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15-826: Multimedia Databases and Data Mining

Lecture #25: Time series mining and forecasting

Christos Faloutsos

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Must-Read Material

- Byong-Kee Yi, Nikolaos D. Sidiropoulos, Theodore Johnson, H.V. Jagadish, Christos Faloutsos and Alex Biliris, *Online Data Mining for Co-Evolving Time Sequences*, ICDE, Feb 2000.
- Chungmin Melvin Chen and Nick Roussopoulos, *Adaptive Selectivity Estimation Using Query Feedbacks*, SIGMOD 1994

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Thanks

Deepay Chakrabarti (CMU)

Prof. Dimitris Gunopulos (UCR)

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Mengzhi Wang (CMU)

Prof. Byoung-Kee Yi (Pohang U.)

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Outline

- Motivation
- Similarity search – distance functions
- Linear Forecasting
- Bursty traffic - fractals and multifractals
- Non-linear forecasting
- Conclusions

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Problem definition

- Given: one or more sequences
  $x_1, x_2, \ldots, x_t, \ldots$
  $(y_1, y_2, \ldots, y_t, \ldots$
  $\ldots)$
- Find
  - similar sequences; forecasts
  - patterns; clusters; outliers

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Motivation - Applications

- Financial, sales, economic series
- Medical
  - ECGs +; blood pressure etc monitoring
  - reactions to new drugs
  - elderly care

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Motivation - Applications (cont'd)

- 'Smart house'
  - sensors monitor temperature, humidity, air quality
- video surveillance

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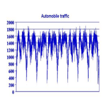
Motivation - Applications (cont'd)

- civil/automobile infrastructure
  - bridge vibrations [Oppenheim+02]
  - road conditions / traffic monitoring



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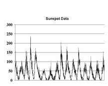
Motivation - Applications (cont'd)

- Weather, environment/anti-pollution
  - volcano monitoring
  - air/water pollutant monitoring



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Motivation - Applications (cont'd)

- Computer systems
  - 'Active Disks' (buffering, prefetching)
  - web servers (ditto)
  - network traffic monitoring
  - ...

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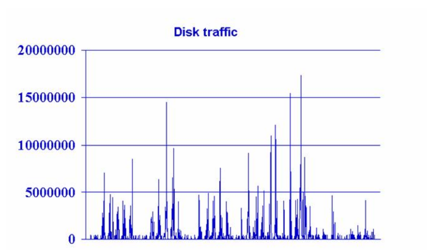
Stream Data: Disk accesses

#bytes



time

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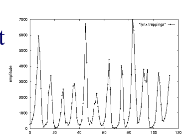
Problem #1:

Goal: given a signal (e.g.., #packets over time)

Find: patterns, periodicities, and/or compress

count



lynx caught per year
(packets per day;
temperature per day)

year

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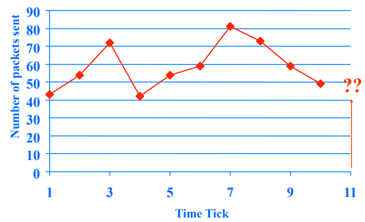
Problem#2: Forecast

Given x_t, x_{t-1}, …, forecast x_{t+1}



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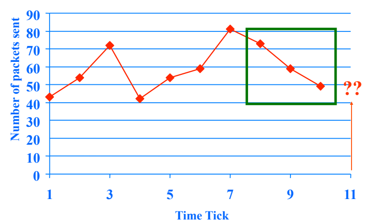
Problem#2': Similarity search

E.g.., Find a 3-tick pattern, similar to the last one



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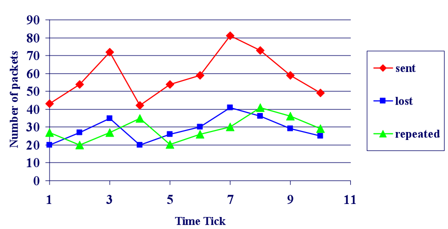
Problem #3:

- Given: A set of **correlated** time sequences
- Forecast 'Sent(t)'



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Important observations

Patterns, rules, forecasting and similarity indexing are closely related:

- To do forecasting, we need
  - to find patterns/rules
  - to find similar settings in the past
- to find outliers, we need to have forecasts
  - (outlier = too far away from our forecast)

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Outline

- Motivation
- Similarity search and distance functions
  - Euclidean
  - Time-warping
- ...

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Importance of distance functions

Subtle, but **absolutely necessary**:

- A ‘must’ for similarity indexing (-> forecasting)
- A ‘must’ for clustering

Two major families
- Euclidean and Lp norms
- Time warping and variations

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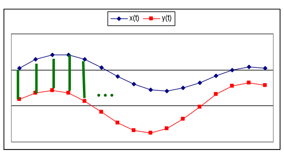
Euclidean and Lp



$$D(\vec{x},\vec{y}) = \sum_{i=1}^{n} (x_i - y_i)^2$$

$$L_p(\vec{x},\vec{y}) = \sum_{i=1}^{n} | x_i - y_i |^p$$

•L_1: city-block = Manhattan
•L_2 = Euclidean
•L_∞

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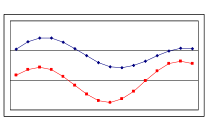
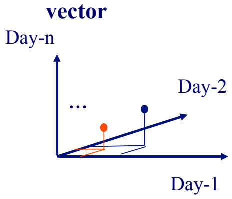
Observation #1



- **Time sequence -> n-d vector**



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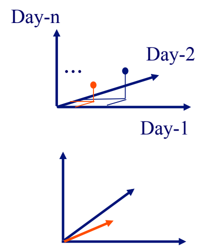
Observation #2

Euclidean distance is closely related to

- cosine similarity
- dot product
- ‘cross-correlation’ function



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Time Warping

- allow accelerations - decelerations
  - (with or w/o penalty)
- THEN compute the (Euclidean) distance (+ penalty)
- related to the string-editing distance

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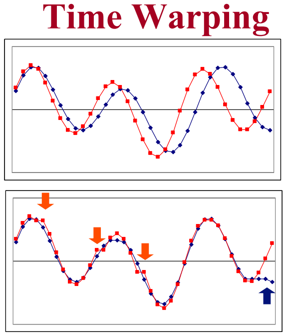
Time Warping



‘stutters’:

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Time warping

Q: how to compute it?

