Gaussian

Chris Piech
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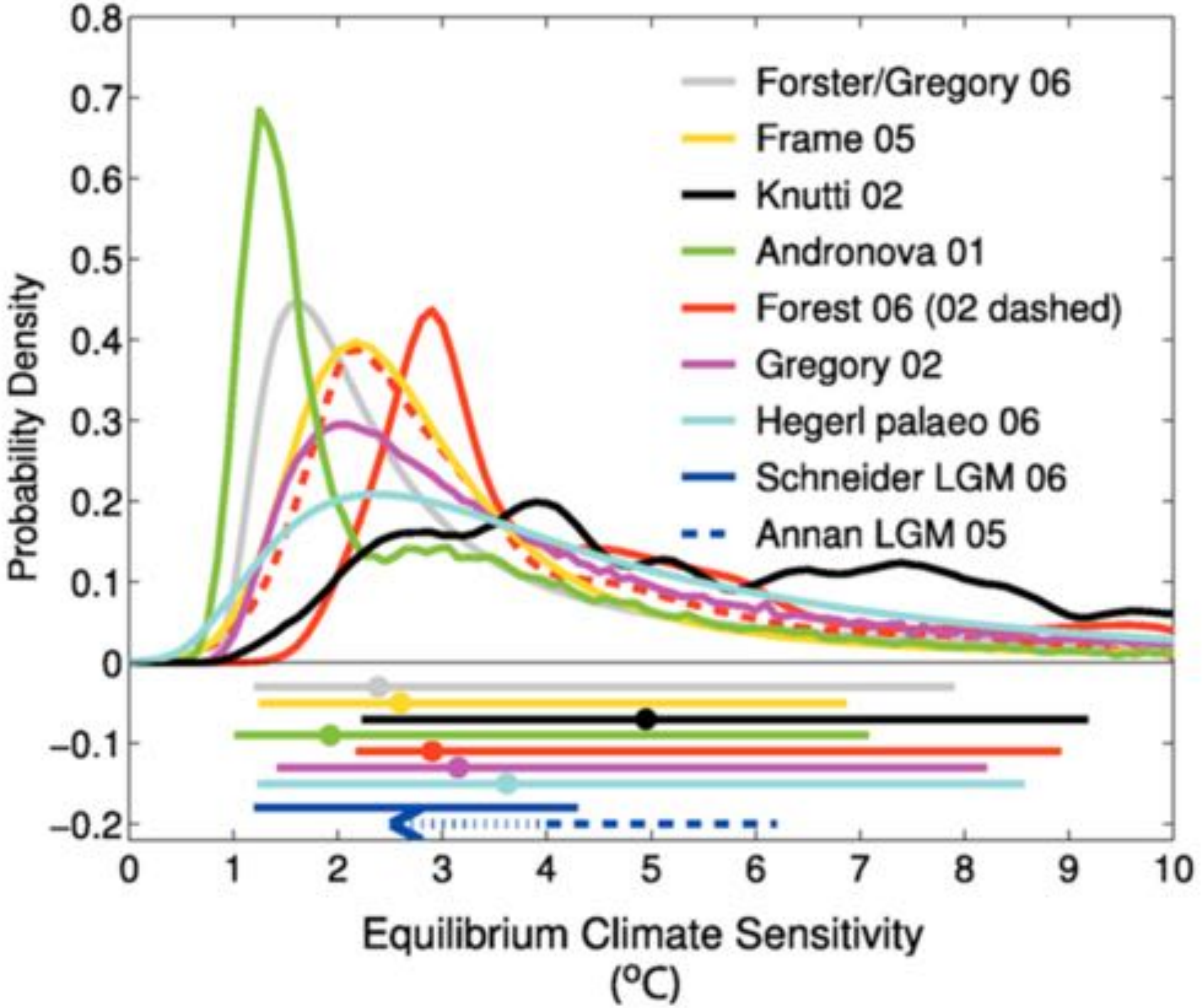
Which is Random?

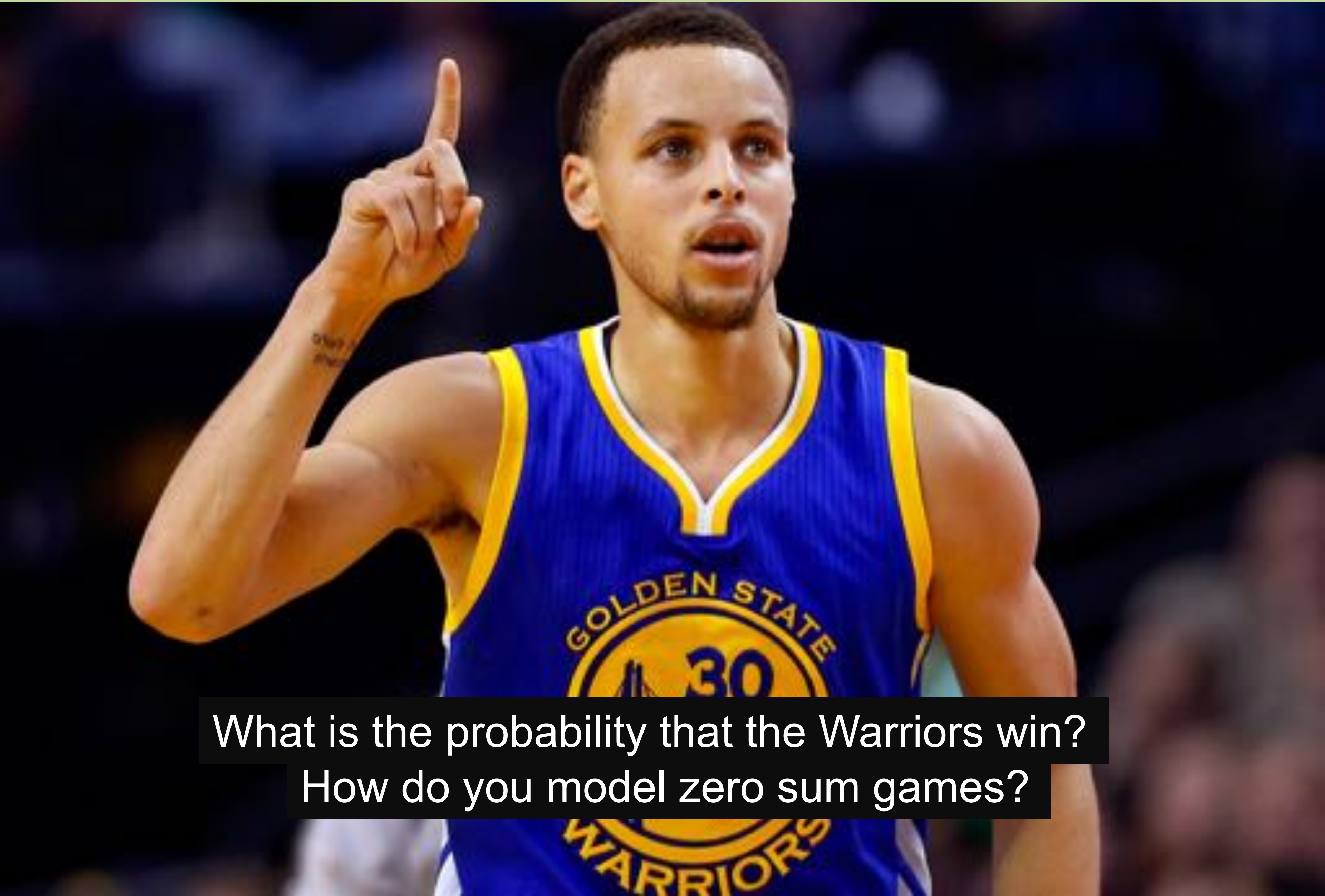
Sequence 1:
TTHHTHTTHTTTHTTTHTTTHTTHTHHTHHTHTHHTTTHHTHTHTTHTHHTTHTHHTHTTTH
HTTHHTTHHHTHHTHTTHTHTTHHTHHHTTHTHTTTHHTTHTHTHTHTHTTHTHTHHHTTHT
HTHHTHHHTHTHTTHTTHHTHTHTHTTHHTTHTHTTHHHTHTHTHTTHTTHHTTHTHHTHHH
TTHHTHTTHTHTHTHTHTHTHHHTHTHTHTTHTHHTHTHTTHTTTHHTHTTTHTHHTHHHHT
TTHHTHTHTHTHHHTTHHTHTTTHTHHTHTHTHHTHTTHTTHTHHTHTHTTT

