

Internet Measurement and Data Analysis (2)

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review of previous class

theme of the class

- ▶ looking at the Internet from different views
 - ▶ learn how to measure what is difficult to measure
 - ▶ learn how to extract useful information from huge data sets

Class 1 Introduction (9/26)

- ▶ Big Data and Collective Intelligence
- ▶ Internet measurement
- ▶ Large-scale data analysis
- ▶ exercise: introduction of Ruby scripting language

today's topics

Data and variability

- ▶ Summary statistics
- ▶ Sampling
- ▶ How to make good graphs
- ▶ exercise: computing summary statistics by Ruby
- ▶ exercise: graph plotting by Gnuplot

data and variability

- ▶ variability of data
 - ▶ variability in measurements against the true value
 - ▶ the mean should be close to the true value
 - ▶ (but, to discuss the precision, we need to understand the variability)
 - ▶ variability in measured target itself
 - ▶ we need to understand the variability
- ▶ ways to understand the variability in data
 - ▶ summary statistics
 - ▶ visualization by graphs

summary statistics

numbers that summarize properties of data

- ▶ measure of location:
 - ▶ mean, median, mode
- ▶ measure of spread:
 - ▶ range, variance, standard deviation

measures of location

- ▶ mean: average, sensitive to outliers

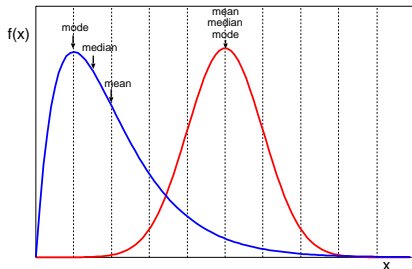
$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

- ▶ median: middle value (50th-percentile)

$$x_{median} = \begin{cases} x_{r+1} & \text{when } m \text{ is odd, } m = 2r + 1 \\ (x_r + x_{r+1})/2 & \text{when } m \text{ is even, } m = 2r \end{cases}$$

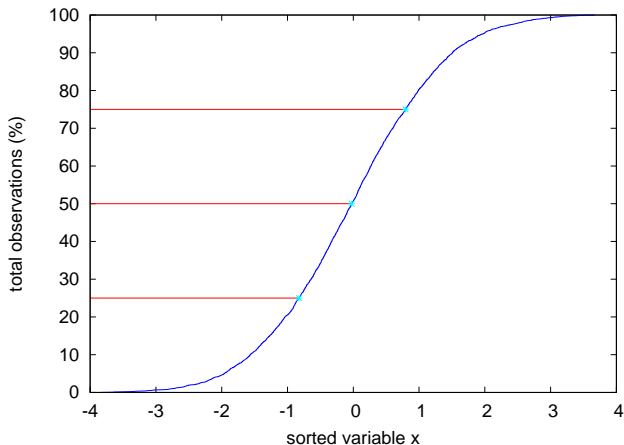
- ▶ mode: value with highest frequency

these are same if measurements have symmetric distribution



percentiles

- ▶ p th-percentile:
 - ▶ $p\%$ of the observed values are less than x_p in variable x_i ;
 - ▶ median = 50th-percentile



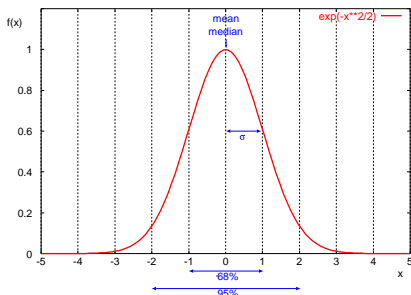
measures of spread

common measures of the spread of a data set

- ▶ range: difference between the max and min
- ▶ variance:

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$$

- ▶ standard deviation: σ
 - ▶ most common measure of statistical dispersion
 - ▶ can be directly compared with mean
- ▶ for a normal distribution, 68% fall into ($mean \pm stddev$), 95% fall into ($mean \pm 2stddev$)



computing variance

variance:

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$$

using the above formula, you need to compute the mean first, and then, compute the variance.

you can compute the variance in one-pass with the following formula.