A: dynamic programming

D(i, j) = cost to match

prefix of length *i* of first sequence *x* with prefix of length *j* of second sequence *y*

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Time warping

Thus, with no penalty for stutter, for sequences

$x_1, x_2, \ldots, x_{i,};\quad y_1, y_2, \ldots, y_j$

$$D(i,j) = \|x[i] - y[j]\| + \min \begin{cases} D(i-1, j-1) & \text{no stutter} \\ D(i, j-1) & \text{x-stutter} \\ D(i-1, j) & \text{y-stutter} \end{cases}$$

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Time warping

VERY SIMILAR to the string-editing distance

$$D(i,j) = \|x[i] - y[j]\| + \min \begin{cases} D(i-1, j-1) & \text{no stutter} \\ D(i, j-1) & \text{x-stutter} \\ D(i-1, j) & \text{y-stutter} \end{cases}$$

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Time warping

- Complexity: O(M*N) - quadratic on the length of the strings
- **Many** variations (penalty for stutters; limit on the number/percentage of stutters; …)
- popular in voice processing [Rabiner + Juang]

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Other Distance functions

- piece-wise linear/flat approx.; compare pieces [Keogh+01] [Faloutsos+97]
- ‘cepstrum’ (for voice [Rabiner+Juang])
  - do DFT; take log of amplitude; do DFT again!
- Allow for small gaps [Agrawal+95]

See tutorial by [Gunopulos + Das, SIGMOD01]

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Other Distance functions

- In [Keogh+, KDD’04]: parameter-free, MDL based

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Conclusions

Prevailing distances:
- Euclidean and
- time-warping

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Linear Forecasting

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Forecasting

"Prediction is very difficult, especially about the future." - Nils Bohr

http://www.hfac.uh.edu/MediaFutures/thoughts.html

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Outline

- Motivation
- ...
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  - Auto-regression: Least Squares; RLS
  - Co-evolving time sequences
  - Examples
  - Conclusions

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Reference

[Yi+00] Byoung-Kee Yi et al.: *Online Data Mining for Co-Evolving Time Sequences*, ICDE 2000. (Describes MUSCLES and Recursive Least Squares)

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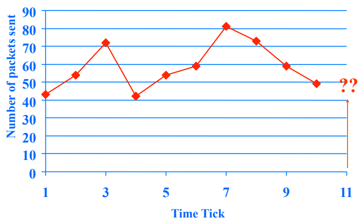
Problem#2: Forecast

- Example: give x_{t-1}, x_{t-2}, …, forecast x_t



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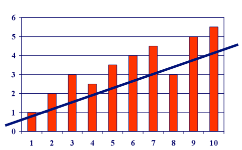
Forecasting: Preprocessing

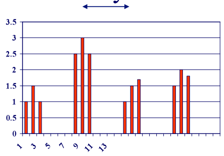
MANUALLY:

remove trends



spot periodicities

7 days



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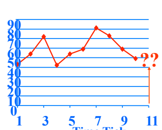
Problem#2: Forecast

- Solution: try to express
  - x_t
  - as a linear function of the past: x_{t-2}, x_{t-2}, …,
  - (up to a window of w)

Formally:

$$\boxed{x_t \;\approx\; a_1 x_{t-1} + \ldots + a_w x_{t-w} + noise}$$



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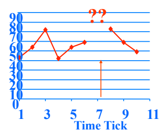
(Problem: Back-cast; interpolate)

- Solution - interpolate: try to express
  x_t
  as a linear function of the past AND the future:
  $x_{t+1}, x_{t+2}, \ldots x_{t+wfuture}; x_{t-1}, \ldots x_{t-wpast}$
  (up to windows of w_{past} , w_{future})
- EXACTLY the same algo's



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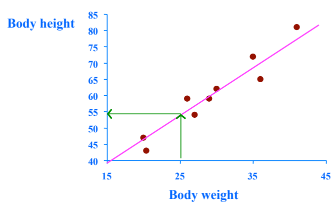
Linear Regression: idea

patient	weight	height
1	27	43
2	43	54
3	54	72
…	…	…
N	25	??



- express what we don't know (= 'dependent variable')
- as a linear function of what we know (= 'indep. variable(s)')

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Linear Auto Regression:

Time	Packets Sent(t)
1	43
2	54
3	72
…	…
N	??

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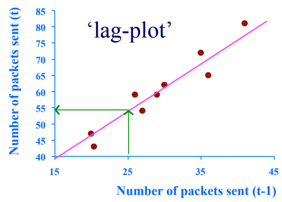
Linear Auto Regression:

Time	Packets Sent (t-1)	Packets Sent(t)
1	-	43
2	43	54
3	54	72
...	...	...
N	25	??



- lag w=1
- Dependent variable = # of packets sent (S [t])
- Independent variable = # of packets sent (S[t-1])

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- ...
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  - Auto-regression: **Least Squares; RLS**
  - Co-evolving time sequences
  - Examples
  - Conclusions

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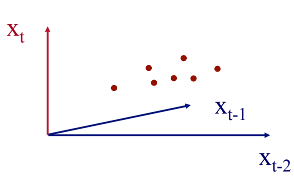
More details:

- Q1: Can it work with window w>1?
- A1: YES!



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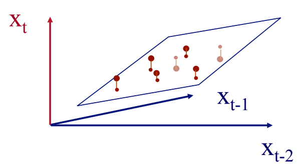
More details:

- Q1: Can it work with window w>1?
- A1: YES! (we'll fit a hyper-plane, then!)



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More details:

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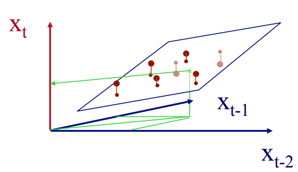

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More details:

- Q1: Can it work with window w>1?
- A1: YES! The problem becomes:

$$\mathbf{X}_{[N \times w]} \times \mathbf{a}_{[w \times 1]} = \mathbf{y}_{[N \times 1]}$$

- OVER-CONSTRAINED
  - **a** is the vector of the regression coefficients
  - **X** has the N values of the w indep. variables
  - **y** has the N values of the dependent variable

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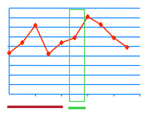
More details:



- $\mathbf{X}_{[N \times w]} \times \mathbf{a}_{[w \times 1]} = \mathbf{y}_{[N \times 1]}$

