Internet Measurement and Data Analysis (6)

Kenjiro Cho

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schedule change

- Class 9 Measuring traffic of the Internet (11/18, Friday) 9:25-10:55 e11
- Class 10 Hot topics (11/18, Friday) 11:10-12:40 e11
- Class 11 Measuring time series of the Internet (11/30)
- NO Class (12/7)

review of previous class

Class 5 Measuring the structure of the Internet

- Internet architecture
- network layers
- topologies
- graph theory
- exercise: topology analysis

today's topics

Class 6 Measuring the characteristics of the Internet

- delay, packet loss, jitter
- correlation and multivariate analysis
- principal component analysis
- exercise: correlation analysis

measurement metrics of the Internet

measurement metrics

- link capacity, throughput
- delay
- jitter
- packet loss rate

methodologies

- active measurement: injects measurement packets (e.g., ping)
- passive measurement: monitors network without interfering in traffic
  - monitor at 2 locations and compare
  - infer from observations (e.g., behavior of TCP)
  - collect measurements inside a transport mechanism

delay measurement

- delay components
  - delay = propagation delay + queueing delay + other overhead
  - if not congested, delay is close to propagation deley
- methods
  - round-trip delay
  - one-way delay requires clock synchronization

  - average delay
  - max delay: e.g., voice communication requires $< 400ms$
  - jitter: variations in delay

some delay numbers

- packet transmission time (so called wire-speed)
  - 1500 bytes at 10Mbps: 1.2msec
  - 1500 bytes at 100Mbps: 120usec
  - 1500 bytes at 1Gbps: 12usec
- speed of light in fiber: about 200,000 km/s
  - 100km round-trip: 1 msec
  - 20,000km round-trip: 200msec
- satellite round-trip delay
  - LEO (Low-Earth Orbit): 200 msec
  - GEO (Geostationary Orbit): 600msec

packet loss measurement

packet loss rate

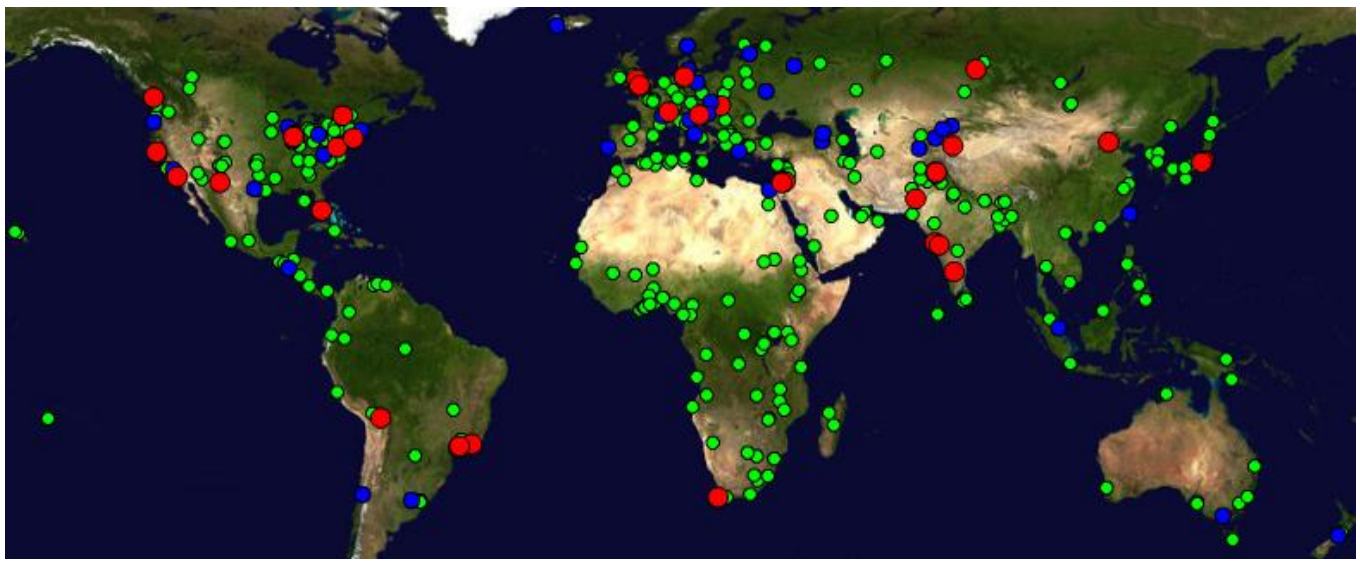
- loss rate is enough if packet loss is random...
- in reality,
  - bursty loss: e.g., buffer overflow
  - packet size dependency: e.g., bit error rate in wireless transmission