$$\begin{aligned}\sigma^2 &= \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 \\ &= \frac{1}{n} \sum_{i=1}^n (x_i^2 - 2x_i\bar{x} + \bar{x}^2) \\ &= \frac{1}{n} \left(\sum_{i=1}^n x_i^2 - 2\bar{x} \sum_{i=1}^n x_i + n\bar{x}^2 \right) \\ &= \frac{1}{n} \sum_{i=1}^n x_i^2 - 2\bar{x}^2 + \bar{x}^2 \\ &= \frac{1}{n} \sum_{i=1}^n x_i^2 - \bar{x}^2\end{aligned}$$

sampling

- ▶ investigating the whole population (census): not realistic in most cases
- ▶ sampling is needed

sampling for the Internet

- ▶ observation points
- ▶ time, duration
- ▶ packet, flow, IP addresses, user IDs

example: packet sampling methods

- ▶ counter-based $1/N$ sampling (deterministic)
 - ▶ simple to implement, widely used
 - ▶ possible synchronization with targets of measurement
- ▶ probabilistic $1/N$ sampling
 - ▶ probabilistically select packets (or other objects)
- ▶ sampling by time
 - ▶ example: take the first minute every hour
- ▶ flow-based sampling
 - ▶ probabilistically sample new flows
 - ▶ observe all packets belonging to a selected flow
 - ▶ advantage: able to analyze flow behaviors
- ▶ many other sampling methods

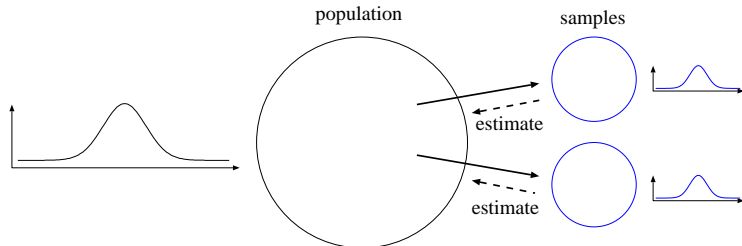
sampling: sample and population

summary statistics and statistical inference

- ▶ summary statistics: numbers that summarize properties of data (e.g., mean and standard deviation)
- ▶ statistical inference: makes inferences about the population based on samples using statistical methods

population: whole data (difficult or impossible to obtain for most cases)

- ▶ need to infer properties of the population from samples
- ▶ variables: properties of the population (fixed)
- ▶ statistics: inferred values based on samples (varying)



expected value

the expected value $E(X)$ of stochastic variable X : mean

- ▶ discrete model

$$E(X) = \mu = \sum_{i=1}^n x_i p_i$$

- ▶ continuous model

$$E(X) = \mu = \int_{-\infty}^{\infty} x f(x) dx$$

properties of expected values

- ▶ $E(c) = c$
- ▶ $E(X + c) = E(X) + c$
- ▶ $E(cX) = cE(X)$
- ▶ $E(X + Y) = E(X) + E(Y)$

sample mean

- ▶ sample mean: \bar{x}

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

- ▶ sample variance: s^2

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

- ▶ sample standard deviation: s
- ▶ note: divide sum of squares by $(n-1)$, not by n
 - ▶ degree of freedom: the number of independent variables in the sum of squares is $(n-1)$ because of \bar{x}

law of large numbers and central limit theorem

law of large numbers

- ▶ as the number of samples increases, the sample mean converges to the population mean

central limit theorem

- ▶ the mean of a sufficiently large number of samples is approximately normally distributed, regardless of the original distribution. $N(\mu, \sigma^2/n)$
- ▶ when the population is normally distributed, it can be applied even when n is small

standard error

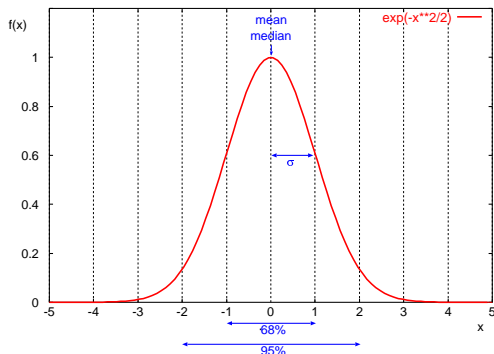
standard error: standard deviation of sample mean (SE)

