CMU SCS

15-826: Multimedia Databases and Data Mining

Lecture #9: Fractals – examples & algo's

C. Faloutsos

CMU SCS

Must-read Material

- Christos Faloutsos and Ibrahim Kamel, *Beyond Uniformity and Independence: Analysis of R-trees Using the Concept of Fractal Dimension*, Proc. ACM SIGACT-SIGMOD-SIGART PODS, May 1994, pp. 4-13, Minneapolis, MN.

CMU SCS

Recommended Material

optional, but **very** useful:

- Manfred Schroeder *Fractals, Chaos, Power Laws: Minutes from an Infinite Paradise* W.H. Freeman and Company, 1991
  - Chapter 10: boxcounting method
  - Chapter 1: Sierpinski triangle

CMU SCS

Outline

Goal: 'Find similar / interesting things'

- Intro to DB
- Indexing - similarity search
- Data Mining

CMU SCS

Indexing - Detailed outline

- primary key indexing
- secondary key / multi-key indexing
- spatial access methods
  - z-ordering
  - R-trees
  - misc
- fractals
  - intro
  - applications
- text

CMU SCS

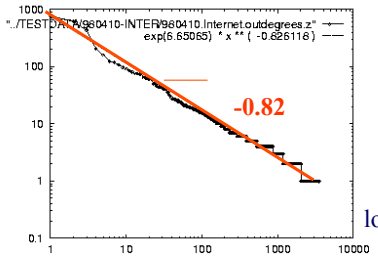
Road map

- Motivation – 3 problems / case studies
- Definition of fractals and power laws
- Solutions to posed problems
- More tools and **examples**
- Discussion - putting fractals to work!
- Conclusions – practitioner's guide
- Appendix: gory details - boxcounting plots

CMU SCS

More power laws on the Internet

log(degree)



log(rank)

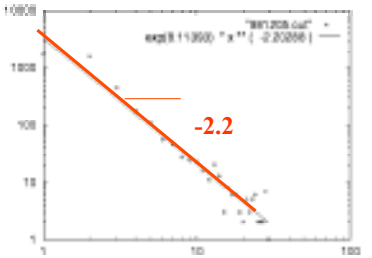
degree vs rank, for Internet domains (log-log) [sigcomm99]

CMU SCS

More power laws - internet

- pdf of degrees: (slope: 2.2)

Log(count)

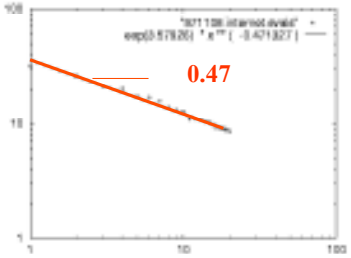


Log(degree)

CMU SCS

Even more power laws on the Internet

log(i-th eigenvalue)



log(i)

Scree plot for Internet domains (log-log) [sigcomm99]

CMU SCS

Fractals & power laws:

appear in numerous settings:

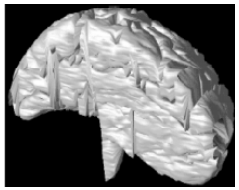
- **medical**
- geographical / geological
- social
- computer-system related

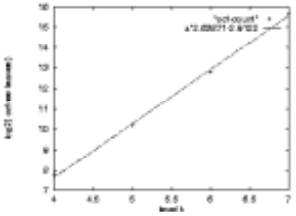
CMU SCS

More apps: Brain scans

- Oct-trees; brain-scans

Log(#octants)





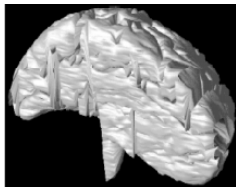
octree levels

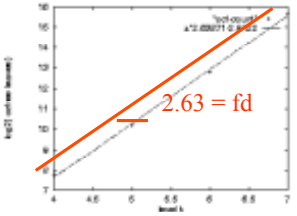
CMU SCS

More apps: Brain scans

- Oct-trees; brain-scans

Log(#octants)





octree levels

CMU SCS

More apps: Medical images

[Burdett et al, SPIE '93]:

- benign tumors: fd ~ 2.37
- malignant: fd ~ 2.56

CMU SCS

More fractals:

- cardiovascular system: 3 (!)
- lungs: 2.9

CMU SCS

Fractals & power laws:

appear in numerous settings:

- medical
- **geographical / geological**
- social
- computer-system related

CMU SCS

More fractals:

- Coastlines: 1.2-1.58

CMU SCS

CMU SCS

More fractals:

- the fractal dimension for the Amazon river is 1.85 (Nile: 1.4)

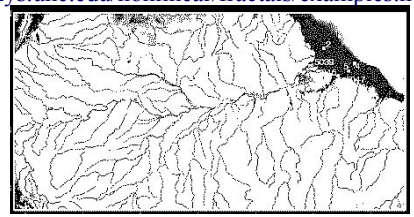
[ems.gphys.unc.edu/nonlinear/fractals/examples.html]

CMU SCS

More fractals:

- the fractal dimension for the Amazon river is 1.85 (Nile: 1.4)

[ems.gphys.unc.edu/nonlinear/fractals/examples.html]

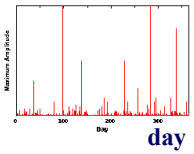


CMU SCS

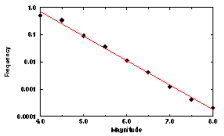
More power laws

- Energy of earthquakes (Gutenberg-Richter law) [simscience.org]

amplitude



day



log(freq)

magnitude

CMU SCS

Fractals & power laws:

appear in numerous settings:

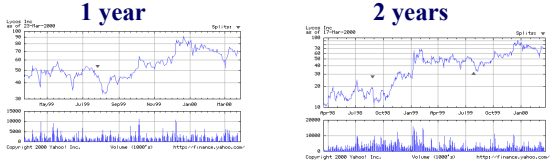
- medical
- geographical / geological
- **social**
- computer-system related

CMU SCS

More fractals:

stock prices (LYCOS) - random walks: 1.5

1 year **2 years**



CMU SCS

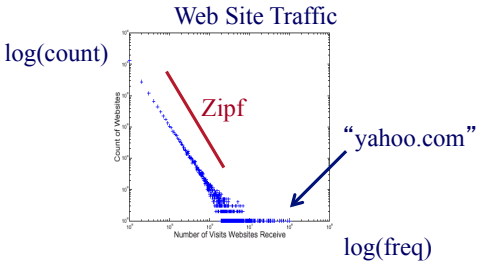
Even more power laws:

- Income distribution (Pareto's law)
- size of firms
- publication counts (Lotka's law)

CMU SCS

Even more power laws:

- web hit counts [w/ A. Montgomery]



CMU SCS

Fractals & power laws:

appear in numerous settings:

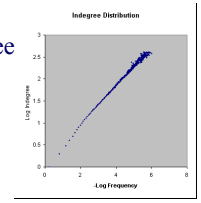
- medical
- geographical / geological
- social
- **computer-system related**

CMU SCS

Power laws, cont'd

- In- and out-degree distribution of web sites [Barabasi], [IBM-CLEVER]

log indegree



from [Ravi Kumar, Prabhakar Raghavan, Sridhar Rajagopalan, Andrew Tomkins]

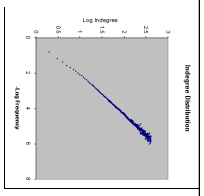
- log(freq)

CMU SCS

Power laws, cont'd

- In- and out-degree distribution of web sites [Barabasi], [IBM-CLEVER]

log(freq)



from [Ravi Kumar, Prabhakar Raghavan, Sridhar Rajagopalan, Andrew Tomkins]

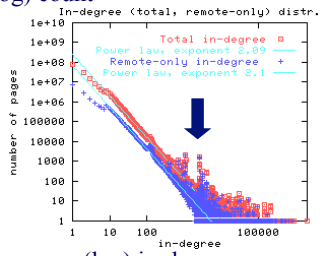
log indegree

CMU SCS

"Foiled by power law"

- [Broder+, WWW'00]