pingER project

- the Internet End-to-end Performance Measurement (IEPM) project by SLAC
- using ping to measure rtt and packet loss around the world
  - http://www-iepm.slac.stanford.edu/pinger/
  - started in 1995
  - over 600 sites in over 125 countries

pingER project monitoring sites

- monitoring (red), beacon (blue), remote (green) sites
  - beacon sites are monitored by all monitors



from pingER web site

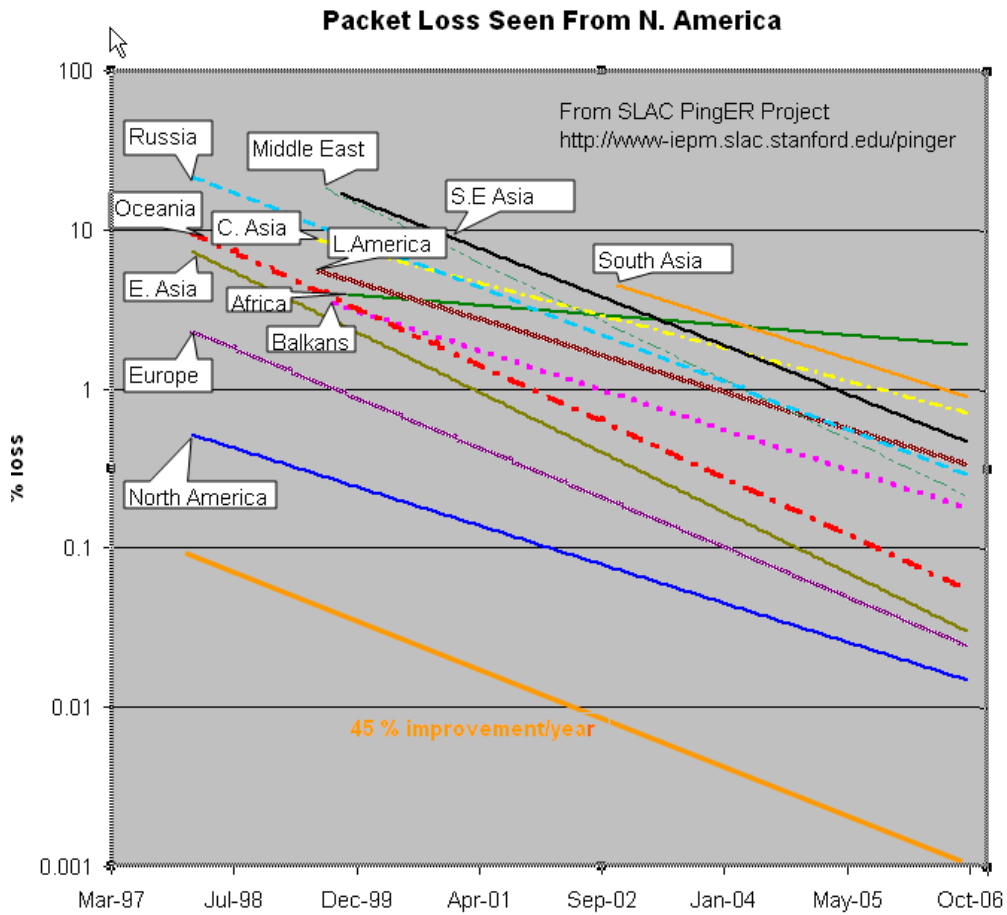
pingER project monitoring sites in east asia