$$SE = \sigma / \sqrt{n}$$

- ▶ you can improve the precision by increasing the number of samples n
 - ▶ standard error becomes smaller but with only $1/\sqrt{n}$
- ▶ the distribution of sample mean from a normal distribution $N(\mu, \sigma^2)$ will be a normal distribution with mean μ and standard deviation $SE = \sigma / \sqrt{n}$

normal distribution

- ▶ also known as gaussian distribution
- ▶ defined by 2 parameters: μ :mean, σ^2 :variance
- ▶ sum of random variables follows normal distribution
- ▶ standard normal distribution: $\mu = 0, \sigma = 1$
- ▶ in normal distribution
 - ▶ 68% within (*mean - stddev, mean + stddev*)
 - ▶ 95% within (*mean - 2 * stddev, mean + 2 * stddev*)



guidelines for plotting

require minimum effort from the reader

- ▶ label the axes clearly
- ▶ label the ticks on the axes
- ▶ identify individual curves/bars
- ▶ select appropriate font size
- ▶ use commonly accepted practices
 - ▶ zero-origins, math symbols, acronyms
- ▶ show variation/distribution of variables
- ▶ select ranges properly
- ▶ do not present too many items in a single chart
- ▶ when comparing data sets, use appropriate normalization
- ▶ when comparing plots, use the same scale for the axes
- ▶ do not use pie-charts or 3D-effects for technical writing
- ▶ when using colors
 - ▶ make sure it is readable in black-and-white print
 - ▶ make sure readable on data projectors (e.g., do not use yellow)

plotting raw data

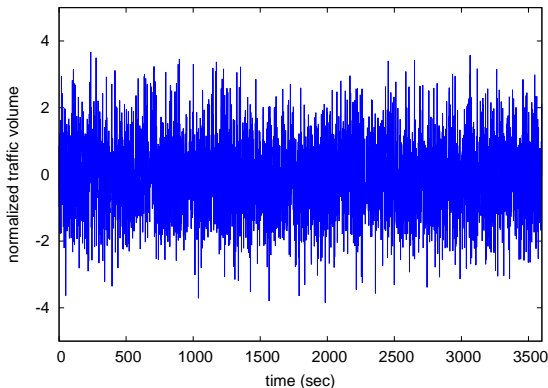
- ▶ time series plots
- ▶ histograms
- ▶ probability plots
- ▶ scatter plots

there are many other plotting techniques

time series plots

time-series plots (or other sequence plots) provides a feel for the data

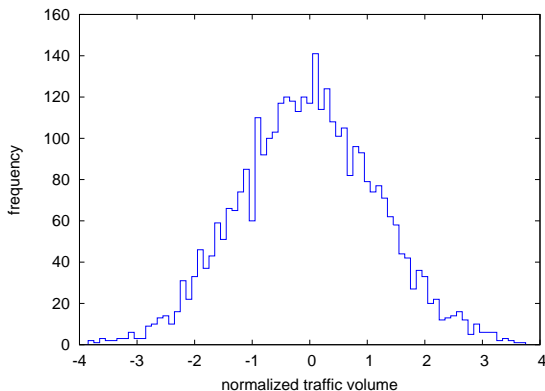
- ▶ you can identify
 - ▶ shifts in locations
 - ▶ shifts in variation
 - ▶ outliers



histograms

to see distribution of the data set

- ▶ split the data into equal-sized bins by value
- ▶ count the frequency of each bin
- ▶ plot
 - ▶ X axis: variable
 - ▶ Y axis: frequency



histograms (cont)

with histograms

- ▶ you can identify
 - ▶ center (i.e., the location) of the data
 - ▶ spread (i.e., the scale) of the data
 - ▶ skewness of the data
 - ▶ presence of outliers
 - ▶ presence of multiple modes in the data