Sequence 2:
HTHHHTHTTHHTTTTTTTTHHHTTTHHTTTTHHTTHHHTTHTHTTTTTTHTHTTTTHHHHTH
THTTHTTTHTTHTTTTHTHHTHHHHTTTTTHHHHTHHHTTTTHTHTTHHHHTHHHHHHHHTT
HHTHHTHHHHHHHTTHTHTTTHHTTTTHTHHTTHTTHTHTHTTHHHHHTTHTTTHTHTHHTT
TTHTTTTTHHTHTHHHHTTTTHTHHHHHHTHTHTHTHHHTHTTHHHTHHHHHHTHHHTHTTT
HHHTTTHHTHTTHHTHHHTHTTHTTHTTTHHTHTHTTTTHTHTHTTHTHTHT

Climate Sensitivity



Will the Warriors Win?



What is the probability that the Warriors win?

How do you model zero sum games?

Continuous Random Variables

Probability Density Function

The **probability density function** (PDF) of a continuous random variable represents the relative likelihood of various values.

Units of probability *divided by units of X*.
Integrate it to get probabilities!

$$P(a < X < b) = \int_{x=a}^{b} \boxed{f_X(x)}\, dx$$

What do you get if you integrate over a probability *density* function?

A probability!

Cumulative Density Function

A cumulative density function (CDF) is a “closed form” equation for the probability that a random variable is less than a given value

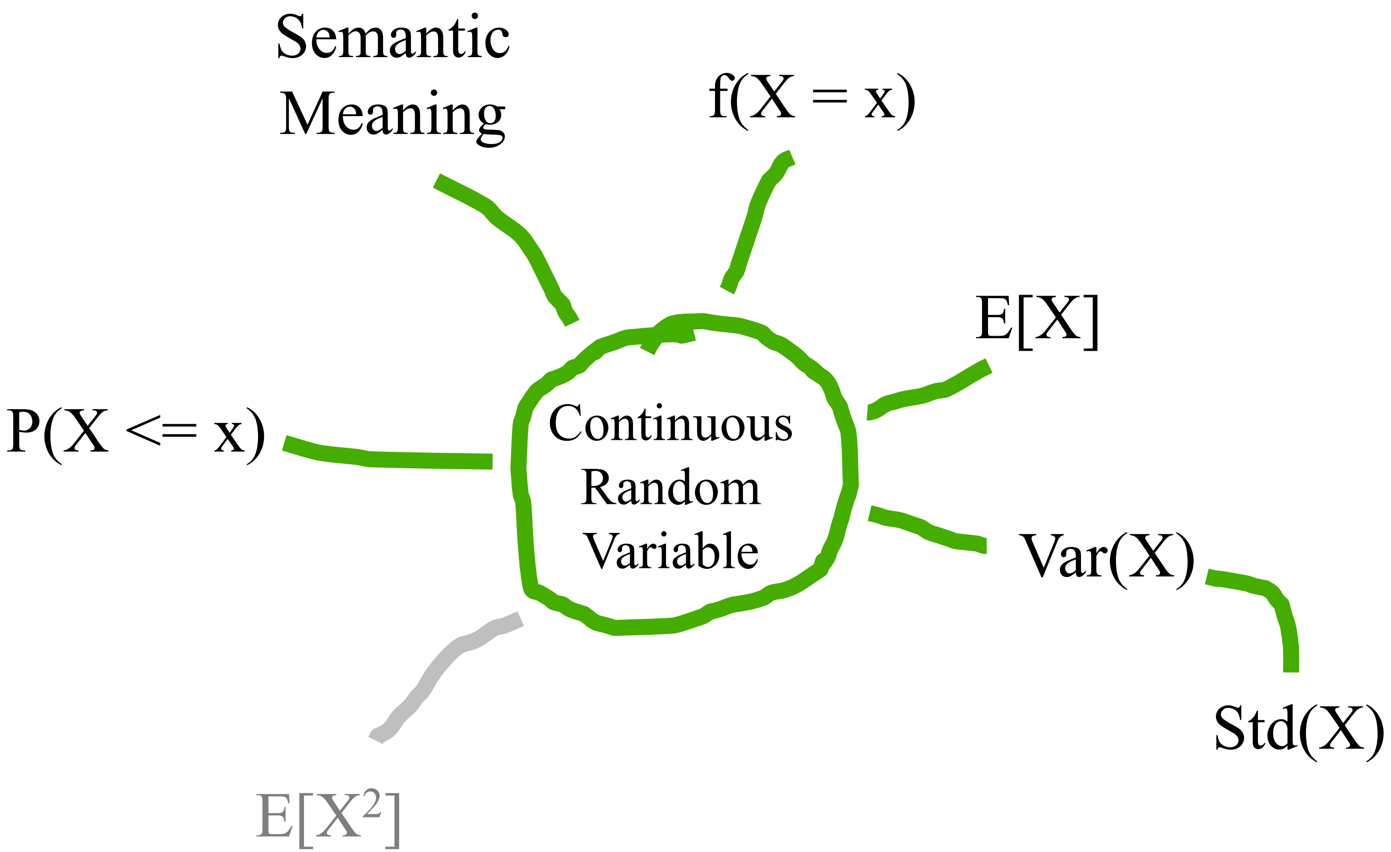
$$F(x) = P(X < x)$$

If you learn how to use a cumulative density function, you can avoid integrals!