Ind-var1 Ind-var-w

time

$$\begin{bmatrix} X_{11}, X_{12}, \cdots, X_{1w} \\ X_{21}, X_{22}, \ldots, X_{2w} \\ \vdots \\ \vdots \\ \vdots \\ X_{N1}, X_{N2}, \ldots, X_{Nw} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_w \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \vdots \\ \vdots \\ y_N \end{bmatrix}$$

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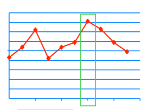
More details:



- $\mathbf{X}_{[N \times w]} \times \mathbf{a}_{[w \times 1]} = \mathbf{y}_{[N \times 1]}$

Ind-var1 Ind-var-w

time

$$\begin{bmatrix} X_{11}, X_{12}, \cdots, X_{1w} \\ X_{21}, X_{22}, \ldots, X_{2w} \\ \vdots \\ \vdots \\ \vdots \\ X_{N1}, X_{N2}, \ldots, X_{Nw} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_w \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \vdots \\ \vdots \\ y_N \end{bmatrix}$$

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More details

- Q2: How to estimate $a_1, a_2, \ldots a_w = \mathbf{a}$?
- A2: with Least Squares fit

$$\boxed{\mathbf{a} = (\mathbf{X}^T \times \mathbf{X})^{-1} \times (\mathbf{X}^T \times \mathbf{y})}$$

- (Moore-Penrose pseudo-inverse)
- **a** is the vector that minimizes the RMSE from **y**
- <**identical** math with 'query feedbacks'>

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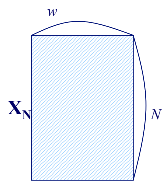
More details

- Straightforward solution:

$$\boxed{\mathbf{a} = (\mathbf{X}^T \times \mathbf{X})^{-1} \times (\mathbf{X}^T \times \mathbf{y})}$$

a : Regression Coeff. Vector
X : Sample Matrix



- Observations:
  - Sample matrix X grows over time
  - needs matrix inversion
  - $\mathbf{O}(N \times w^2)$ computation
  - $\mathbf{O}(N \times w)$ storage

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Even more details

- Q3: Can we estimate **a** incrementally?
- A3: Yes, with the brilliant, classic method of 'Recursive Least Squares' (RLS) (see, e.g., [Yi+00], for details).
- We can do the matrix inversion, WITHOUT inversion! (How is that possible?!)

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Even more details

- Q3: Can we estimate **a** incrementally?
- A3: Yes, with the brilliant, classic method of 'Recursive Least Squares' (RLS) (see, e.g., [Yi+00], for details).
- We can do the matrix inversion, WITHOUT inversion! (How is that possible?!)
- A: our matrix has special form: $(X^T X)$

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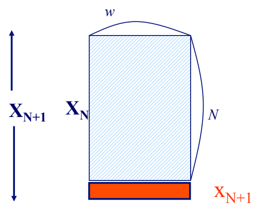
More details

At the $N+1$ time tick:



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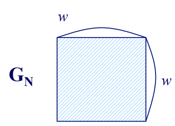
More details

- Let $\mathbf{G}_N = (\mathbf{X}_N^T \times \mathbf{X}_N)^{-1}$ (``gain matrix'')
- $\mathbf{G}_{N+1}$ can be computed recursively from $\mathbf{G}_N$



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EVEN more details:

$$G_{N+1} = G_N - [c]^{-1} \times [G_N \times x_{N+1}{}^T] \times x_{N+1} \times G_N$$

1 x *w* row vector

$$c = [1 + x_{N+1} \times G_N \times x_{N+1}{}^T]$$

Let's elaborate
(VERY IMPORTANT, VERY VALUABLE!)

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EVEN more details:

$$a = [X_{N+1}{}^T \times X_{N+1}]^{-1} \times [X_{N+1}{}^T \times y_{N+1}]$$

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EVEN more details:

$$a = [X_{N+1}{}^T \times X_{N+1}]^{-1} \times [X_{N+1}{}^T \times y_{N+1}]$$

[w x 1] [(N+1) x w] [(N+1) x 1]

[w x (N+1)] [w x (N+1)]

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EVEN more details:

$$a = \boxed{[X_{N+1}{}^T \times X_{N+1}]^{-1}} \times [X_{N+1}{}^T \times y_{N+1}]$$

[(N+1) x w]

[w x (N+1)]

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EVEN more details:

$$a = [X_{N+1}{}^T \times X_{N+1}]^{-1} \times [X_{N+1}{}^T \times y_{N+1}]$$

‘gain matrix’ $G_{N+1} \equiv [X_{N+1}{}^T \times X_{N+1}]^{-1}$

1 x w row vector

$$G_{N+1} = G_N - [c]^{-1} \times [G_N \times x_{N+1}{}^T] \times x_{N+1} \times G_N$$

$$c = [1 + x_{N+1} \times G_N \times x_{N+1}{}^T]$$

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EVEN more details:

$$G_{N+1} = G_N - [c]^{-1} \times [G_N \times x_{N+1}{}^T] \times x_{N+1} \times G_N$$

$$c = [1 + x_{N+1} \times G_N \times x_{N+1}{}^T]$$

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EVEN more details:

1x1

1xw

wxw wxw wxw wx1 wxw

$$G_{N+1} = G_N - [c]^{-1} \times [G_N \times x_{N+1}{}^T] \times x_{N+1} \times G_N$$

SCALAR! $c = [1 + x_{N+1} \times G_N \times x_{N+1}{}^T]$

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Altogether:

$$a = [X_{N+1}{}^T \times X_{N+1}]^{-1} \times [X_{N+1}{}^T \times y_{N+1}]$$

$$G_{N+1} \equiv [X_{N+1}{}^T \times X_{N+1}]^{-1}$$

$$G_{N+1} = G_N - [c]^{-1} \times [G_N \times x_{N+1}{}^T] \times x_{N+1} \times G_N$$

$$c = [1 + x_{N+1} \times G_N \times x_{N+1}{}^T]$$

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Altogether:

$$G_0 \equiv \delta\, I$$

where
I: w x w identity matrix
δ: a large positive number

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Comparison:

- Straightforward Least Squares
  - Needs huge matrix (**growing** in size) $O(N \times w)$
  - Costly matrix operation $O(N \times w^2)$
- Recursive LS
  - Need much smaller, fixed size matrix $O(w \times w)$
  - Fast, incremental computation $O(1 \times w^2)$
  - **no matrix inversion**

