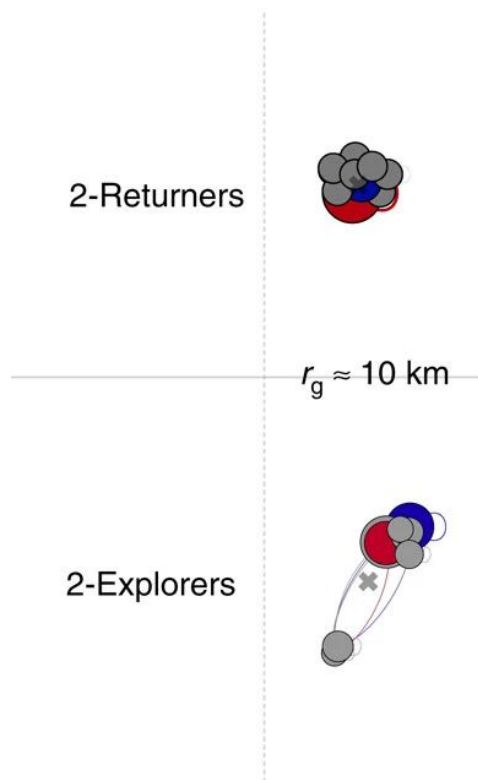


Returners and Explorers

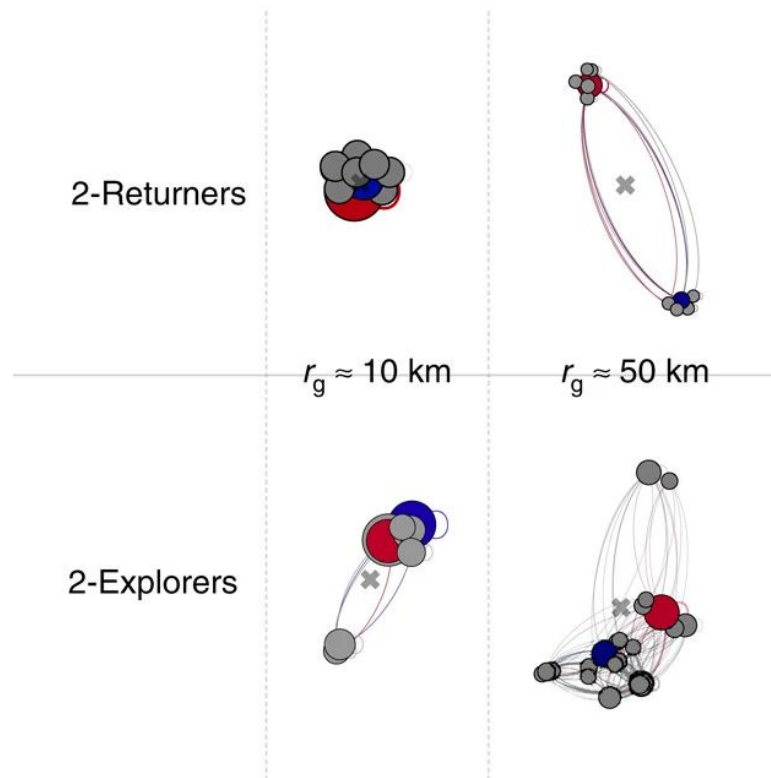


Correlation between total r_g and $r_g^{(k)}$ for $k=2, 4, 8$ for CDRs and GPS traces. Each point is coloured from blue to red, indicating the density of points in the corresponding region.