(log) count



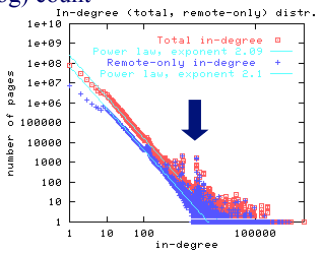
(log) in-degree

CMU SCS

"Foiled by power law"

- [Broder+, WWW' 00]

(log) count



(log) in-degree

"The anomalous bump at 120 on the *x*-axis is due a large clique formed by a single spammer"

CMU SCS

Power laws, cont' d

- In- and out-degree distribution of web sites [Barabasi], [IBM-CLEVER]
- length of file transfers [Crovella+Bestavros '96]
- duration of UNIX jobs [Harchol-Balter]

CMU SCS

Even more power laws:

- Distribution of UNIX file sizes
- web hit counts [Huberman]

CMU SCS

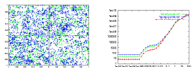
Road map

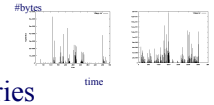
- Motivation – 3 problems / case studies
- Definition of fractals and power laws
- Solutions to posed problems
- More examples and tools
- Discussion - putting fractals to work!
- Conclusions – practitioner's guide
- Appendix: gory details - boxcounting plots

CMU SCS

What else can they solve?

- ✓ separability [KDD'02]
- forecasting [CIKM'02]
- dimensionality reduction [SBBD'00]
- non-linear axis scaling [KDD'02]
- ✓ disk trace modeling [Wang+'02]
- selectivity of spatial/multimedia queries [PODS'94, VLDB'95, ICDE'00]
- ...





CMU SCS

Settings for fractals:

Points; areas (-> fat fractals), eg:

CMU SCS

Settings for fractals:

Points; areas, eg:

- cities/stores/hospitals, over earth's surface
- time-stamps of events (customer arrivals, packet losses, criminal actions) over time
- regions (sales areas, islands, patches of habitats) over space

CMU SCS

Settings for fractals:

- customer feature vectors (age, income, frequency of visits, amount of sales per visit)

CMU SCS

Some uses of fractals:

- Detect non-existence of rules (if points are uniform)
- Detect non-homogeneous regions (eg., legal login time-stamps may have different fd than intruders')
- Estimate number of neighbors / customers / competitors within a radius

CMU SCS

Multi-Fractals

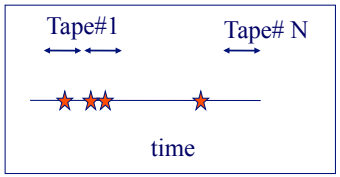
Setting: points or objects, w/ some value, eg:

- cities w/ populations
- positions on earth and amount of gold/water/oil underneath
- product ids and sales per product
- people and their salaries
- months and count of accidents

CMU SCS

Use of multifractals:

- Estimate tape/disk accesses
  - *how many of the 100 tapes contain my 50 phonecall records?*
  - *how many days without an accident?*

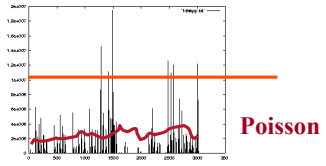


CMU SCS

Use of multifractals

- how often do we exceed the threshold?

#bytes

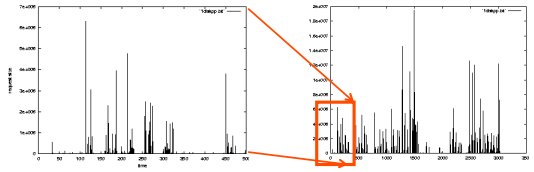


CMU SCS

Use of multifractals cont'd

- Extrapolations for/from samples

#bytes

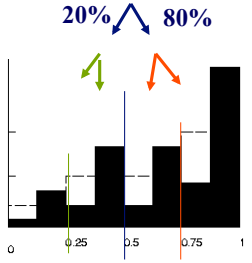


time

CMU SCS

Use of multifractals cont'd

- *How many distinct products account for 90% of the sales?*



CMU SCS

Road map

- Motivation – 3 problems / case studies
- Definition of fractals and power laws
- Solutions to posed problems
- More examples and tools
- Discussion - putting fractals to work!
- Conclusions – practitioner's guide
- Appendix: gory details - boxcounting plots