$\boxed{N = 10^6, \quad w = 1\text{-}100}$

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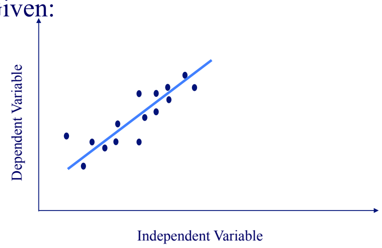
Pictorially:

- Given:



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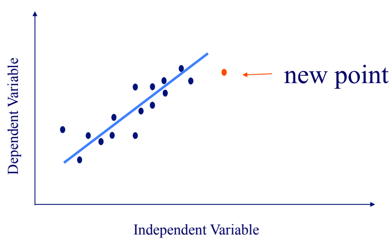
Pictorially:



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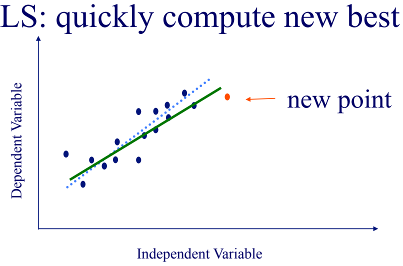
Pictorially:

RLS: quickly compute new best fit



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Even more details

- Q4: can we 'forget' the older samples?
- A4: Yes - RLS can easily handle that [Yi+00]:

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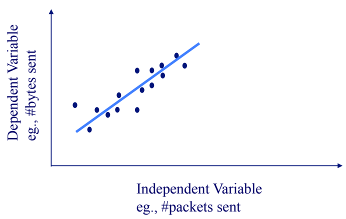
Adaptability - 'forgetting'



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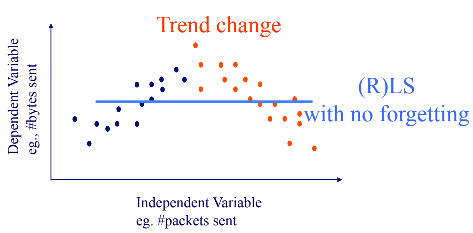
Adaptability - 'forgetting'



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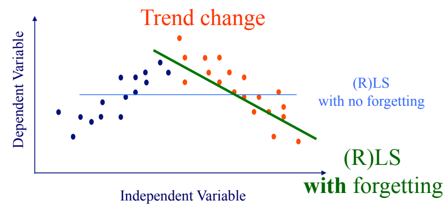
Adaptability - ‘forgetting’



- RLS: can *trivially* handle ‘forgetting’

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SKIP

How to choose ‘*w*’?

- goal: capture arbitrary periodicities
- with NO human intervention
- on a semi-infinite stream

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SKIP

Reference

[Papadimitriou+ vldb2003] Spiros Papadimitriou, Anthony Brockwell and Christos Faloutsos *Adaptive, Hands-Off Stream Mining* VLDB 2003, Berlin, Germany, Sept. 2003

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SKIP

Answer:

- 'AWSOM' (Arbitrary Window Stream fOrecasting Method) [Papadimitriou+, vldb2003]
- idea: do AR on each wavelet level
- in detail:

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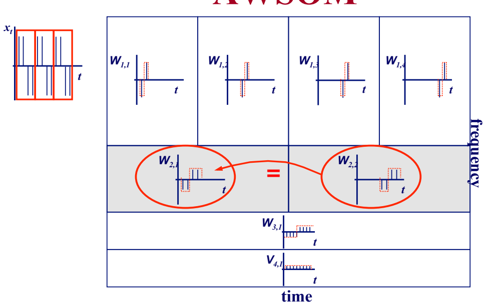
SKIP

AWSOM



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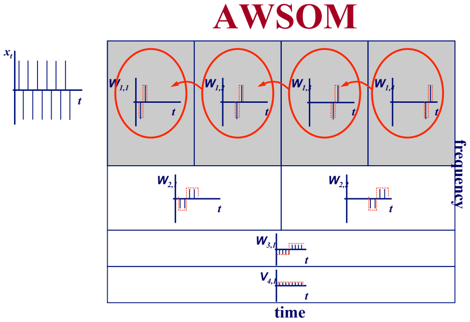
AWSOM



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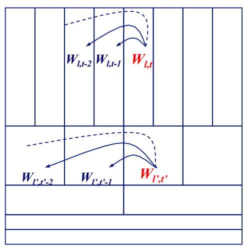
AWSOM - idea



$W_{l,t} = \beta_{l,1} W_{l,t-1} + \beta_{l,2} W_{l,t-2} + \dots$

$W_{l',t'} = \beta_{l',1} W_{l',t'-1} + \beta_{l',2} W_{l',t'-2} + \dots$

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More details…

- Update of wavelet coefficients (incremental)
- Update of linear models (incremental; RLS)
- Feature selection (single-pass)
  - Not all correlations are significant
  - Throw away the insignificant ones ("noise")

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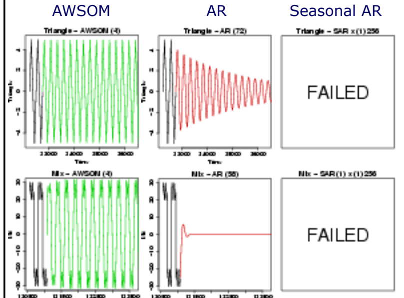
Results - Synthetic data



- Triangle pulse
- Mix (sine + square)
- AR captures wrong trend (or none)
- Seasonal AR estimation fails

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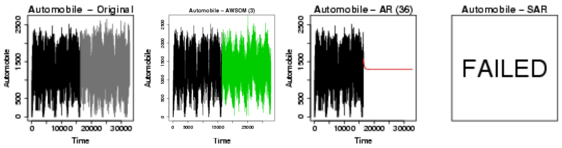
Results - Real data



- Automobile traffic
  - Daily periodicity
  - Bursty “noise” at smaller scales
- AR fails to capture any trend
- Seasonal AR estimation fails

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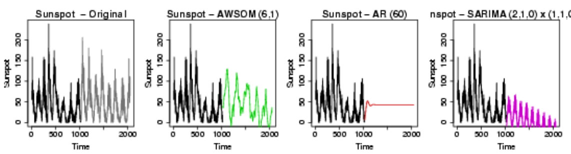
Results - real data



- Sunspot intensity
  - Slightly time-varying “period”
- AR captures wrong trend
- Seasonal ARIMA
  - wrong downward trend, despite help by human!