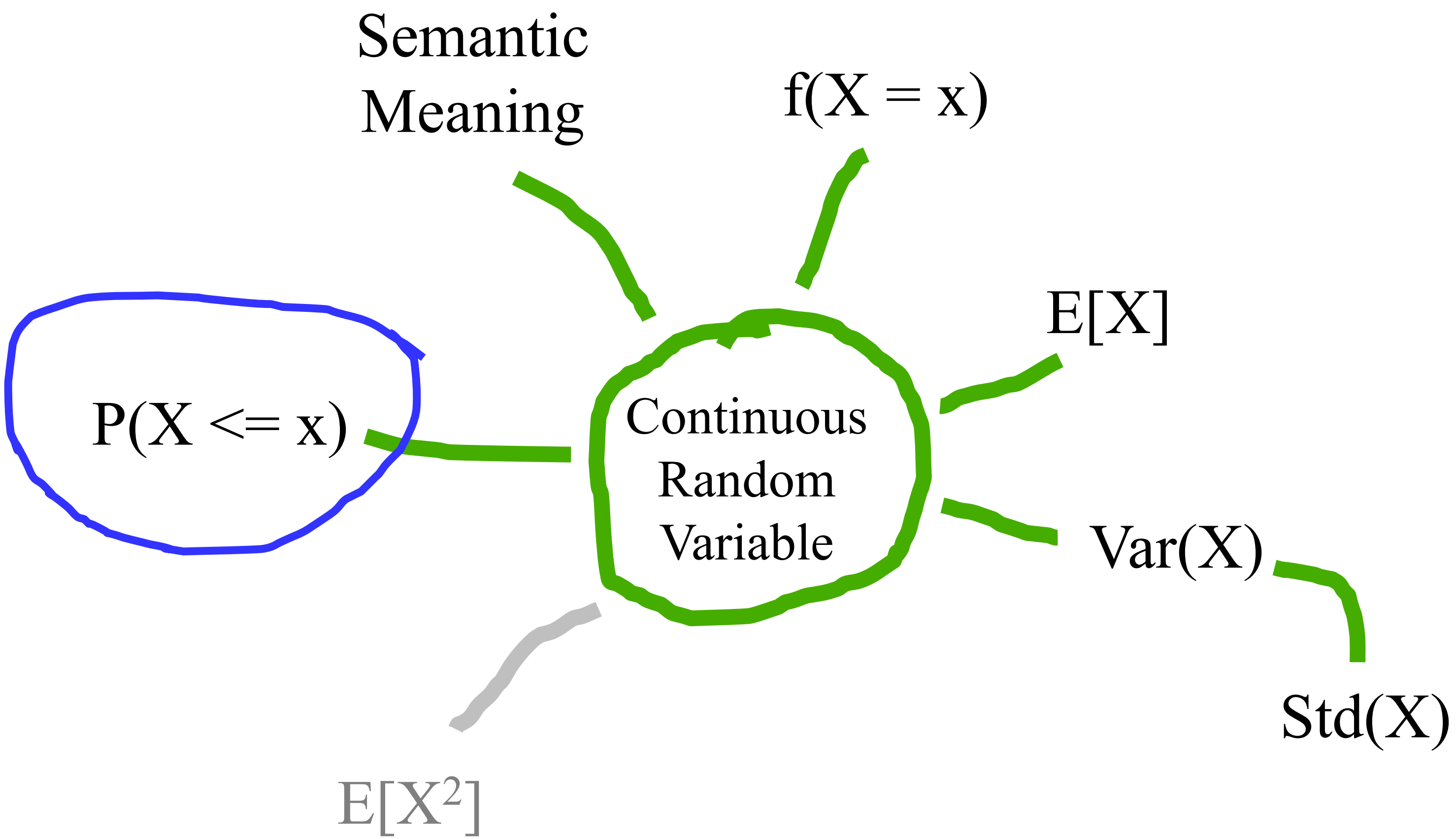
$$F_X(x)$$

This is also shorthand notation for the PMF

Fundamental Properties



Fundamental Properties



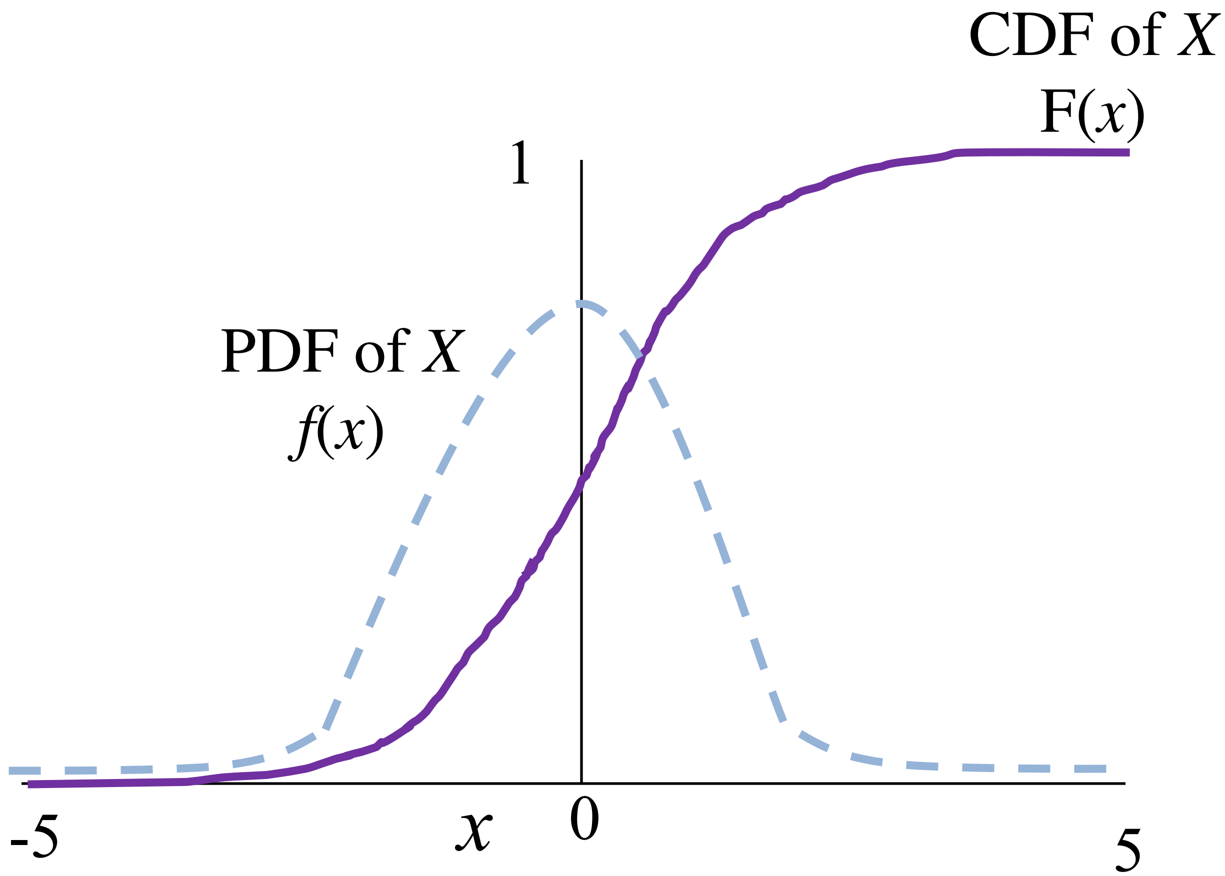
Notation

$p(a)$ or $p_X(a)$ Probability Mass Function (discrete) $P(X = a)$

$f(a)$ or $f_X(a)$ Probability Density Function (continuous)

$F(a)$ or $F_X(a)$ Cumulative Density Function $P(X \leq a)$

Density vs Cumulative



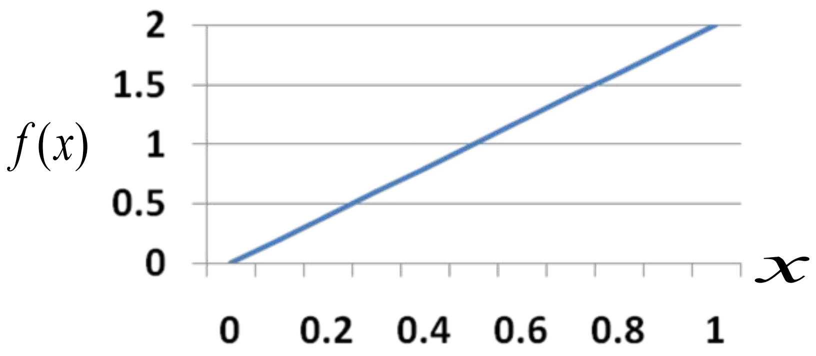
$f(x)$ = derivative of probability

$F(x) = P(X < x)$

Finding Constants

- X is a continuous random variable with PDF:

$$f(x) = \begin{cases} 2x & 0 \le x \le 1 \\ 0 & \text{otherwise} \end{cases}$$



What about $f(x) = 3x$?

$$\int_0^1 2x\ dx = x^2|_0^1 = 1$$

valid PDF

$$\int_0^1 3x\ dx = \frac{3}{2}x^2|_0^1 = \frac{3}{2}$$

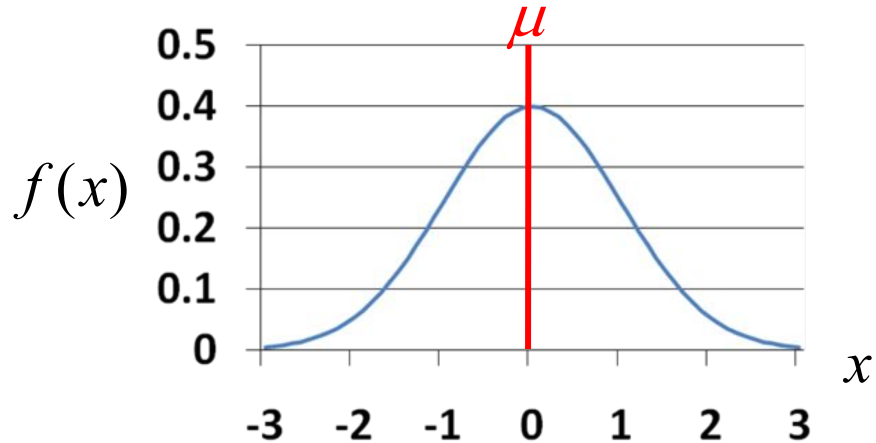
Not a valid PDF

Big Day

