

Lecture 1

Probability and Statistics

Wikipedia:

- Benjamin Disraeli, British statesman and literary figure (1804 – 1881):
 - ★ There are three kinds of lies: **lies, damned lies, and statistics**.
 - ◆ popularized in US by Mark Twain
 - ◆ the statement shows the persuasive power of numbers
 - 👉 use of statistics to bolster weak arguments
 - 👉 tendency of people to disparage statistics that do not support their positions
- The purpose of P416:
 - ★ how to understand the statistical uncertainty of observation/measurement
 - ★ how to use statistics to argue against a weak argument (or bolster a weak argument?)
 - ★ how to argue against people disparaging statistics that do not support their positions
 - ★ how to lie with statistics?

Introduction:

- Understanding of many physical phenomena depend on statistical and probabilistic concepts:
 - ★ Statistical Mechanics (physics of systems composed of many parts: gases, liquids, solids.)
 - ◆ 1 mole of anything contains 6×10^{23} particles (Avogadro's number)
 - ◆ impossible to keep track of all 6×10^{23} particles even with the fastest computer imaginable
 - ☞ resort to learning about the group properties of all the particles
 - ☞ partition function: calculate energy, entropy, pressure... of a system
 - ★ Quantum Mechanics (physics at the atomic or smaller scale)
 - ◆ wavefunction = probability amplitude
 - ☞ probability of an electron being located at (x,y,z) at a certain time.
- Understanding/interpretation of experimental data depend on statistical and probabilistic concepts:
 - ★ how do we extract the best value of a quantity from a set of measurements?
 - ★ how do we decide if our experiment is consistent/inconsistent with a given theory?
 - ★ how do we decide if our experiment is internally consistent?
 - ★ how do we decide if our experiment is consistent with other experiments?
 - ☞ In this course we will concentrate on the above experimental issues!

Definition of probability:

- Suppose we have N trials and a specified event occurs r times.
 - ★ example: rolling a dice and the event could be rolling a 6.
- ◆ define probability (P) of an event (E) occurring as:
 $P(E) = r/N$ when $N \rightarrow \infty$
- ★ examples:
 - six sided dice: $P(6) = 1/6$
 - coin toss: $P(\text{heads}) = 0.5$
 - ☞ $P(\text{heads})$ should approach 0.5 the more times you toss the coin.
 - ☞ for a single coin toss we can never get $P(\text{heads}) = 0.5!$
- ◆ by definition probability is a non-negative real number bounded by $0 \leq P \leq 1$
 - ★ if $P = 0$ then the event never occurs
 - ★ if $P = 1$ then the event always occurs
 - ★ sum (or integral) of all probabilities if they are mutually exclusive must = 1.
 - events are independent if: $P(A \cap B) = P(A)P(B)$
 - coin tosses are independent events, the result of next toss does not depend on previous toss.
 - events are mutually exclusive (disjoint) if: $P(A \cap B) = 0$ or $P(A \cup B) = P(A) + P(B)$
 - in coin tossing, we either get a head or a tail.

$\cap \equiv$ intersection, $\cup \equiv$ union

- Probability can be a discrete or a continuous variable.

- ◆ Discrete probability: P can have certain values only.

- ★ examples:

- tossing a six-sided dice: $P(x_i) = P_i$ here $x_i = 1, 2, 3, 4, 5, 6$ and $P_i = 1/6$ for all x_i .

- tossing a coin: only 2 choices, heads or tails.

- ★ for both of the above discrete examples (and in general)

when we sum over all mutually exclusive possibilities:

$$\sum_i P(x_i) = 1$$

- ◆ Continuous probability: P can be any number between 0 and 1.

- ★ define a “probability density function”, pdf, $f(x)$

$$f(x)dx = dP(x \leq \alpha \leq x + dx) \quad \text{with } \alpha \text{ a continuous variable}$$

- ★ probability for x to be in the range $a \leq x \leq b$ is:

$$P(a \leq x \leq b) = \int_a^b f(x)dx$$

- ★ just like the discrete case the sum of all probabilities must equal 1.

$$\int_{-\infty}^{+\infty} f(x)dx = 1$$

- ☞ $f(x)$ is **normalized** to one.

- ★ probability for x to be **exactly** some number is zero since:

$$\int_{x=a}^{x=a} f(x)dx = 0$$

Notation:
 x_i is called a
random variable

- Examples of some common $P(x)$'s and $f(x)$'s:

Discrete = $P(x)$ Continuous = $f(x)$

binomial uniform, i.e. constant

Poisson Gaussian

exponential

chi square

- How do we describe a probability distribution?