CMU SCS

Conclusions

- Real data often **disobey** textbook assumptions (Gaussian, Poisson, uniformity, independence)

CMU SCS

Conclusions

- Real data often **disobey** textbook assumptions (Gaussian, Poisson, uniformity, independence)

CMU SCS

Conclusions - cont'd

Self-similarity & power laws: appear in **many** cases

Bad news:
lead to skewed distributions
(no Gaussian, Poisson,
uniformity, independence,
mean, variance)

CMU SCS

Conclusions - cont'd

Self-similarity & power laws: appear in **many** cases

Bad news:
lead to skewed distributions
(no Gaussian, Poisson,
uniformity, independence,
mean, variance)

Good news:

- 'correlation integral' for separability
- rank/frequency plots
- 80-20 (multifractals)
- (Hurst exponent,
- strange attractors,
- renormalization theory,
- ++)

CMU SCS

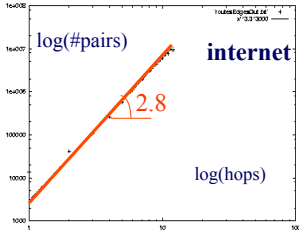
Conclusions

- **tool#1: (for points) 'correlation integral'**: (#pairs within <= *r*) vs (distance *r*)
- **tool#2: (for categorical values) rank-frequency** plot (a' la Zipf)
- **tool#3: (for numerical values) CCDF:** Complementary cumulative distr. function (#of elements with value >= *a*)

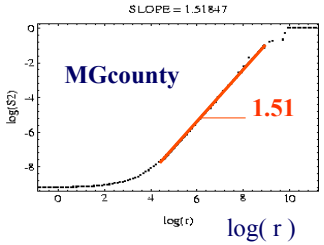
CMU SCS

Practitioner's guide:

- **tool#1**: #pairs vs distance, for a **set of objects**, with a distance function (slope = intrinsic dimensionality)



log(#pairs(within <= r))



log(r)

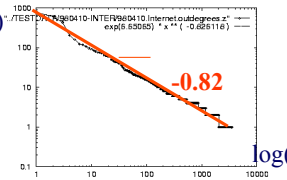
CMU SCS

Practitioner's guide:

- **tool#2**: rank-frequency plot (for **categorical attributes**)

internet domains

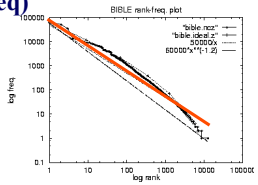
log(degree)



log(rank)

Bible

log(freq)



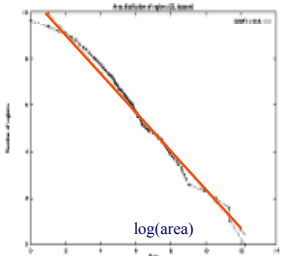
log(rank)

CMU SCS

Practitioner's guide:

- **tool#3**: CCDF, for (skewed) **numerical attributes**, eg. areas of islands/lakes, UNIX jobs...)

log(count(>= area))



scandinavian lakes

CMU SCS

Resources:

- Software for fractal dimension
  - www.cs.cmu.edu/~christos/software.html
  - And specifically 'fdnq_h':
  - www.cs.cmu.edu/~christos/SRC/fdnq_h.zip
- Also, in 'R': 'fdim' package

CMU SCS

Books

- Strongly recommended intro book:
  - Manfred Schroeder *Fractals, Chaos, Power Laws: Minutes from an Infinite Paradise* W.H. Freeman and Company, 1991
- Classic book on fractals:
  - B. Mandelbrot *Fractal Geometry of Nature,* W.H. Freeman, 1977

CMU SCS

References

- [vldb95] Alberto Belussi and Christos Faloutsos, *Estimating the Selectivity of Spatial Queries Using the `Correlation' Fractal Dimension* Proc. of VLDB, p. 299-310, 1995
- [Broder+' 00] Andrei Broder, Ravi Kumar , Farzin Maghoul1, Prabhakar Raghavan , Sridhar Rajagopalan , Raymie Stata, Andrew Tomkins , Janet Wiener, *Graph structure in the web* , WWW' 00
- M. Crovella and A. Bestavros, *Self similarity in World wide web traffic: Evidence and possible causes* , SIGMETRICS ' 96.