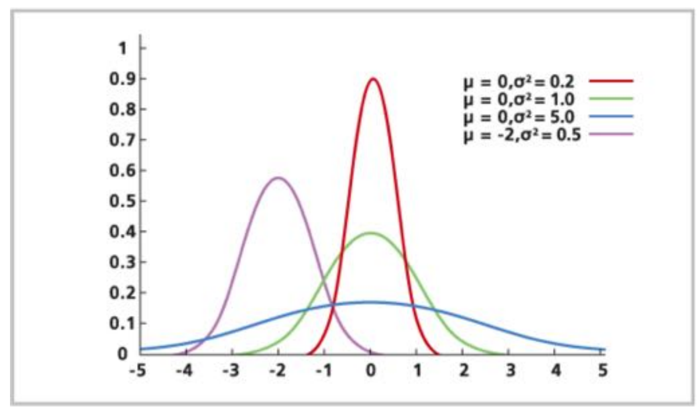
The Normal Distribution

- X is a **Normal Random Variable**: $X \sim N(\mu, \sigma^2)$
  - Probability Density Function (PDF):

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \quad \text{where} \quad -\infty < x < \infty$$



  - $E[X] = \mu$
  - $Var(X) = \sigma^2$
  - Also called "Gaussian"
  - Note: $f(x)$ is symmetric about μ



Why use the normal?

- Common for natural phenomena: heights, weights, etc.
- Often results from the sum of multiple variables
- Most noise is Normal.
- Sample means are distributed normally.

Or that is what they want you to believe

But I Encourage you to be Critical

These are log-normal

- Common for natural phenomena: heights, weights, etc.

Only if they are equally weighted

- Often results from the sum of multiple variables

Most noise is assumed normal

- Most noise is Normal.