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Complexity

- Model update

  Space: $O(lgN + mk^2) \approx O(lgN)$

  Time: $O(k^2) \approx O(1)$
- Where
  - ***N:*** number of points (so far)
  - ***k:*** number of regression coefficients; fixed
  - ***m:***number of linear models; ***O(lgN)***

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Outline

- Motivation
- ...
- Linear Forecasting
  - Auto-regression: Least Squares; RLS
  - Co-evolving time sequences
  - Examples
  - Conclusions

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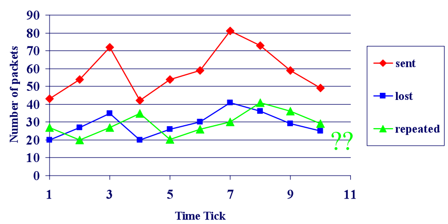
Co-Evolving Time Sequences

- Given: A set of **correlated** time sequences
- Forecast '**Repeated(t)**'



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Solution:

Q: what should we do?

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Solution:

Least Squares, with

- Dep. Variable: Repeated(t)
- Indep. Variables: Sent(t-1) … Sent(t-w); Lost(t-1) …Lost(t-w); Repeated(t-1), ...
- (named: 'MUSCLES' [Yi+00])

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Forecasting - Outline

- Auto-regression
- Least Squares; recursive least squares
- Co-evolving time sequences
- Examples
- Conclusions

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Examples - Experiments

- Datasets
  - Modem pool traffic (14 modems, 1500 time-ticks; #packets per time unit)
  - AT&T WorldNet internet usage (several data streams; 980 time-ticks)
- Measures of success
  - Accuracy : Root Mean Square Error (RMSE)

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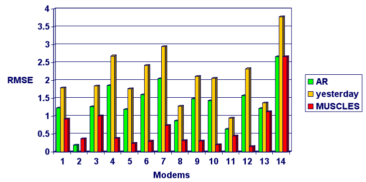
Accuracy - “Modem”



MUSCLES outperforms AR & “yesterday”

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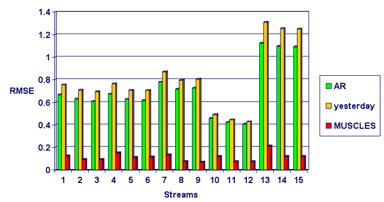
Accuracy - “Internet”



MUSCLES consistently outperforms AR & “yesterday”

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Linear forecasting - Outline

- Auto-regression
- Least Squares; recursive least squares
- Co-evolving time sequences
- Examples
- Conclusions

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Conclusions - Practitioner's guide

- AR(IMA) methodology: prevailing method for linear forecasting
- Brilliant method of Recursive Least Squares for fast, incremental estimation.
- See [Box-Jenkins]
- (AWSOM: no human intervention)

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Resources: software and urls

- MUSCLES: Prof. Byoung-Kee Yi:
  http://www.postech.ac.kr/~bkyi/
  or **christos@cs.cmu.edu**
- free-ware: 'R' for stat. analysis
  (clone of Splus)
  http://cran.r-project.org/

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Books

- George E.P. Box and Gwilym M. Jenkins and Gregory C. Reinsel, *Time Series Analysis: Forecasting and Control*, Prentice Hall, 1994 (the classic book on ARIMA, 3rd ed.)
- Brockwell, P. J. and R. A. Davis (1987). Time Series: Theory and Methods. New York, Springer Verlag.

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Additional Reading

- [Papadimitriou+ vldb2003] Spiros Papadimitriou, Anthony Brockwell and Christos Faloutsos *Adaptive, Hands-Off Stream Mining* VLDB 2003, Berlin, Germany, Sept. 2003
- [Yi+00] Byoung-Kee Yi et al.: *Online Data Mining for Co-Evolving Time Sequences*, ICDE 2000. (Describes MUSCLES and Recursive Least Squares)

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Outline

- Motivation
- Similarity search and distance functions
- Linear Forecasting
- Bursty traffic - fractals and multifractals
- Non-linear forecasting
- Conclusions

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Bursty Traffic & Multifractals

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Outline

- Motivation
- ...
- Linear Forecasting
- Bursty traffic - fractals and multifractals
  - Problem
  - Main idea (80/20, Hurst exponent)
  - Results

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Reference:

[Wang+02] Mengzhi Wang, Tara Madhyastha, Ngai Hang Chang, Spiros Papadimitriou and Christos Faloutsos, *Data Mining Meets Performance Evaluation: Fast Algorithms for Modeling Bursty Traffic*, ICDE 2002, San Jose, CA, 2/26/2002 - 3/1/2002.

Full thesis: CMU-CS-05-185 *Performance Modeling of Storage Devices using Machine Learning* Mengzhi Wang, Ph.D. Thesis Abstract, .ps.gz, .pdf

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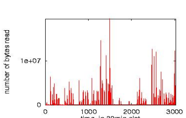
Recall: Problem #1:

Goal: given a signal (eg., #bytes over time)

Find: patterns, periodicities, and/or compress

#bytes



Bytes per 30'
(packets per day;
earthquakes per year)

time

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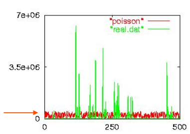
Problem #1

- model bursty traffic
- generate realistic traces
- (Poisson does not work)

bytes

Poisson



time

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Motivation

- predict queue length distributions (e.g., to give probabilistic guarantees)
- "learn" traffic, for buffering, prefetching, 'active disks', web servers

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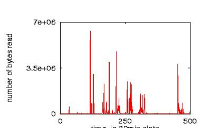
Q: any 'pattern'?

- Not Poisson
- spike; silence; more spikes; more silence…
- any rules?

bytes



time

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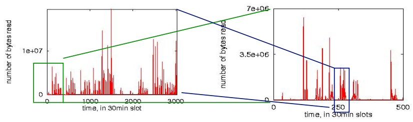
Solution: self-similarity

bytes

bytes



time

time

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But:

- Q1: How to generate realistic traces; extrapolate; give guarantees?
- Q2: How to estimate the model parameters?