CMU SCS

References

- [ieeeTN94] W. E. Leland, M.S. Taqqu, W. Willinger, D.V. Wilson, *On the Self-Similar Nature of Ethernet Traffic,* IEEE Transactions on Networking, 2, 1, pp 1-15, Feb. 1994.
- [pods94] Christos Faloutsos and Ibrahim Kamel, *Beyond Uniformity and Independence: Analysis of R-trees Using the Concept of Fractal Dimension,* PODS, Minneapolis, MN, May 24-26, 1994, pp. 4-13

CMU SCS

References

- [vldb96] Christos Faloutsos, Yossi Matias and Avi Silberschatz, *Modeling Skewed Distributions Using Multifractals and the `80-20 Law'* Conf. on Very Large Data Bases (VLDB), Bombay, India, Sept. 1996.

CMU SCS

References

- [vldb96] Christos Faloutsos and Volker Gaede *Analysis of the Z-Ordering Method Using the Hausdorff Fractal Dimension* VLD, Bombay, India, Sept. 1996
- [sigcomm99] Michalis Faloutsos, Petros Faloutsos and Christos Faloutsos, *What does the Internet look like? Empirical Laws of the Internet Topology,* SIGCOMM 1999

CMU SCS

References

- [icde99] Guido Proietti and Christos Faloutsos, *I/O complexity for range queries on region data stored using an R-tree* International Conference on Data Engineering (ICDE), Sydney, Australia, March 23-26, 1999
- [sigmod2000] Christos Faloutsos, Bernhard Seeger, Agma J. M. Traina and Caetano Traina Jr., *Spatial Join Selectivity Using Power Laws*, SIGMOD 2000

CMU SCS

References

- [Wang+' 02] Mengzhi Wang, Anastassia Ailamaki and Christos Faloutsos, Capturing the spatio-temporal behavior of real traffic data Performance 2002 (IFIP Int. Symp. on Computer Performance Modeling, Measurement and Evaluation), Rome, Italy, Sept. 2002

CMU SCS

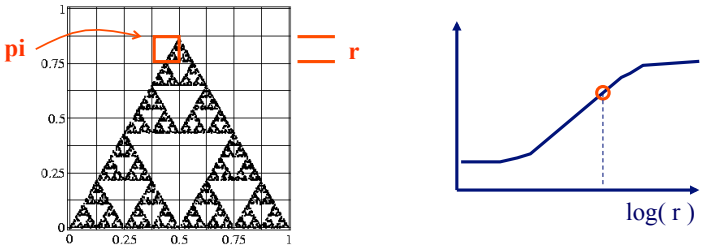
Appendix - Gory details

- Bad news: There are more than one fractal dimensions
  - Minkowski fd; Hausdorff fd; Correlation fd; Information fd
- Great news:
  - they can all be computed fast!
  - they usually have nearby values

CMU SCS

Fast estimation of fd(s):

- How, for the (correlation) fractal dimension?
- A: Box-counting plot:



CMU SCS

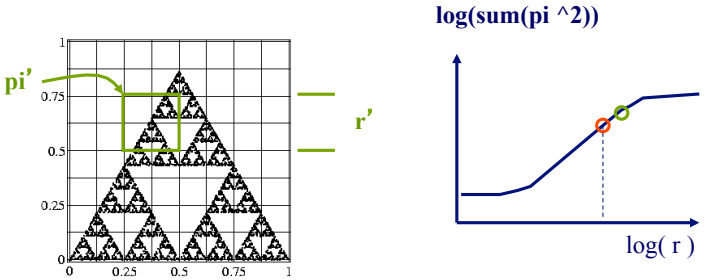
Definitions

- *pi* : the percentage (or count) of points in the *i*-th cell
- *r*: the side of the grid