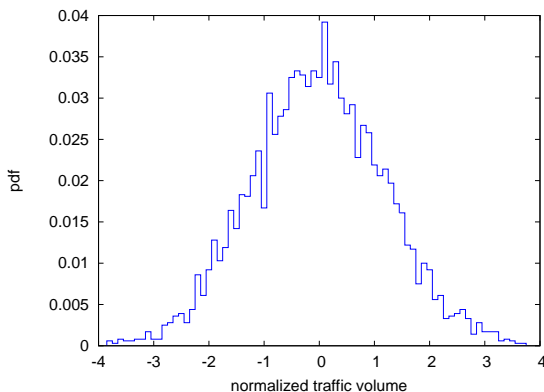
limitations of histograms

- ▶ needs appropriate bin size
 - ▶ too small: each bin doesn't have enough samples (e.g., empty bins)
 - ▶ too large: only few regions available
 - ▶ difficult for highly skewed distribution
- ▶ enough samples needed

probability density function (pdf)

- ▶ normalize the frequency (count)
 - ▶ sum of the area under the histogram to be 1
 - ▶ divide the count by the total number of observations times the bin width
- ▶ probability density function: probability of observing x

$$f(x) = P[X = x]$$



cumulative distribution function (cdf)

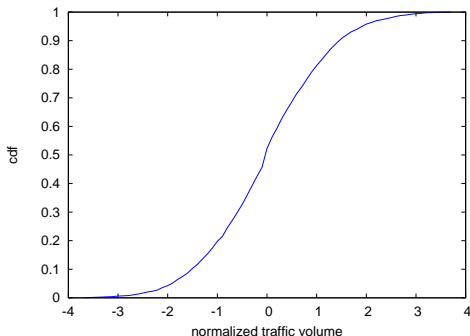
- ▶ density function: probability of observing x

$$f(x) = P[X = x]$$

- ▶ cumulative distribution function: probability of observing x or less

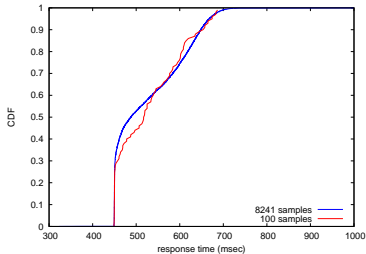
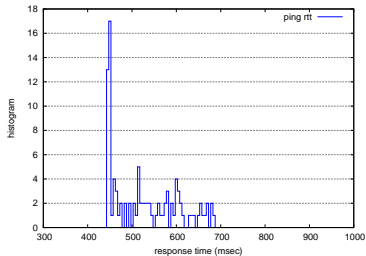
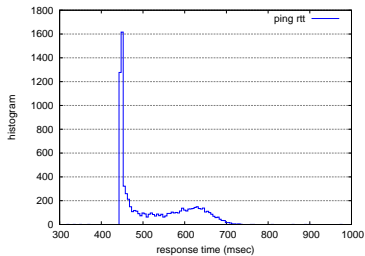
$$F(x) = P[X \leq x]$$

- ▶ better than histogram when distribution is highly skewed, sample count is not enough, or outliers are not negligible



histogram vs cdf

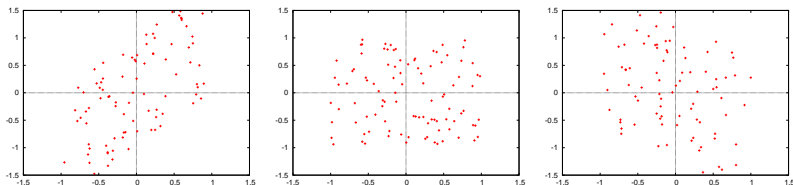
- ▶ no need to worry about bin size or sample count for cdf



original data (left), 100 samples (right), cdfs (bottom)