- monitoring (red) and remote (green) sites

from pingER web site

pingER packet loss

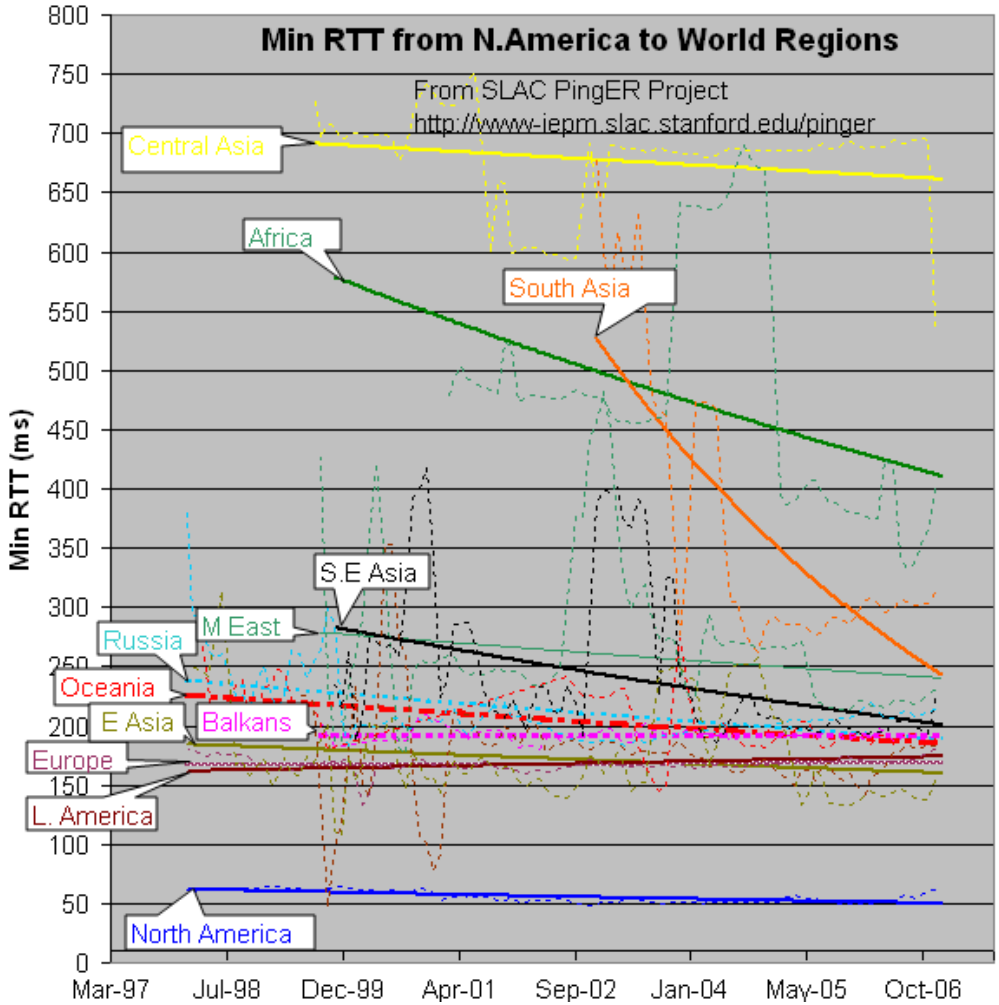
- packet loss observed from N. Ameria
- exponential improvement in 10 years



from pingER web site

pinger minimum rtt

- minimum rtts observed from N. America
- gradual shift from satellite to fiber in S. Asia and Africa