- mean, mode, median, and variance
- for a continuous distribution, these quantities are defined by:

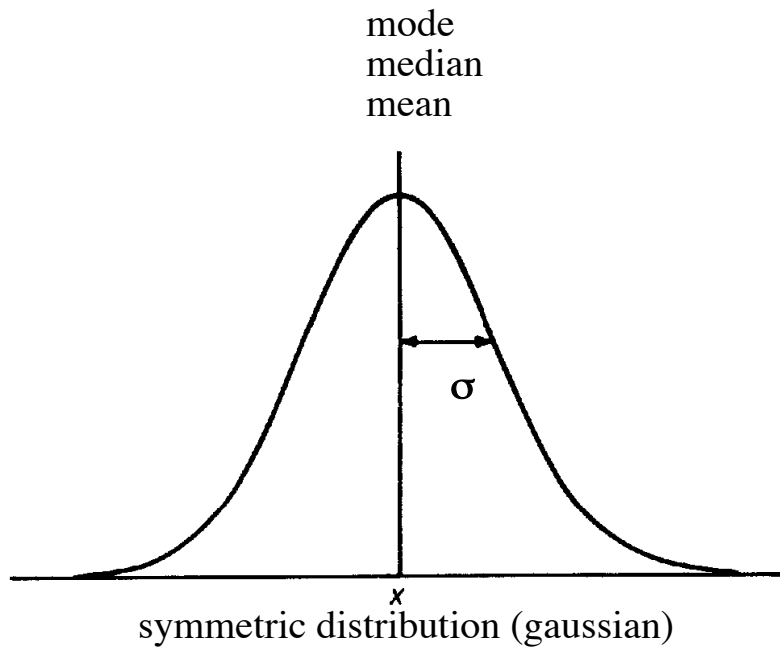
Mean	Mode	Median	Variance
average	most probable	50% point	width of distribution
$\mu = \int_{-\infty}^{+\infty} xf(x)dx$	$\left. \frac{\partial f(x)}{\partial x} \right _{x=a} = 0$	$0.5 = \int_{-\infty}^a f(x)dx$	$\sigma^2 = \int_{-\infty}^{+\infty} f(x)(x - \mu)^2 dx$

- for a discrete distribution, the mean and variance are defined by:

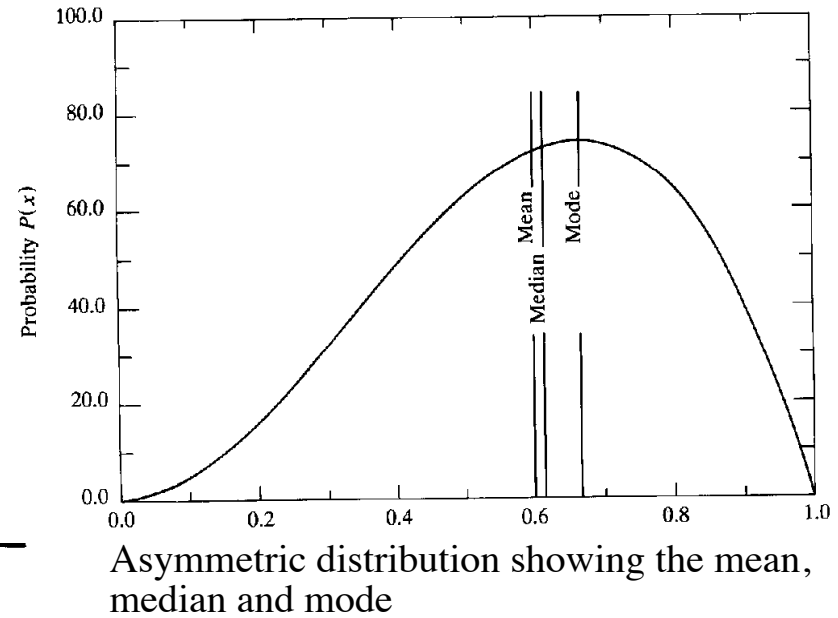
$$\mu = \frac{1}{n} \sum_{i=1}^n x_i$$

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

- Some continuous *pdf*:
 - Probability is the area under the curves!



For a Gaussian pdf,
the mean, mode,
and median are
all at the same x .



For most pdfs,
the mean, mode,
and median are
at different locations.

- Calculation of mean and variance:

- ◆ example: a discrete data set consisting of three numbers: {1, 2, 3}

- ★ average (μ) is just:

$$\mu = \sum_{i=1}^n \frac{x_i}{n} = \frac{1+2+3}{3} = 2$$

- ★ complication: suppose some measurement are more precise than others.

- ☞ if each measurement x_i have a weight w_i associated with it:

$$\mu = \sum_{i=1}^n x_i w_i / \sum_{i=1}^n w_i$$

“weighted average”

- ★ **variance** (σ^2) or average squared deviation from the mean is just:

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

variance describes the width of the pdf!