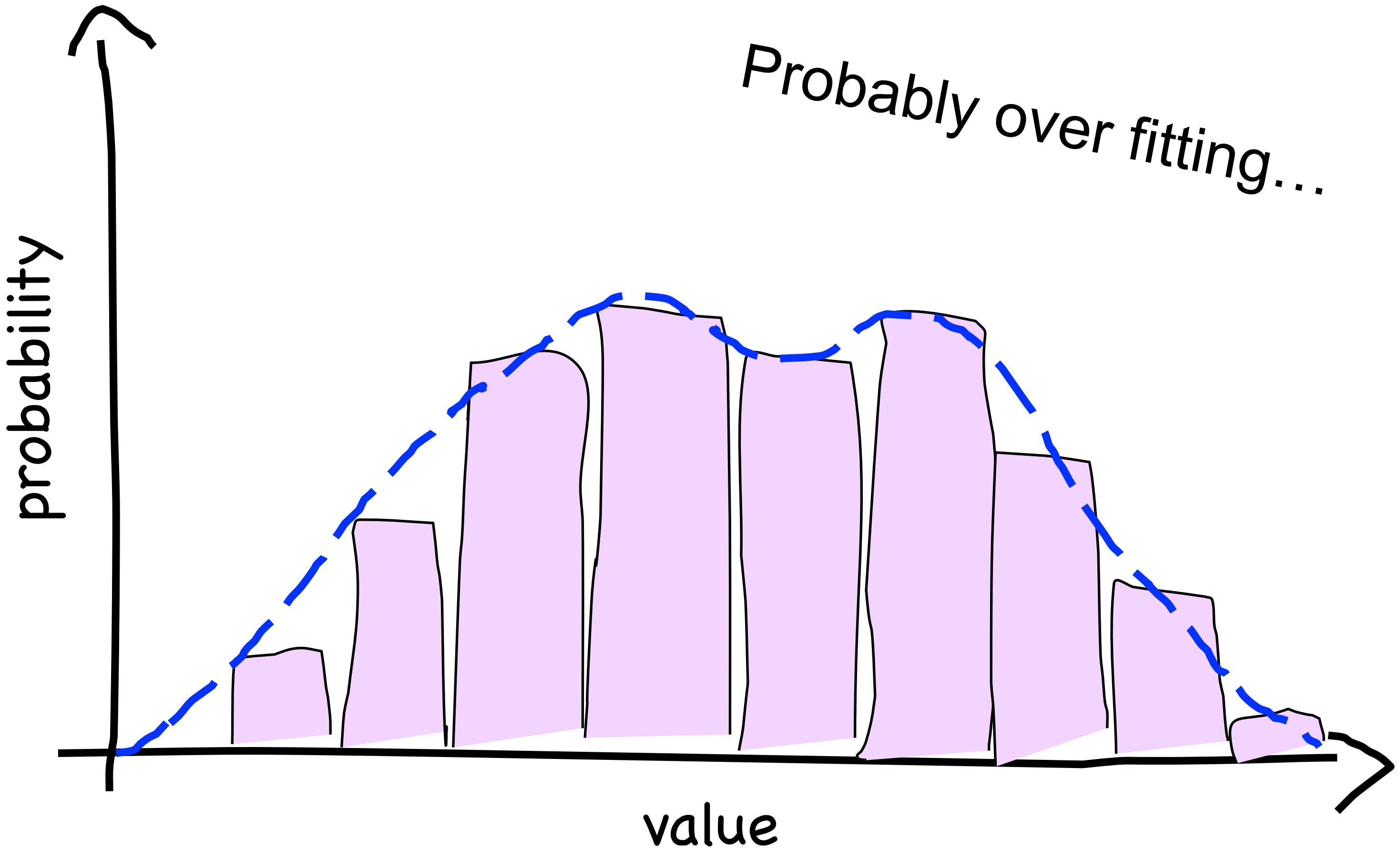
- Sample means are distributed normally.

It is the most important distribution

Because of a deeper truth…

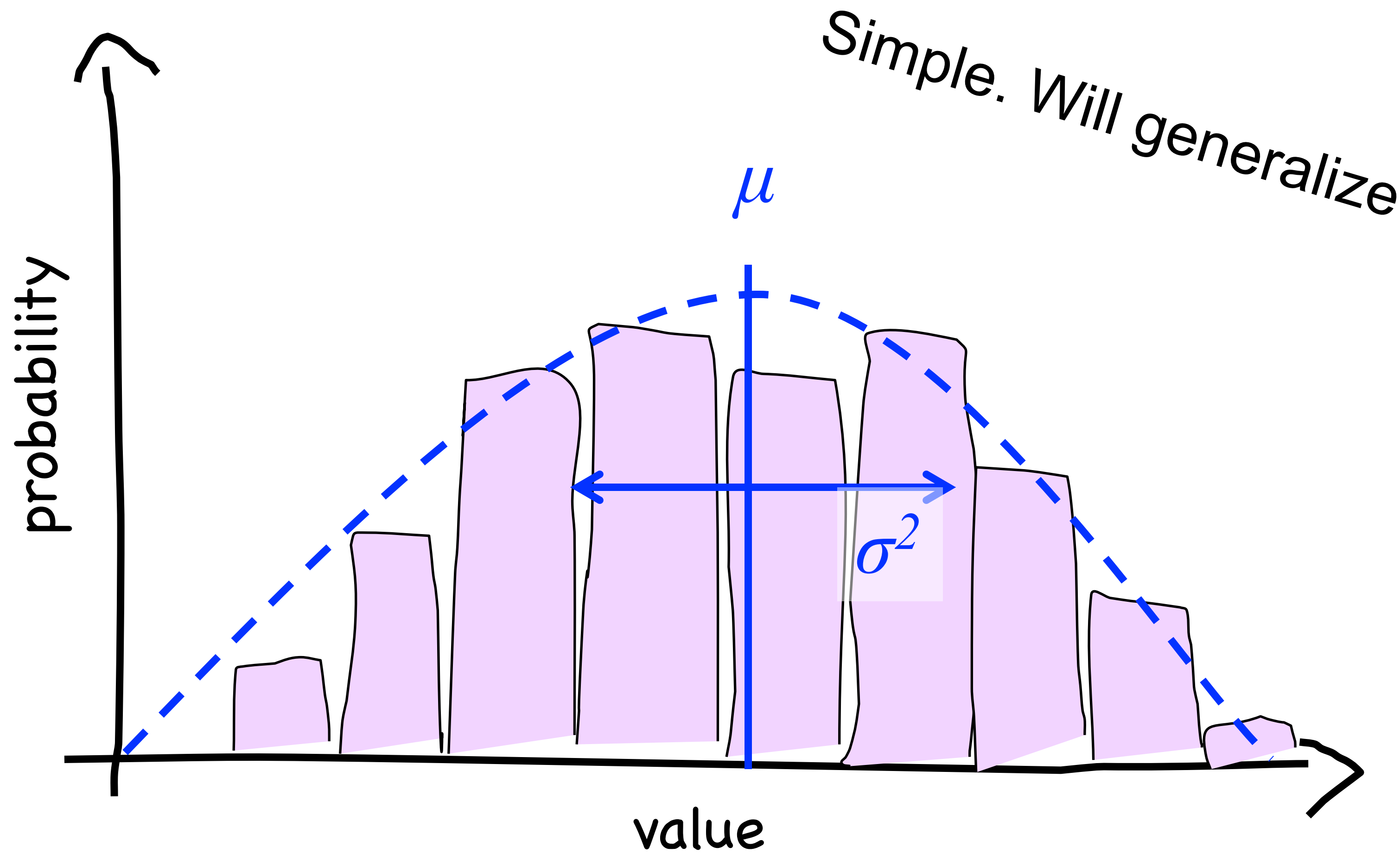
“The simplest explanation is usually the best one”