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)

plotting tools

- ▶ gnuplot
 - ▶ command-line tool suitable for automated plotting
 - ▶ <http://gnuplot.info/>
- ▶ grace
 - ▶ comes with graphical user interface
 - ▶ powerful for fine-tuning the output
 - ▶ <http://plasma-gate.weizmann.ac.il/Grace/>

previous exercise: a program to count text lines

count the number of text lines in a file given by the argument

```
filename = ARGV[0]
count = 0
file = open(filename)
while text = file.gets
  count += 1
end
file.close
puts count
```

write to “count.rb” and then run it

```
$ ruby count.rb foo.txt
```

rewrite it in a more rubyish way

```
#!/usr/bin/env ruby
count = 0
ARGV.each_line do |line|
  count += 1
end
puts count
```

exercise: computing summary statistics

- ▶ mean
- ▶ standard deviation
- ▶ median

- ▶ finish-time data of a city marathon: from P. K. Janert
“Gnuplot in Action”

<http://web.sfc.keio.ac.jp/~kjc/classes/sfc2012f-measurement/marathon.txt>

```
% head marathon.txt
# Minutes Count
133 1
134 7
135 1
136 4
137 3
138 3
141 7
142 24
143 13
```

exercise: computing mean

- ▶ read finish-time(in minutes) and the number of finishers from each line, sum up the product, and finally divide it by the total number of finishers

```
# regular expression to read minutes and count
```

```
re = /^(\d+)\s+(\d+)/
```

```
sum = 0 # sum of data
```

```
n = 0 # the number of data
```

```
ARGF.each_line do |line|
```

```
  if re.match(line)
```

```
    min = $1.to_i
```

```
    cnt = $2.to_i
```

```
    sum += min * cnt
```

```
    n += cnt
```

```
  end
```

```
end
```

```
mean = Float(sum) / n
```

```
printf "n:%d mean:%.1f\n", n, mean
```

```
% ruby mean.rb marathon.txt
```

```
n:2355 mean:171.3
```

exercise: computing standard deviation

► algorithm: $\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$

```
# regular expression to read minutes and count
re = /^(d+)\s+(d+)/

data = Array.new
sum = 0 # sum of data
n = 0 # the number of data
ARGF.each_line do |line|
  if re.match(line)
    min = $1.to_i
    cnt = $2.to_i
    sum += min * cnt
    n += cnt
    for i in 1 .. cnt
      data.push min
    end
  end
end

mean = Float(sum) / n
sqsum = 0.0
data.each do |i|
  sqsum += (i - mean)**2
end
var = sqsum / n
stddev = Math.sqrt(var)
printf "n:%d mean:%.1f variance:%.1f stddev:%.1f\n", n, mean, var, stddev
```

```
% ruby stddev.rb marathon.txt
n:2355 mean:171.3 variance:199.9 stddev:14.1
```

exercise: computing standard deviation in one-pass

► one-pass algorithm: $\sigma^2 = \frac{1}{n} \sum_{i=1}^n x_i^2 - \bar{x}^2$

```
# regular expression to read minutes and count
re = /^(d+)\s+(d+)/

sum = 0 # sum of data
n = 0 # the number of data
sqsum = 0 # su of squares
ARGF.each_line do |line|
  if re.match(line)
    min = $1.to_i
    cnt = $2.to_i
    sum += min * cnt
    n += cnt
    sqsum += min**2 * cnt
  end
end

mean = Float(sum) / n
var = Float(sqsum) / n - mean**2
stddev = Math.sqrt(var)

printf "n:%d mean:%.1f variance:%.1f stddev:%.1f\n", n, mean, var, stddev

% ruby stddev2.rb marathon.txt
n:2355 mean:171.3 variance:199.9 stddev:14.1
```


exercise: computing median

- ▶ create an array of each finish time, sort the array by value, and extract the central value

```
# regular expression to read minutes and count
re = /^(d+)\s+(d+)/
```

```
data = Array.new
```

```
ARGF.each_line do |line|
  if re.match(line)
    min = $1.to_i
    cnt = $2.to_i
    for i in 1 .. cnt
      data.push min
    end
  end
end
```

```
data.sort! # just in case data is not sorted
```