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Outline

- Motivation
- ...
- Linear Forecasting
- Bursty traffic - fractals and multifractals
  - Problem
  - Main idea (80/20, Hurst exponent)
  - Results

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Approach

- Q1: How to generate a sequence, that is
  - bursty
  - self-similar
  - and has similar queue length distributions

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Approach

- A: ‘binomial multifractal’ [Wang+02]
- ~ 80-20 ‘law’:
  - 80% of bytes/queries etc on first half
  - repeat recursively
- *b*: bias factor (eg., 80%)

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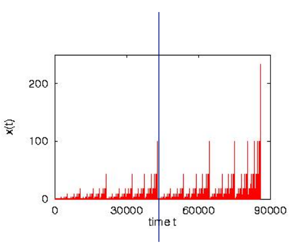
Binary multifractals

20 **80**



15-8 111

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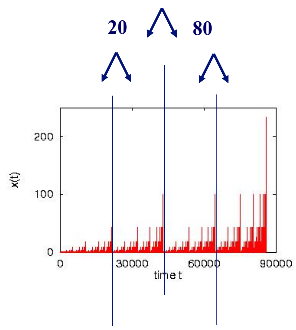
Binary multifractals



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Parameter estimation

- Q2: How to estimate the bias factor *b*?

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Parameter estimation

- Q2: How to estimate the bias factor *b*?
- A: MANY ways [Crovella+96]
  - Hurst exponent
  - variance plot
  - even DFT amplitude spectrum! (‘periodogram’)
  - More robust: ‘entropy plot’ [Wang+02]

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Entropy plot

- Rationale:
  - burstiness: inverse of uniformity
  - entropy measures uniformity of a distribution
  - find entropy at several granularities, to see whether/how our distribution is close to uniform.

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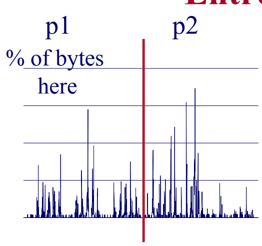
Entropy plot



- Entropy *E(n)* after *n* levels of splits
- n=1: E(1)= - p1 $\log_2$(p1)- p2 $\log_2$(p2)

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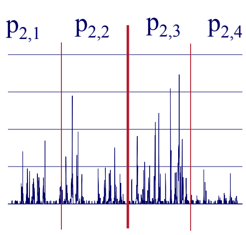
Entropy plot



- Entropy *E(n)* after *n* levels of splits
- n=1: E(1)= - p1 log(p1)- p2 log(p2)
- n=2: $E(2) = - \Sigma_i\, p_{2,i} * \log_2 (p_{2,i})$

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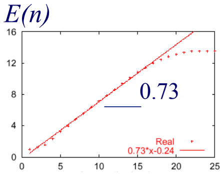
Real traffic

Entropy
E(n)



# of levels (*n*)

- Has linear entropy plot (-> self-similar)

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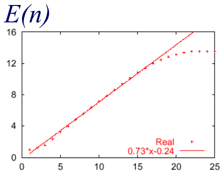
Observation - intuition:

Entropy
E(n)



# of levels (*n*)

intuition: slope =
intrinsic dimensionality =
info-bits per coordinate-bit
- unif. Dataset: slope =?
- multi-point: slope = ?

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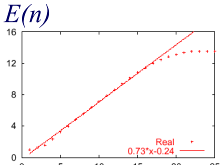
Observation - intuition:

Entropy
E(n)



# of levels (*n*)

intuition: slope =
intrinsic dimensionality =
info-bits per coordinate-bit
- unif. Dataset: slope =1
- multi-point: slope = 0

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SKIP

Entropy plot - Intuition

- Slope ~ intrinsic dimensionality (in fact, 'Information fractal dimension')
- = info bit per coordinate bit - eg

Dim = 1 

Pick a point;
reveal its coordinate bit-by-bit -
how much info is each bit worth to me?

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SKIP

Entropy plot

- Slope ~ intrinsic dimensionality (in fact, 'Information fractal dimension')
- = info bit per coordinate bit - eg

Dim = 1 

Is MSB 0?

'info' value = E(1): 1 bit

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SKIP

Entropy plot

- Slope ~ intrinsic dimensionality (in fact, 'Information fractal dimension')
- = info bit per coordinate bit - eg

Dim = 1 

Is MSB 0?

Is next MSB =0?

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SKIP

Entropy plot

- Slope ~ intrinsic dimensionality (in fact, 'Information fractal dimension')
- = info bit per coordinate bit - eg

Dim = 1

Is MSB 0?

Info value =1 bit
= E(2) - E(1) =
slope!

Is next MSB =0?

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SKIP

Entropy plot

- Repeat, for all points at same position:

Dim=0

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Entropy plot

- Repeat, for all points at same position:
- we need 0 bits of info, to determine position
- -> slope = 0 = intrinsic dimensionality

Dim=0

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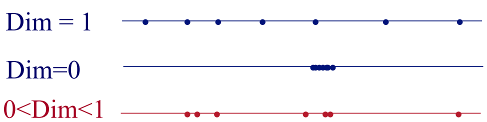
Entropy plot

- Real (and 80-20) datasets can be in-between: bursts, gaps, smaller bursts, smaller gaps, at every scale



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(Fractals, again)

- What set of points could have behavior between point and line?

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Cantor dust

- Eliminate the middle third
- Recursively!

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Cantor dust

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Cantor dust

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Cantor dust

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Cantor dust

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Cantor dust

Dimensionality?
(no length; infinite # points!)
Answer: log2 / log3 = 0.6

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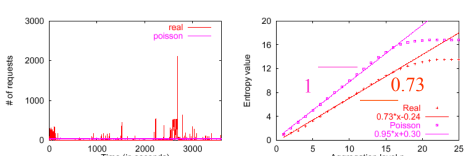
Some more entropy plots:

- Poisson vs real



Poisson: slope = ~1 -> uniformly distributed

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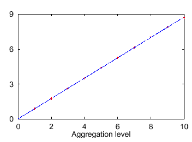
b-model

E(n)



n

- b-model traffic gives perfectly linear plot
- Lemma: its slope is
  $slope = -b \log_2 b - (1-b) \log_2 (1-b)$
- Fitting: do entropy plot; get slope; solve for *b*

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Outline

- Motivation
- ...
- Linear Forecasting
- Bursty traffic - fractals and multifractals
  - Problem
  - Main idea (80/20, Hurst exponent)
  - Experiments - Results

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Experimental setup

- Disk traces (from HP [Wilkes 93])
- web traces from LBL
  http://repository.cs.vt.edu/lbl-conn-7.tar.Z