- σ is called the **standard deviation**

- ☞ rewrite the above expression by expanding the summations:

$$\sigma^2 = \frac{1}{n} \left[\sum_{i=1}^n x_i^2 + \sum_{i=1}^n \mu^2 - 2\mu \sum_{i=1}^n x_i \right]$$

$$= \frac{1}{n} \sum_{i=1}^n x_i^2 + \mu^2 - 2\mu^2$$

$$= \frac{1}{n} \sum_{i=1}^n x_i^2 - \mu^2$$

$$= \langle x^2 \rangle - \langle x \rangle^2$$

$\langle \rangle \equiv \text{average}$

- n in the denominator would be $n - 1$ if we determined the average (μ) from the data itself.

- ★ using the definition of μ from above we have for our example of $\{1,2,3\}$:

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n x_i^2 - \mu^2 = 4.67 - 2^2 = 0.67$$

- ★ the case where the measurements have different weights is more complicated:

$$\sigma^2 = \sum_{i=1}^n w_i (x_i - \mu)^2 / \sum_{i=1}^n w_i = \sum_{i=1}^n w_i x_i^2 / \sum_{i=1}^n w_i - \mu^2$$

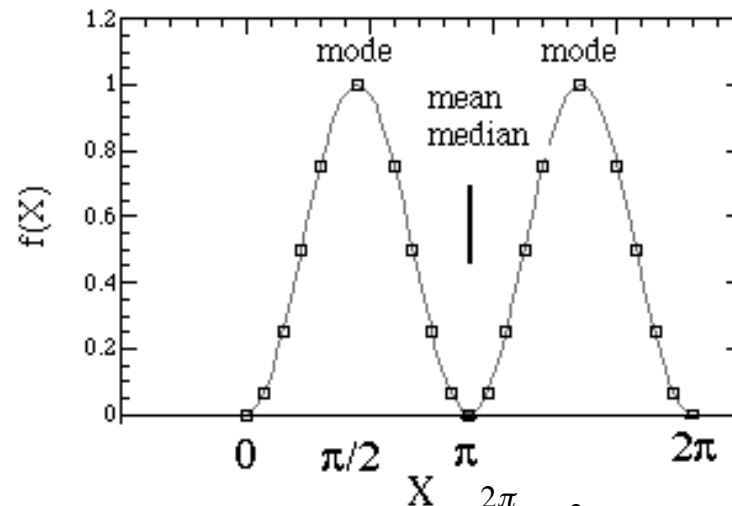
- μ is the **weighted** mean

- if we calculated μ from the data, σ^2 gets multiplied by a factor $n/(n-1)$.

- ◆ example: a continuous probability distribution, $f(x) = \sin^2 x$ for $0 \leq x \leq 2\pi$

- ★ has two modes!

- ★ has same mean and median, but differ from the mode(s).



- ★ $f(x)$ is not properly normalized: $\int_0^{2\pi} \sin^2 x dx = \pi \neq 1$

- ✉ normalized pdf: $f(x) = \sin^2 x / \int_0^{2\pi} \sin^2 x dx = \frac{1}{\pi} \sin^2 x$

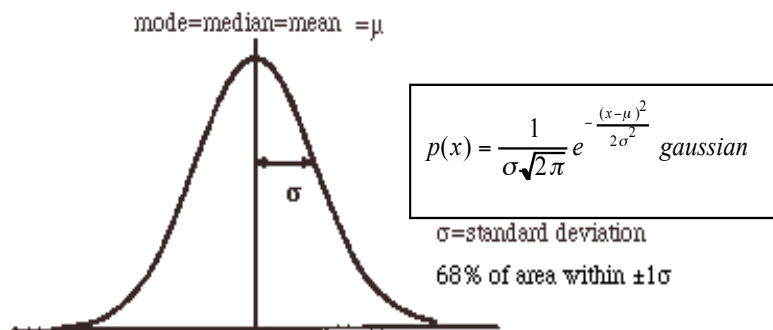
- ★ for continuous probability distributions, the mean, mode, and median are calculated using either integrals or derivatives:

$$\mu = \frac{1}{\pi} \int_0^{2\pi} x \sin^2 x dx = \pi$$

$$\text{mode} : \frac{\partial}{\partial x} \sin^2 x = 0 \Rightarrow \frac{\pi}{2}, \frac{3\pi}{2}$$