Complexity is Tempting



* That describes the training data, but will it generalize?

Simplicity is Humble



* A Gaussian maximizes entropy for a given mean and variance

Carl Friedrich Gauss

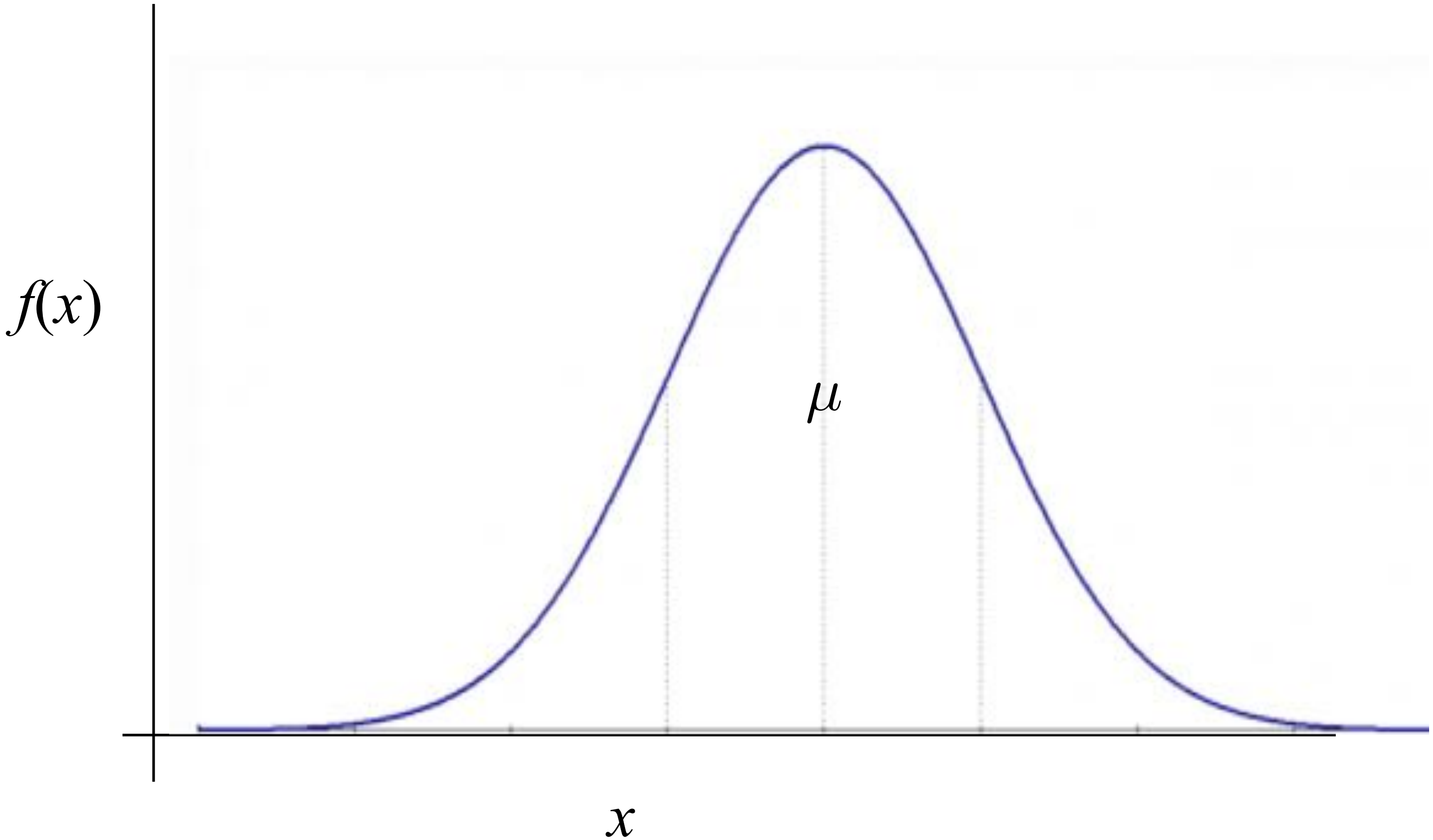
- Carl Friedrich Gauss (1777-1855) was a remarkably influential German mathematician

- Started doing groundbreaking math as teenager
  - Did not invent Normal distribution, but popularized it
- He looked like Martin Sheen
  - Who is, of course, Charlie Sheen's father