CMU SCS

Fast estimation of fd(s):

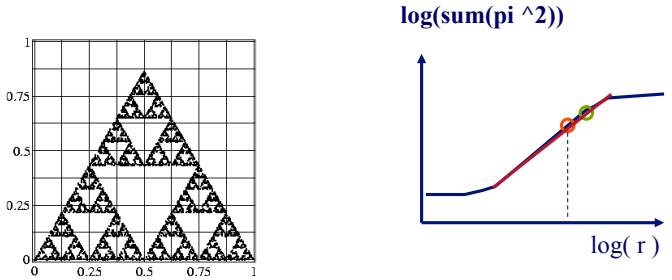
- compute sum(pi^2) for another grid side, r'



CMU SCS

Fast estimation of fd(s):

- etc; if the resulting plot has a linear part, its slope is the correlation fractal dimension D2



CMU SCS

Definitions (cont' d)

- Many more fractal dimensions Dq (related to Renyi entropies):

$$D_q = \frac{1}{q-1}\frac{\partial \log(\sum p_i^q)}{\partial \log(r)} \qquad q \neq 1$$

$$D_1 = \frac{\partial \sum p_i \log(p_i)}{\partial \log(r)}$$

CMU SCS

Hausdorff or box-counting fd:

- Box counting plot: Log(N (r)) vs Log (r)
- r: grid side
- N (r): count of non-empty cells
- (Hausdorff) fractal dimension D0:

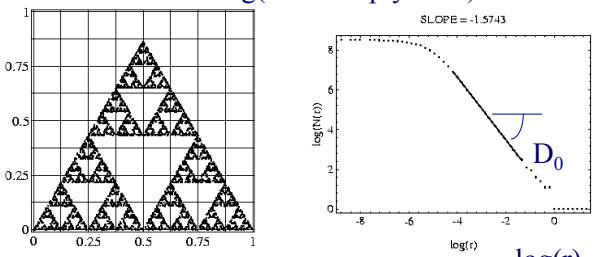
$$D_0 = -\frac{\partial \log(N(r))}{\partial \log(r)}$$

CMU SCS

Definitions (cont' d)

- Hausdorff fd:

r __ log(#non-empty cells)



log(r)

CMU SCS

Observations

- q=0: Hausdorff fractal dimension
- q=2: Correlation fractal dimension (**identical** to the exponent of the number of neighbors vs radius)
- q=1: Information fractal dimension

CMU SCS

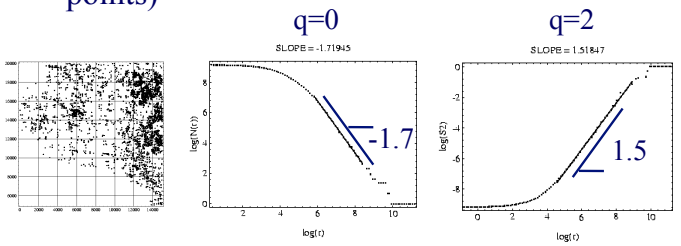
Observations, cont'd

- in general, the Dq's take similar, but not identical, values.
- except for perfectly self-similar point-sets, where Dq=Dq' for any *q, q'*

CMU SCS

Examples:MG county

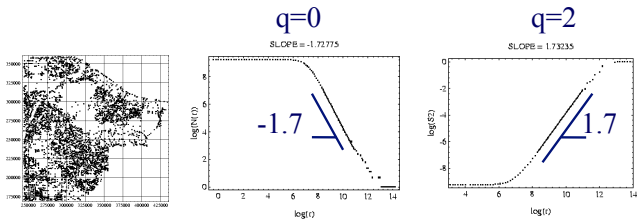
- Montgomery County of MD (road end-points)



CMU SCS

Examples:LB county

- Long Beach county of CA (road end-points)



CMU SCS

Conclusions

- many fractal dimensions, with nearby values
- can be computed quickly
  (O(N) or O(N log(N))
- (code: on the web:
  - www.cs.cmu.edu/~christos/SRC/fdnq_h.zip
  - Or `R' ('fdim' package)