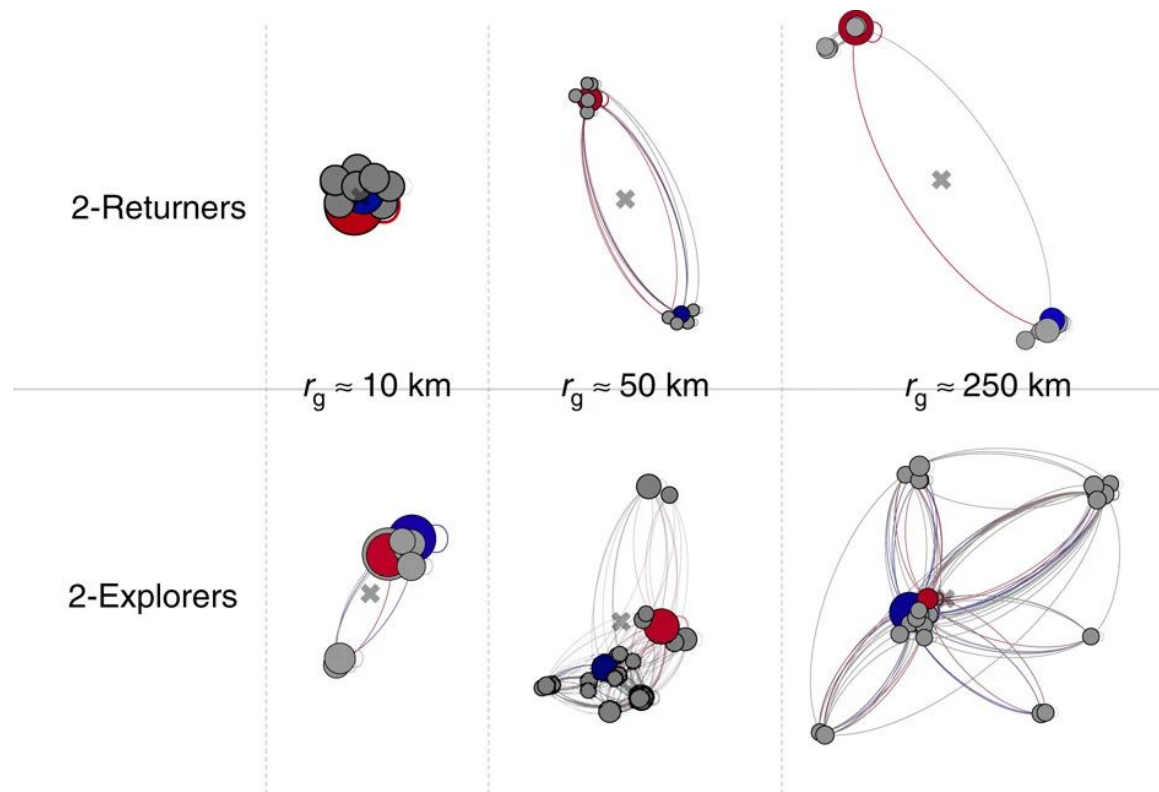
Returners and Explorers



Returners and Explorers

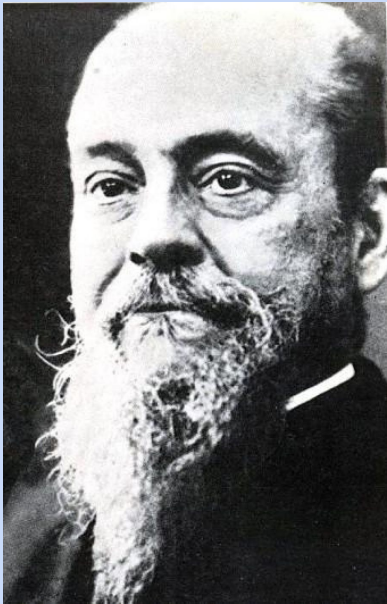


Returners and Explorers



INTERVALLO

Vilfredo Pareto and the 80/20 rule



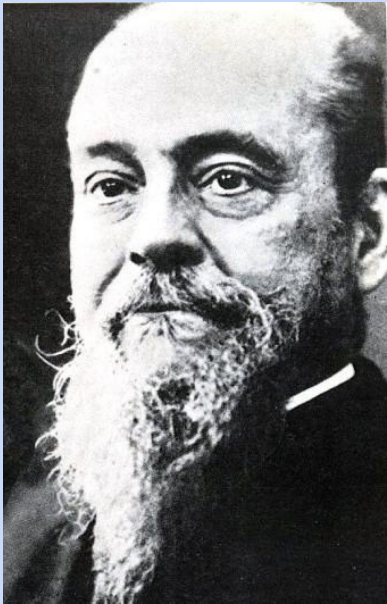
He noticed that in Italy a few wealthy individuals earned most of the money, while the majority of the population earned rather small amounts.

He connected this disparity to the observation that **incomes follow a power law**, representing the first known report of a power-law distribution.