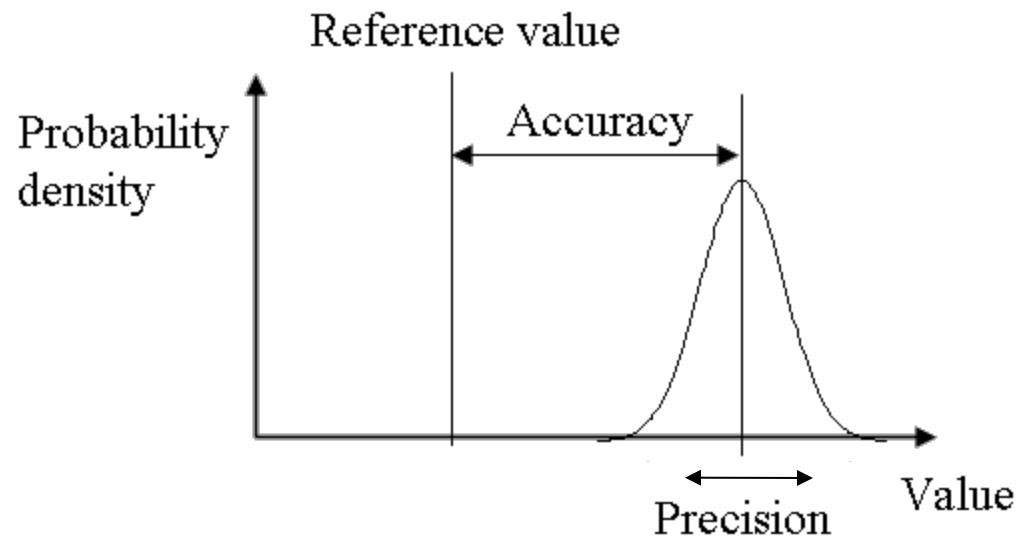
$$\text{median} : \frac{1}{\pi} \int_0^{\alpha} \sin^2 x dx = \frac{1}{2} \Rightarrow \alpha = \pi$$

- ◆ example: Gaussian distribution function, a continuous probability distribution



Accuracy and Precision:

- Accuracy: The accuracy of an experiment refers to how close the experimental measurement is to the true value of the quantity being measured.
- Precision: This refers to how well the experimental result has been determined, without regard to the true value of the quantity being measured.
 - ◆ just because an experiment is precise it does not mean it is accurate!!



Measurement Errors (Uncertainties)

- Use results from probability and statistics as a way of indicating how “good” a measurement is.
 - ◆ most common quality indicator:
relative precision = [uncertainty of measurement]/measurement
 - ★ example: we measure a table to be 10 inches with uncertainty of 1 inch.
relative precision = $1/10 = 0.1$ or 10% (% relative precision)
 - ◆ uncertainty in measurement is usually square root of variance:
 σ = standard deviation
 - ★ usually calculated using the technique of “propagation of errors”.

Statistics and Systematic Errors

- Results from experiments are often presented as:
 $N \pm XX \pm YY$
 - N : value of quantity measured (or determined) by experiment.
 - XX : statistical error, usually assumed to be from a Gaussian distribution.
 - ◆ with the assumption of Gaussian statistics we can say (calculate) something about how well our experiment agrees with other experiments and/or theories.
 - ★ Expect an 68% chance that the true value is between $N - XX$ and $N + XX$.
 - YY : systematic error. Hard to estimate, distribution of errors usually not known.
 - ◆ examples: mass of proton = 0.9382769 ± 0.0000027 GeV (only statistical error given)
mass of W boson = $80.8 \pm 1.5 \pm 2.4$ GeV

- What's the difference between statistical and systematic errors?

$$N \pm XX \pm YY$$

- ◆ statistical errors are “random” in the sense that if we repeat the measurement enough times:

$$XX \rightarrow 0$$

- ◆ systematic errors do **not** $\rightarrow 0$ with repetition.

- ★ examples of sources of systematic errors:

- voltmeter not calibrated properly

- a ruler not the length we think is (meter stick might really be $<$ meter!)

- ◆ because of systematic errors, an experimental result can be precise, but not accurate!

- How do we combine systematic and statistical errors to get one estimate of precision?

☞ **big problem!**

- ◆ two choices:

- ★ $\sigma_{\text{tot}} = XX + YY$ add them linearly

- ★ $\sigma_{\text{tot}} = (XX^2 + YY^2)^{1/2}$ add them in quadrature

- Some other ways of quoting experimental results

- ◆ lower limit: “the mass of particle X is > 100 GeV”

- ◆ upper limit: “the mass of particle X is < 100 GeV”

- ◆ asymmetric errors: mass of particle $X = 100_{-3}^{+4}$ GeV

- Don't quote any measurement to more than three digits as it is difficult to achieve 0.1% precision:

- ◆ 0.231 ± 0.013 , 791 ± 57 , $(5.98 \pm 0.43) \times 10^{-5}$

- ◆ measurement and uncertainty should have the same number of digits