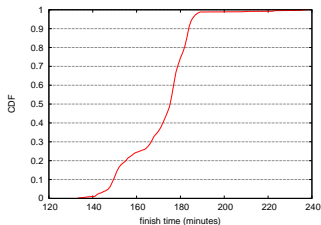
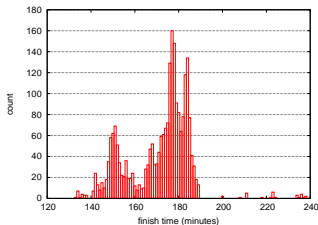
```
n = data.length # number of array elements
r = n / 2 # when n is odd, n/2 is rounded down
if n % 2 != 0
  median = data[r]
else
  median = (data[r - 1] + data[r])/2
end
```

```
printf "r:%d median:%d\n", r, median
```

```
% ruby median.rb marathon.txt
r:1177 median:176
```

exercise: gnuplot

- ▶ plotting simple graphs using gnuplot
 - ▶ to intuitively understand the data



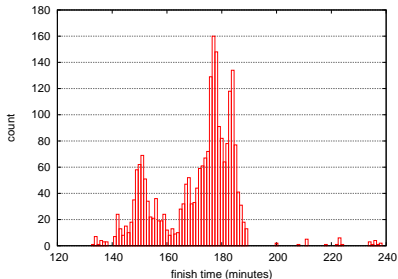
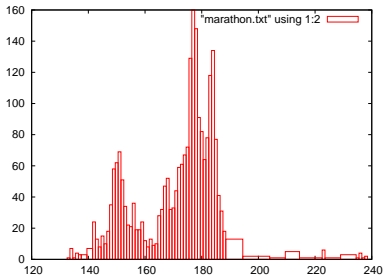
histogram

- ▶ distribution of finish time of a city marathon

```
plot "marathon.txt" using 1:2 with boxes
```

make the plot look better (right)

```
set boxwidth 1
set xlabel "finish time (minutes)"
set ylabel "count"
set yrange [0:180]
set grid y
plot "marathon.txt" using 1:2 with boxes notitle
```



exercise: plotting CDF of finish-time

original data:

```
# Minutes Count
133 1
134 7
135 1
136 4
137 3
138 3
141 7
142 24
...
```

add cumulative count:

```
# Minutes Count CumulativeCount
133 1 1
134 7 8
135 1 9
136 4 13
137 3 16
138 3 19
141 7 26
142 24 50
...
```

exercise: CDF (2)

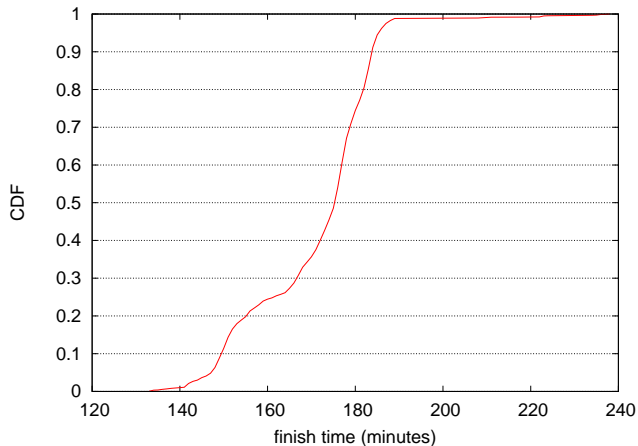
ruby code:

```
re = /^(d+)\s+(d+)/
cum = 0
ARGF.each_line do |line|
  begin
    if re.match(line)
      # matched
      time, cnt = $~.captures
      cum += cnt.to_i
      puts "#{time}\t#{cnt}\t#{cum}"
    end
  end
end
```

gnuplot command:

```
set boxwidth 1
set xlabel "finish time (minutes)"
set ylabel "CDF"
set grid y
plot "marathon-cdf.txt" using 1:($3 / 2355) with lines notitle
```

CDF plot of finish-time of city marathon



summary

Data and variability

- ▶ Summary statistics
- ▶ Sampling
- ▶ How to make good graphs
- ▶ exercise: graph plotting by Gnuplot

next class

NO CLASS on 10/10

Class 3 Data recording and log analysis (10/17)

- ▶ Network management tools
- ▶ Data format
- ▶ Log analysis methods
- ▶ exercise: log data and regular expression