The 80/20 rule: Roughly 80 percent of money is earned by only 20 percent of the population.

INTERVALLO

Vilfredo Pareto and the 80/20 rule

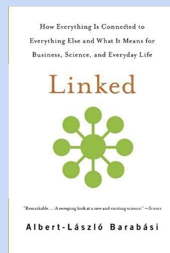


The 80/20 rule emerges in many areas:

- 80% of profits are produced by 20% of the employees
- 80% of decisions are made during 20% of meeting time
- 80% of links on the Web point to only 15% of webpages
- 80% of citations go to only 38% of scientist
- 80% of links in Hollywood connected to 30% of actors
- **The 1% phenomena:**
 - In the US, 1% of the population earns 15% of the total income
 - signature of income disparity, it is a consequence of the power-law nature of the income distribution

References

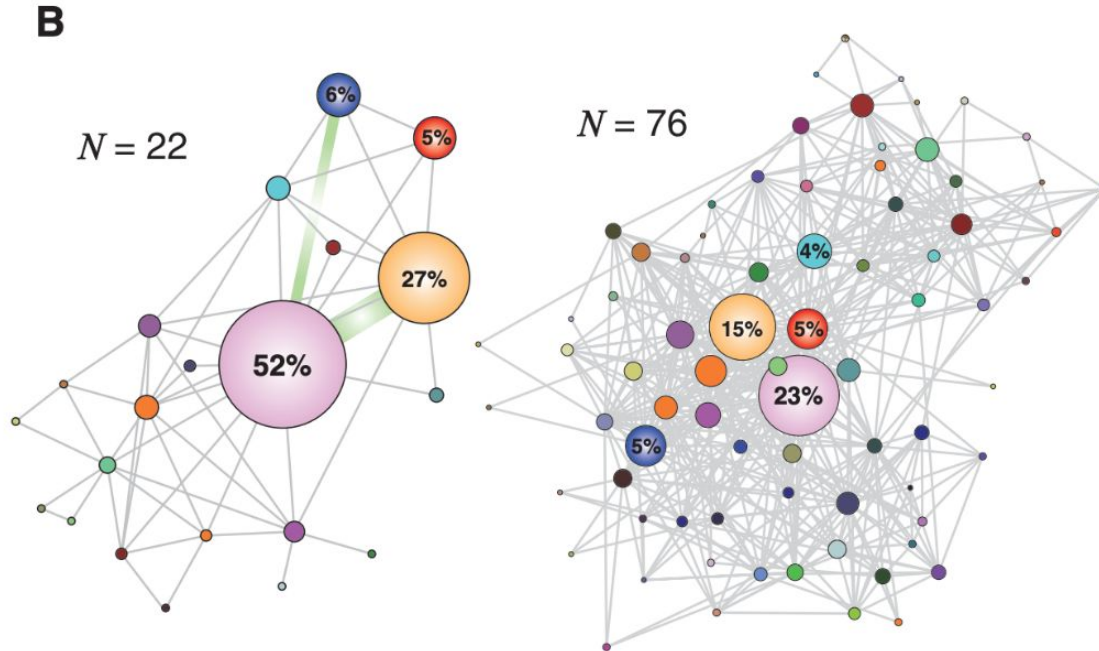
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Predictability

Individual Mobility Network

A network where nodes are an individual's visited locations and edges movements between locations