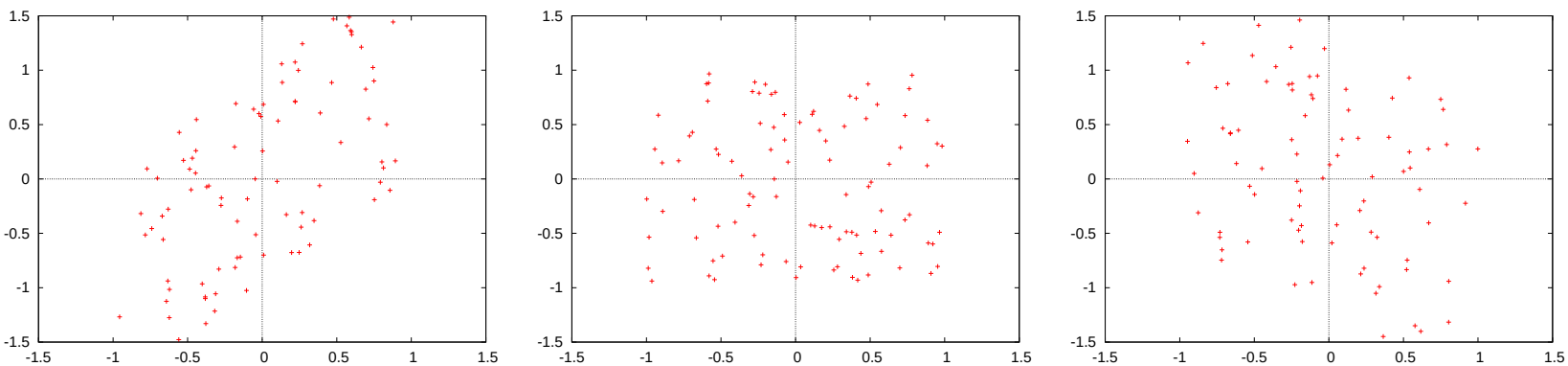
from pingER web site

variables in data set

- univariate analysis
  - explores a single variable in a data set, separately
- multivariate analysis
  - looks at more than one variables at a time
  - enabled by computers
  - finding hidden trends (data mining)

scatter plots

- explores relationships between 2 variables
  - X-axis: variable X
  - Y-axis: corresponding value of variable Y
- you can identify
  - whether variables X and Y related
    - no relation, positive correlation, negative correlation
  - whether the variation in Y changes depending on X
  - outliers
- examples: positive correlation 0.7 (left), no correlation 0.0 (middle), negative correlation -0.5 (right)



examples: positive correlation 0.7 (left), no correlation 0.0 (middle), negative correlation -0.5 (right)

correlation

- covariance:

$$\sigma_{xy}^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})$$

- correlation coefficient:

$$\rho_{xy} = \frac{\sigma_{xy}^2}{\sigma_x \sigma_y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

- correlation coefficient: the covariance of 2 variables normalized by their product of their standard deviations, a value between -1 and $+1$ inclusive.
- sensitive to outliers. so, you should use a scatter plot to observe outliers.
- correlation and causality
  - correlation does not imply causal relationship
    - third factor C causes both A and B
    - coincidence

correlation and multivariate analysis

multivariate analysis: statistical methods to analyze more than one variable at a time

- visualization of relationship
  - cluster analysis: calculate distance (or similarity) between variables, and assign the variables into groups (or clusters)
- demensionality reduction
  - principal component analysis: a technique to reduce the number of variables

principal component analysis; PCA

purpose of PCA

- convert a set of possibly correlated variables into a smaller set of uncorrelated variables

PCA can be solved by eigenvalue decomposition of a covariance matrix

applications of PCA

- demensionality reduction
  - sort principal components by contribution ratio, components with small contribution ratio can be ignored
- principal component labeling
  - find means of produced principal components

notes:

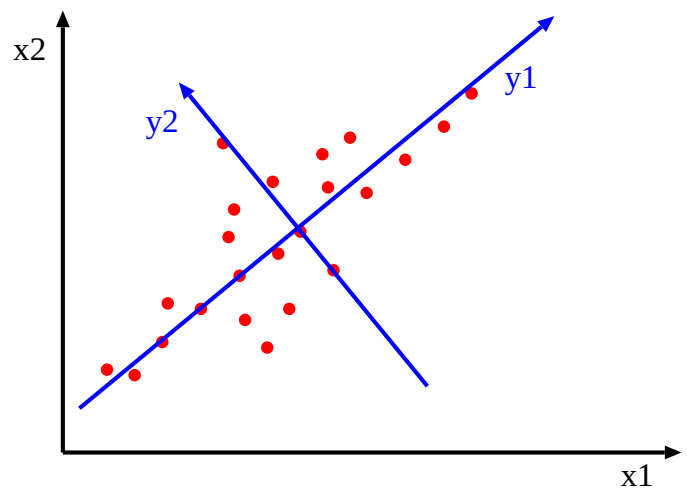
- PCA just extracts components with large variance
  - not simple if axes are not in the same unit
- a convenient method to automatically analyze complex relationship, but it does not explain the complex relationship

PCA: intuitive explanation

a view of cordinate transformation using a 2D graph

- draw the first axis (the 1st PCA axis) that goes through the centroid, along the direction of the maximal variability
- draw the 2nd axis that goes through the centroid, is orthogonal to the 1st axis, along the direction of the 2nd maximal variability
- draw the subsequent axes in the same manner

For example, "height" and "weight" can be mapped to "body size" and "slimness". we can add "sitting height" and "chest measurement" in a similar manner



PCA (appendix)

principal components can be found as the eigenvectors of a covariance matrix.
let X be a d-demensional random variable. we want to find a dxd orthogonal transformation matrix P that convers X to its principal components Y.

$$Y = P^\top X$$

solve this equation, assuming $cov(Y)$ being a diagonal matrix (components are independent), and P being an orthogonal matrix. ($P^{-1} = P^\top$)
the covariance matrix of Y is

$$\begin{aligned} cov(Y) &= E[YY^\top] = E[(P^\top X)(P^\top X)^\top] = E[(P^\top X)(X^\top P)] \\ &= P^\top E[XX^\top]P = P^\top cov(X)P \end{aligned}$$

thus,

$$Pcov(Y) = PP^\top cov(X)P = cov(X)P$$

rewrite P as a $dx1$ matrix:

$$P = [P_1, P_2, \ldots, P_d]$$

also, $cov(Y)$ is a diagonal matrix (components are independent)

$$cov(Y) = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_d \end{bmatrix}$$

this can be rewritten as

$$[\lambda_1 P_1, \lambda_2 P_2, \ldots, \lambda_d P_d] = [cov(X)P_1, cov(X)P_2, \ldots, cov(X)P_d]$$

for $\lambda_i P_i = cov(X)P_i$, P_i is an eigenvector of the covariance matrix X
thus, we can find a transformation matrix P by finding the eigenvectors.

previous exercise: Dijkstra algorithm

- read a topology file, and compute shortest paths

```
% cat topology.txt
a - b 5
a - c 8
b - c 2
b - d 1
b - e 6
c - e 3
d - e 3
c - f 3
e - f 2
d - g 4
e - g 5
f - g 4
% ruby dijkstra.rb -s a topology.txt
a: (0) a
b: (5) a b
c: (7) a b c
d: (6) a b d
e: (9) a b d e
f: (10) a b c f
g: (10) a b d g
%
```

previous exercise: sample code (1/4)

```
# dijkstra's algorithm based on the pseudo code in the wikipedia
# http://en.wikipedia.org/wiki/Dijkstra%27s_algorithm
#
require 'optparse'

source = nil # source of spanning-tree

OptionParser.new {|opt|
  opt.on('-s VAL') {|v| source = v}
  opt.parse!(ARGV)
}

INFINITY = 0x7fffffff # constant to represent a large number
```