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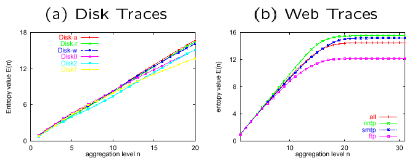
Model validation

- Linear entropy plots

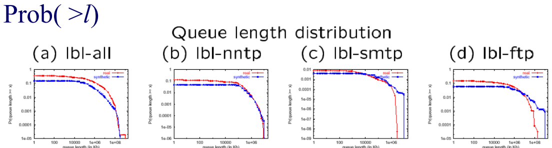


Bias factors *b*: 0.6-0.8
smallest *b* / smoothest: nntp traffic

Web traffic - results

- LBL, NCDF of queue lengths (log-log scales)

Prob(>*l*)

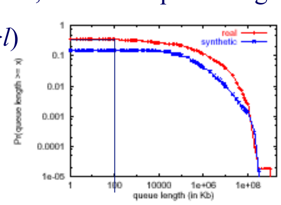


How to give guarantees? (queue length *l*)

Web traffic - results

- LBL, NCDF of queue lengths (log-log scales)

Prob(>*l*)



20% of the requests will see queue lengths <100

(queue length *l*)

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Conclusions

- Multifractals (80/20, 'b-model', Multiplicative Wavelet Model (MWM)) for analysis and synthesis of bursty traffic

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Books

- Fractals: Manfred Schroeder: *Fractals, Chaos, Power Laws: Minutes from an Infinite Paradise* W.H. Freeman and Company, 1991 (Probably the BEST book on fractals!)

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Further reading:

- Crovella, M. and A. Bestavros (1996). Self-Similarity in World Wide Web Traffic, Evidence and Possible Causes. Sigmetrics.
- [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.

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Further reading

Entropy plots

- [Riedi+99] R. H. Riedi, M. S. Crouse, V. J. Ribeiro, and R. G. Baraniuk, *A Multifractal Wavelet Model with Application to Network Traffic*, IEEE Special Issue on Information Theory, 45. (April 1999), 992-1018.
- [Wang+02] Mengzhi Wang, Tara Madhyastha, Ngai Hang Chang, Spiros Papadimitriou and Christos Faloutsos, *Data Mining Meets Performance Evaluation: Fast Algorithms for Modeling Bursty Traffic*, ICDE 2002, San Jose, CA, 2/26/2002 - 3/1/2002.

Outline

- Motivation
- ...
- Linear Forecasting
- Bursty traffic - fractals and multifractals
- Non-linear forecasting
- Conclusions

Chaos and non-linear forecasting

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Reference:

[Deepay Chakrabarti and Christos Faloutsos *F4: Large-Scale Automated Forecasting using Fractals* CIKM 2002, Washington DC, Nov. 2002.]

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Detailed Outline

- Non-linear forecasting
  - Problem
  - Idea
  - How-to
  - Experiments
  - Conclusions

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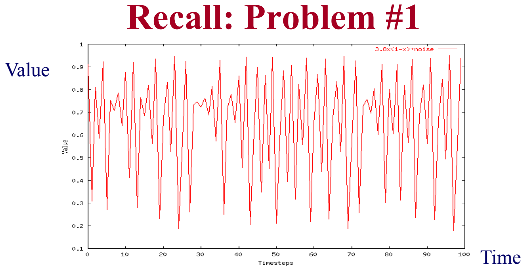
Recall: Problem #1



Given a time series $\{x_t\}$, predict its future course, that is, x_{t+1}, x_{t+2}, ...

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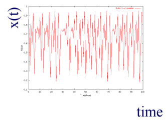
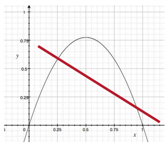
Datasets



Logistic Parabola:

$x_t = ax_{t-1}(1-x_{t-1})$ + noise

Models population of flies [R. May/1976]



Lag-plot

ARIMA: fails

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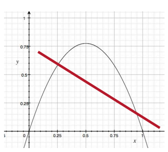
How to forecast?

- ARIMA - but: linearity assumption



Lag-plot

ARIMA: fails

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How to forecast?

- ARIMA - but: linearity assumption
- ANSWER: ‘Delayed Coordinate Embedding’ = Lag Plots [Sauer92]

  ~ nearest-neighbor search, for past incidents

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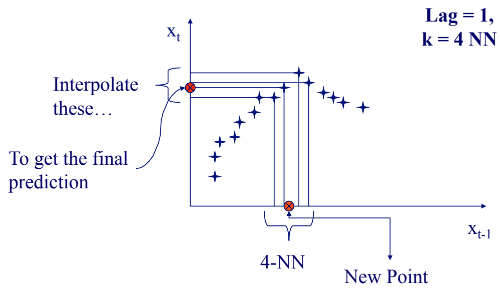
General Intuition (Lag Plot)



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Questions:

- Q1: How to choose lag *L*?
- Q2: How to choose *k* (the # of NN)?
- Q3: How to interpolate?
- Q4: why should this work at all?

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Q1: Choosing lag *L*

- Manually (16, in award winning system by [Sauer94])

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Q2: Choosing number of neighbors *k*

- Manually (typically ~ 1-10)

Q3: How to interpolate?

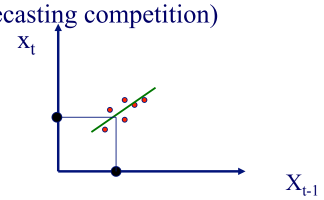
How do we interpolate between the *k* nearest neighbors?

A3.1: Average

A3.2: Weighted average (weights drop with distance - how?)

Q3: How to interpolate?

A3.3: Using SVD - seems to perform best ([Sauer94] - first place in the Santa Fe forecasting competition)



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Q4: Any theory behind it?

A4: YES!

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Theoretical foundation

- Based on the 'Takens theorem' [Takens81]
- which says that long enough delay vectors can do prediction, even if there are unobserved variables in the dynamical system (= diff. equations)

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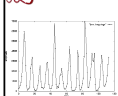
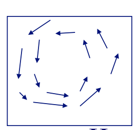
Skip



Theoretical foundation

Example: Lotka-Volterra equations

$$dH/dt = r\,H - a\,H{*}P$$
$$dP/dt = b\,H{*}P - m\,P$$



H is count of prey (e.g., hare)
P is count of predators (e.g., lynx)

Suppose only P(t) is observed (t=1, 2, …).