The role of randomness

1. What is the role of randomness in human mobility?
2. To what degree are our movements predictable?

Entropy

Random entropy

$$S^{rand} = \log_2 N$$

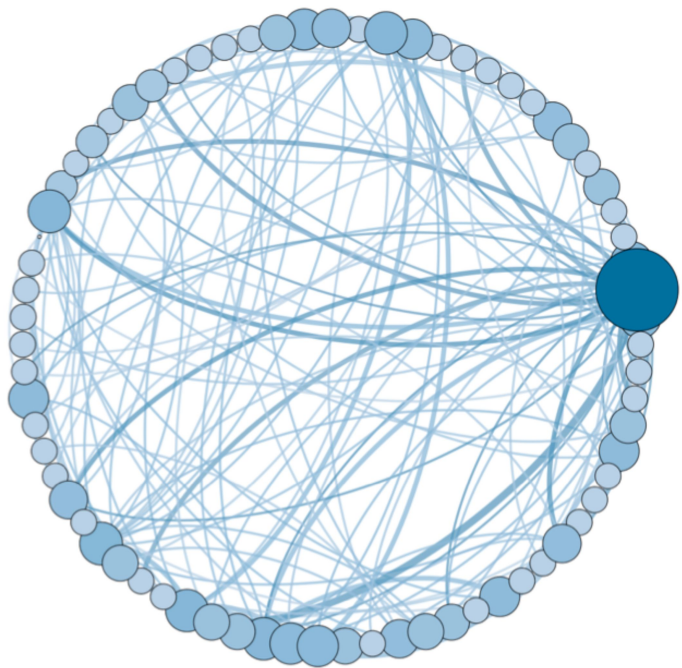
Uncorrelated entropy

$$S^{unc} = - \sum_{i=1}^n p_i \log_2 p_i$$

Real entropy

$$S = - \sum_{T'_i \subset T_i} p_{T'_i} \log_2 p_{T'_i}$$

Who's the most predictable?

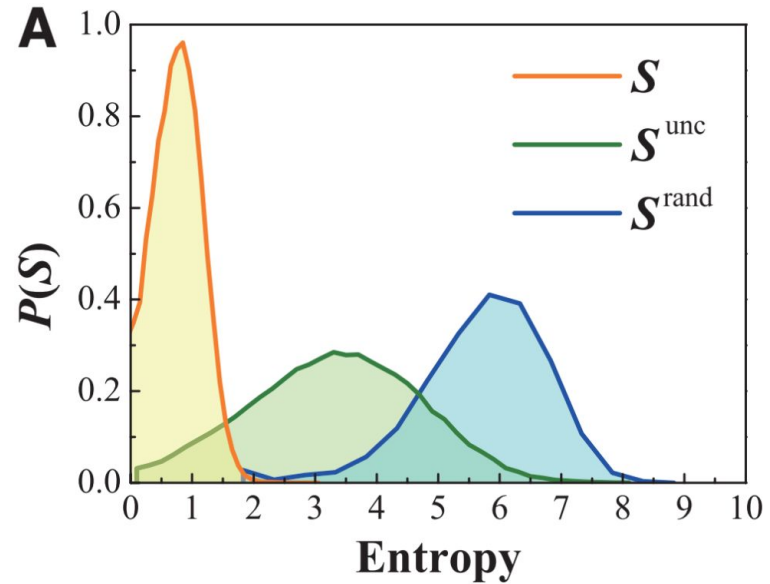


Entropy

Song et al., 2010:

- 50,000 users (CDRs)
- S peaks at 0.8

$$2^{0.8} = 1.74$$

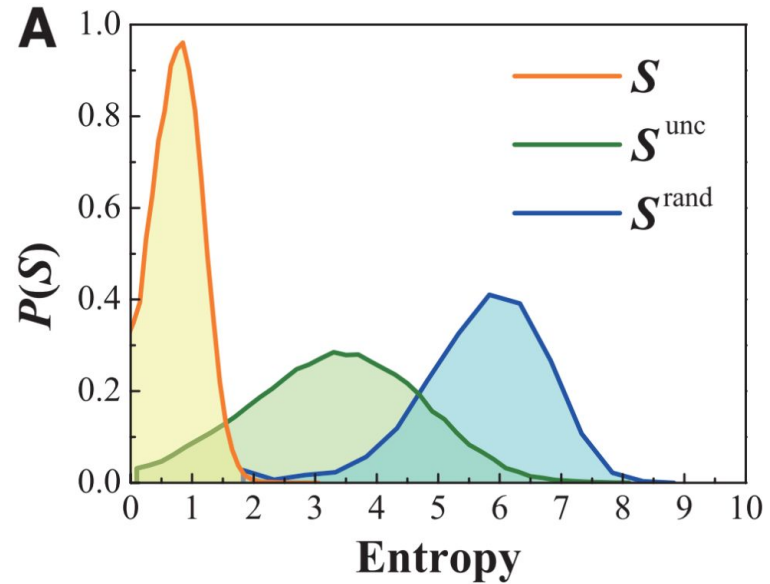


Entropy

Song et al., 2010:

- 50,000 users (CDRs)
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$$2^{0.8} = 1.74$$



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