previous exercise: sample code (2/4)

```
# read topology file and initialize nodes and edges
# each line of topology file should be "node1 (-|->) node2 weight_val"
nodes = Array.new # all nodes in graph
edges = Hash.new # all edges in graph
ARGF.each_line do |line|
  s, op, t, w = line.split
  next if line[0] == ?# || w == nil
  unless op == "-" || op == "->"
    raise ArgumentError, "edge_type should be either '-' or '->'"
  end
  weight = w.to_i
  nodes << s unless nodes.include?(s) # add s to nodes
  nodes << t unless nodes.include?(t) # add t to nodes
  # add this to edges
  if (edges.has_key?(s))
    edges[s][t] = weight
  else
    edges[s] = {t=>weight}
  end
  if (op == "-")  # if this edge is undirected, add the reverse directed edge
    if (edges.has_key?(t))
      edges[t][s] = weight
    else
      edges[t] = {s=>weight}
    end
  end
end
# sanity check
if source == nil
  raise ArgumentError, "specify source_node by '-s source'"
end
unless nodes.include?(source)
  raise ArgumentError, "source_node(#{source}) is not in the graph"
end
```

previous exercise: sample code (3/4)

```
# create and initialize 2 hashes: distance and previous
dist = Hash.new # distance for destination
prev = Hash.new # previous node in the best path
nodes.each do |i|
  dist[i] = INFINITY # Unknown distance function from source to v
  prev[i] = -1 # Previous node in best path from source
end

# run the dijkstra algorithm
dist[source] = 0 # Distance from source to source
while (nodes.length > 0)
  # u := vertex in Q with smallest dist[]
  u = nil
  nodes.each do |v|
    if (!u) || (dist[v] < dist[u])
      u = v
    end
  end
  if (dist[u] == INFINITY)
    break # all remaining vertices are inaccessible from source
  end
  nodes = nodes - [u] # remove u from Q
  # update dist[] of u's neighbors
  edges[u].keys.each do |v|
    alt = dist[u] + edges[u][v]
    if (alt < dist[v])
      dist[v] = alt
      prev[v]  = u
    end
  end
end
```

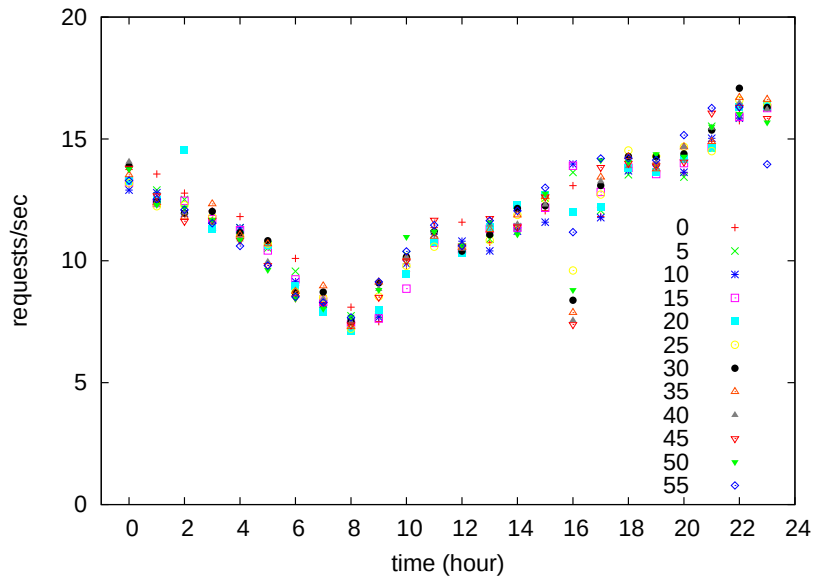
previous exercise: sample code (4/4)

```
# print the shortest-path spanning-tree
dist.sort.each do |v, d|
  print "#{v}: " # destination node
  if d != INFINITY
    print "(#{d}) " # distance
    # construct path from dest to source
    i = v
    path = "#{i}"
    while prev[i] != -1 do
      path.insert(0, "#{prev[i]} ") # prepend previous node
      i = prev[i]
    end
    puts "#{path}" # print path from source to dest
  else
    puts "unreachable"
  end
end
```

exercise: correlation

request-table in Class 4:

- use the 5-minute bin output from the previous class
- focus on the request counts
- use 12 5-minute bins for an hour as 12 samples per hour



exercise: correlation (cont'd)

an hourly request table

- row: hourly data (0 .. 23)
- column: hour samples(00 05 10 ... 55) mean stddev

correlation computation

- use 12 5-minute bins as 12 time-series
- compute correlation coefficient among time slots (columns)

#hour	00	05	10	...	55	mean	stddev
0	4123	3963	3871	...	3987	4046.8	102.3
1	4068	3871	3838	...	3760	3774.9	106.2
2	3833	3755	3580	...	3628	3703.6	219.0
3	3614	3433	3418	...	3462	3515.5	86.2
...							
22	4724	4790	4757	...	4893	4882.2	113.4
23	4922	4932	4889	...	4188	4818.9	203.8

correlation matrix

compute correlation matrix for the 12 time-series data

correlation matrix

	00	05	10	15	20	25	30	35	40	45	50	55
00	1.000	0.982	0.983	0.974	0.953	0.917	0.872	0.849	0.850	0.841	0.862	0.870
05	0.982	1.000	0.992	0.982	0.961	0.914	0.871	0.845	0.848	0.841	0.874	0.899
10	0.983	0.992	1.000	0.983	0.944	0.904	0.855	0.828	0.825	0.814	0.848	0.882
15	0.974	0.982	0.983	1.000	0.963	0.917	0.864	0.846	0.841	0.831	0.864	0.901
20	0.953	0.961	0.944	0.963	1.000	0.951	0.910	0.893	0.893	0.876	0.902	0.912
25	0.917	0.914	0.904	0.917	0.951	1.000	0.985	0.981	0.972	0.956	0.965	0.939
30	0.872	0.871	0.855	0.864	0.910	0.985	1.000	0.994	0.992	0.982	0.975	0.932
35	0.849	0.845	0.828	0.846	0.893	0.981	0.994	1.000	0.992	0.982	0.972	0.917
40	0.850	0.848	0.825	0.841	0.893	0.972	0.992	0.992	1.000	0.993	0.986	0.931
45	0.841	0.841	0.814	0.831	0.876	0.956	0.982	0.982	0.993	1.000	0.987	0.937
50	0.862	0.874	0.848	0.864	0.902	0.965	0.975	0.972	0.986	0.987	1.000	0.959
55	0.870	0.899	0.882	0.901	0.912	0.939	0.932	0.917	0.931	0.937	0.959	1.000

sample code (1/2)

```
#!/usr/bin/env ruby

# read request-table.txt
re = /(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d+)\s+(\d

hourly = Array.new(24){ Array.new(12) }
ARGF.each_line do |line|
  if re.match(line)
    for min in 0 .. 11
      hourly[$1.to_i][min] = Regexp.last_match(min + 2).to_i
    end
  end
end

means = Array.new(12)
for min in 0 .. 11
  mean = 0
  for hour in 0 .. 23
    mean += hourly[hour][min]
  end
  means[min] = Float(mean) / 24
end
```

sample code (2/2)

```
cc_matrix = Array.new(12){ Array.new(12) }
for m0 in 0 .. 11
  for min in 0 .. 11
    cov = 0
    sum_dx2 = sum_dy2 = 0
    for hour in 0 .. 23
      x = hourly[hour][m0]
      y = hourly[hour][min]
      cov += (x - means[m0]) * (y - means[min])
      sum_dx2 += (x - means[m0])**2
      sum_dy2 += (y - means[min])**2
    end
    cc_matrix[m0][min] = Float(cov) / Math.sqrt(sum_dx2 * sum_dy2)
  end
end

for m0 in 0 .. 11
  for min in 0 .. 11
    printf "%.3f ", cc_matrix[m0][min]
  end
  print "\n"
end
```

summary

Class 6 Measuring the characteristics of the Internet

- delay, packet loss, jitter
- correlation and multivariate analysis
- principal component analysis
- exercise: correlation analysis

next class

Class 7 Measuring the diversity and complexity of the Internet (11/9)

- sampling
- statistical analysis
- histogram
- exercise: histogram, CDF