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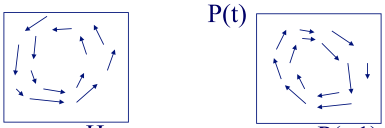
Skip

Theoretical foundation

- But the delay vector space is a faithful reconstruction of the internal system state
- So prediction in **delay vector space** is as good as prediction in **state space**

P P(t)



H P(t-1)

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Detailed Outline

- Non-linear forecasting
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  - Experiments
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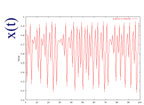
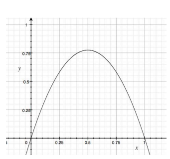
Datasets



Logistic Parabola:

$x_t = a x_{t-1}(1-x_{t-1})$ + noise

Models population of flies [R. May/1976]



Lag-plot

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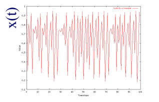
Datasets



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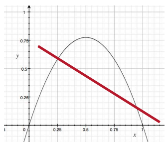

Lag-plot
ARIMA: fails

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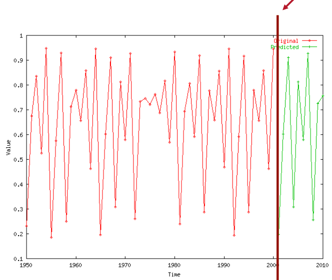
Logistic Parabola



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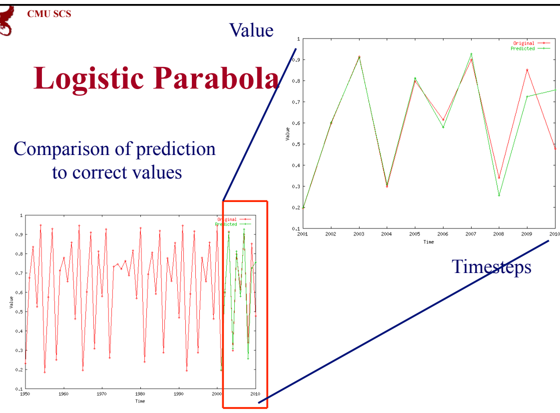
Logistic Parabola

Comparison of prediction to correct values



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Value

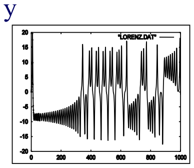
Datasets

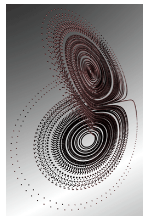
LORENZ: Models convection currents in the air

$dx / dt = a (y - x)$

$dy / dt = x (b - z) - y$

$dz / dt = xy - c z$





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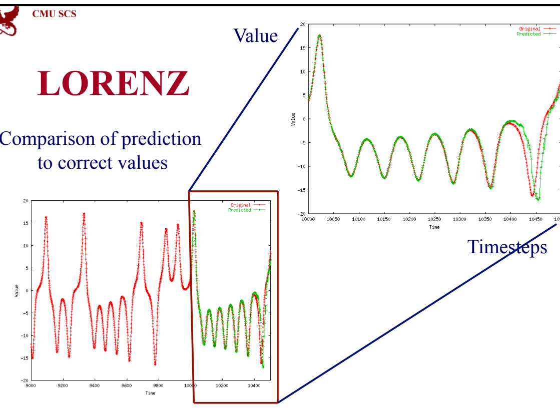
Value

LORENZ

Comparison of prediction to correct values



Timesteps

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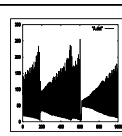
Value

Datasets

- LASER: fluctuations in a Laser over time (used in Santa Fe competition)



Time

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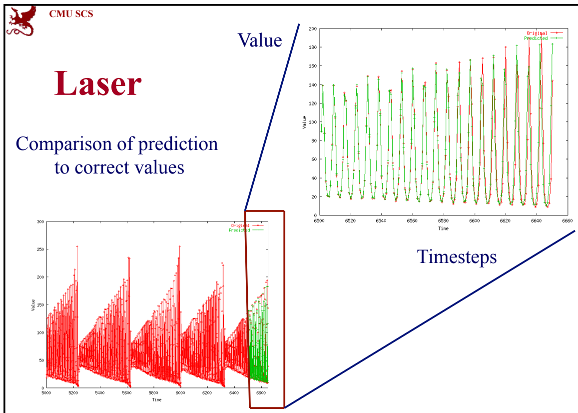
Laser

Comparison of prediction to correct values



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Conclusions

- Lag plots for non-linear forecasting (Takens' theorem)
- suitable for 'chaotic' signals

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References

- Deepay Chakrabarti and Christos Faloutsos *F4: Large-Scale Automated Forecasting using Fractals* CIKM 2002, Washington DC, Nov. 2002.
- Sauer, T. (1994). *Time series prediction using delay coordinate embedding*. (in book by Weigend and Gershenfeld, below) Addison-Wesley.
- Takens, F. (1981). *Detecting strange attractors in fluid turbulence*. Dynamical Systems and Turbulence. Berlin: Springer-Verlag.

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References

- Weigend, A. S. and N. A. Gerschenfeld (1994). *Time Series Prediction: Forecasting the Future and Understanding the Past*, Addison Wesley. (Excellent collection of papers on chaotic/non-linear forecasting, describing the algorithms behind the winners of the Santa Fe competition.)

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Overall conclusions

- Similarity search: **Euclidean**/time-warping; **feature extraction** and **SAMs**

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Overall conclusions

- Similarity search: **Euclidean**/time-warping; **feature extraction** and **SAMs**
- Signal processing: **DWT** is a powerful tool

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Overall conclusions

- Similarity search: **Euclidean**/time-warping; **feature extraction** and **SAMs**
- Signal processing: **DWT** is a powerful tool
- Linear Forecasting: **AR** (Box-Jenkins) methodology; AWSOM

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Overall conclusions

- Similarity search: **Euclidean**/time-warping; **feature extraction** and **SAMs**
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- Linear Forecasting: **AR** (Box-Jenkins) methodology; AWSOM
- Bursty traffic: **multifractals** (80-20 'law')

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Overall conclusions

- Similarity search: **Euclidean**/time-warping; **feature extraction** and **SAMs**
- Signal processing: **DWT** is a powerful tool
- Linear Forecasting: **AR** (Box-Jenkins) methodology; AWSOM
- Bursty traffic: **multifractals** (80-20 'law')
- Non-linear forecasting: **lag-plots** (Takens)

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