Probability Density Function

$$\mathcal{N}(\mu, \sigma^2)$$

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$



Anatomy of a beautiful equation

$\mathcal{N}(\mu, \sigma^2)$

"exponential"

the distance to the mean

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

probability density at x

a constant

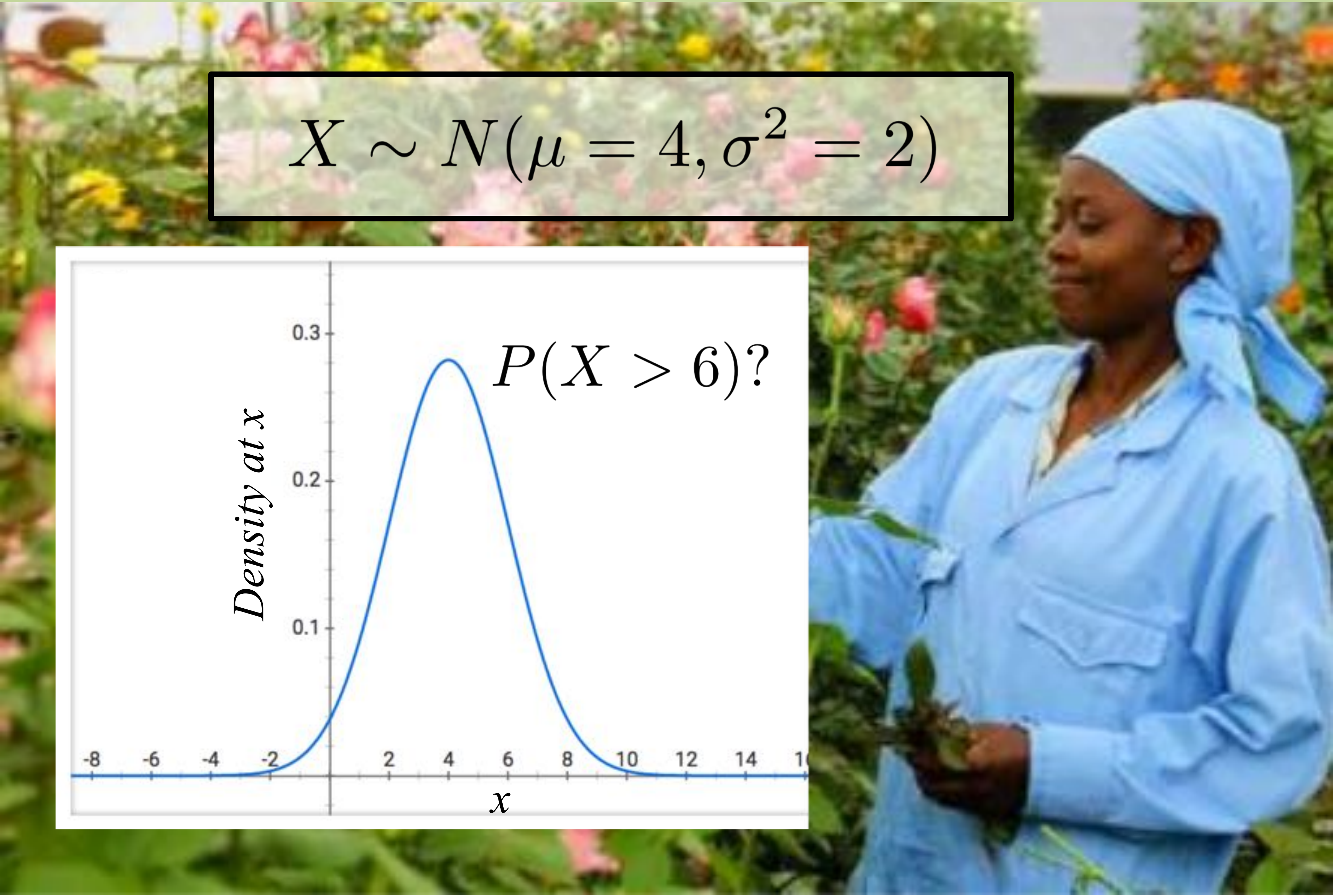
sigma shows up twice

Flowers on a Rose Bush

$$X \sim N(\mu = 4, \sigma^2 = 2)$$

Scientist from Kenya

$$X \sim N(\mu = 4, \sigma^2 = 2)$$



$$P(X > 6)?$$

Let's try and integrate it!

$$P(a \leq X \leq b) =$$

$$\int_a^b \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} dx$$

* Call me if you find an equation for this

No closed form for the integral

No closed form for $F(x)$

Spoiler Alert

$\mathcal{N}(\mu, \sigma^2)$

A function that has been solved for numerically

$$F(x) = \Phi\left(\frac{x - \mu}{\sigma}\right)$$

The cumulative density function of any normal

* We are going to spend the next few slides getting here

Linear Transform of Normal is Normal

Let $X \sim \mathcal{N}(\mu, \sigma^2)$

If $Y = aX + b$ then Y is also Normal

$$\begin{aligned} E[Y] &= E[aX + b] \\ &= aE[X] + b \\ &= a\mu + b \end{aligned}$$

$$\begin{aligned} Var(Y) &= Var(aX + b) \\ &= a^2 Var(X) \\ &= a^2\sigma^2 \end{aligned}$$

$$Y \sim \mathcal{N}(a\mu + b, a^2\sigma^2)$$

Special Linear Transform

If $Y = aX + b$ then Y is also Normal

$$Y \sim \mathcal{N}(a\mu + b, a^2\sigma^2)$$

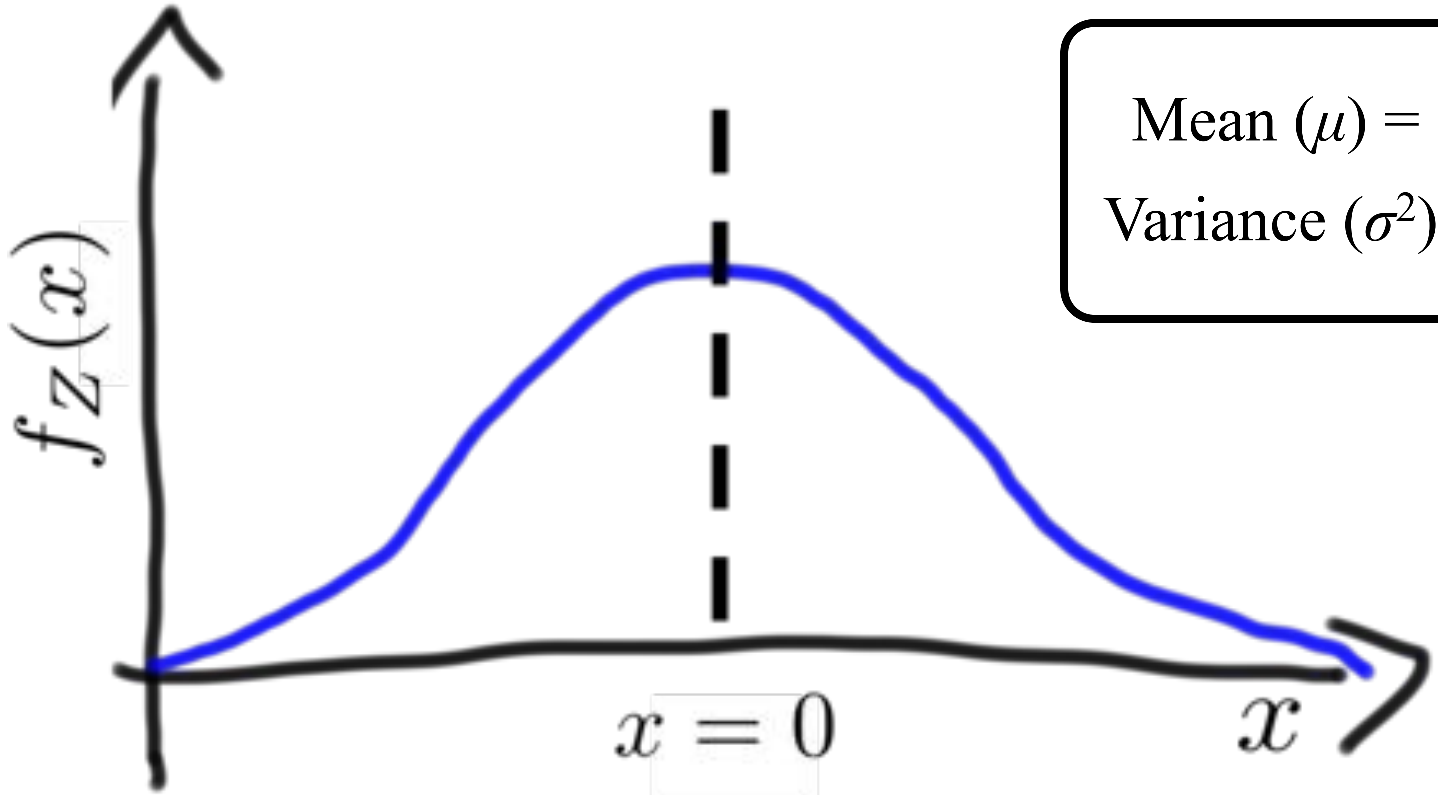
There is a special case of linear transform for any X:

$$Z = \frac{X - \mu}{\sigma} = \frac{1}{\sigma}X - \frac{\mu}{\sigma} \qquad a = \frac{1}{\sigma} \quad b = -\frac{\mu}{\sigma}$$

$$\begin{aligned} Z &\sim \mathcal{N}(a\mu + b, a^2\sigma^2) \\ &\sim \mathcal{N}(\frac{\mu}{\sigma} - \frac{\mu}{\sigma}, \frac{\sigma^2}{\sigma^2}) \\ &\sim \mathcal{N}(0, 1) \end{aligned}$$

The Standard Normal

$$Z \sim N(\mu = 0, \sigma^2 = 1)$$



Mean (μ) = 0

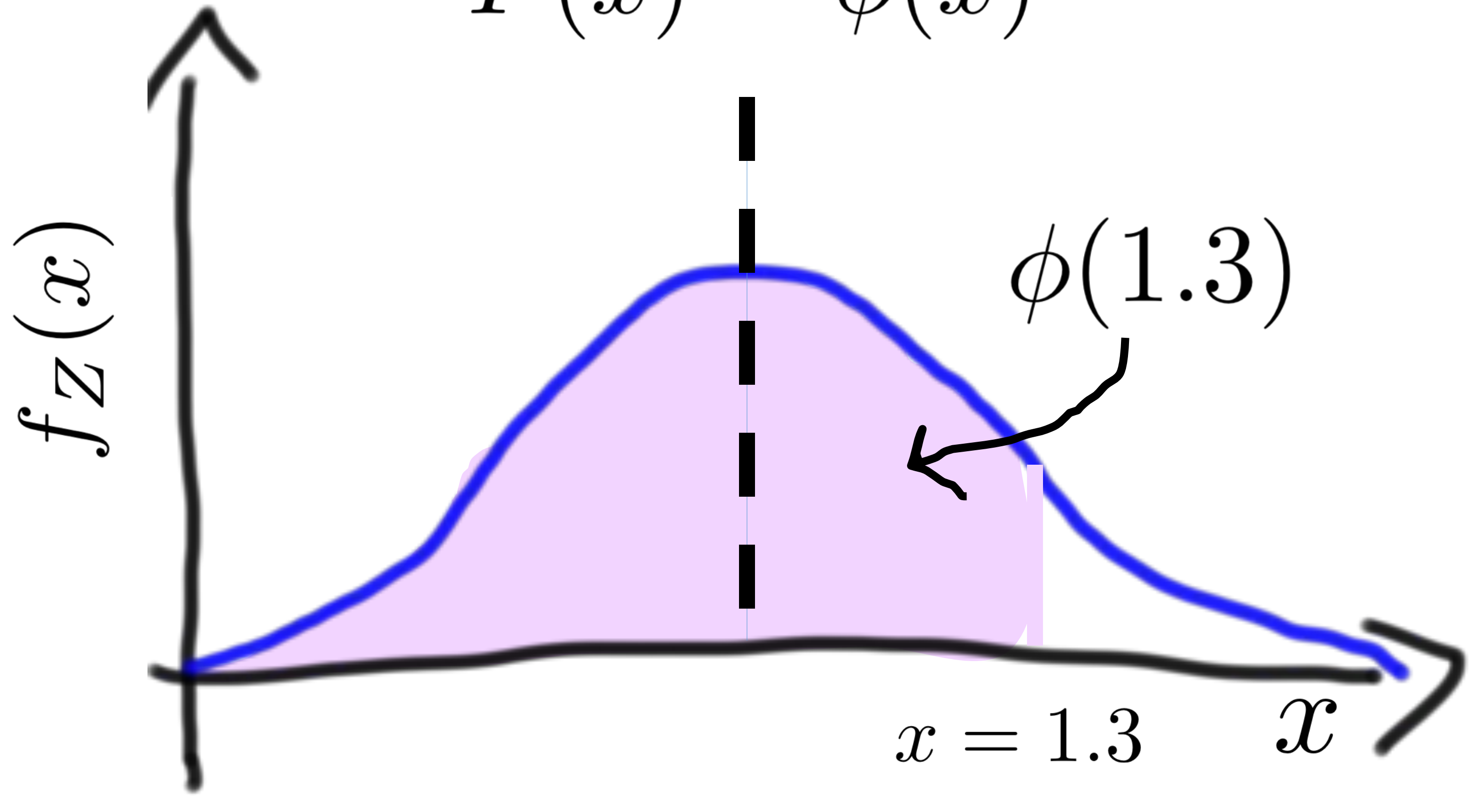
Variance (σ^2) = 1

*This is the probability density function for the standard normal

Phi

$$Z \sim N(\mu = 0, \sigma^2 = 1)$$

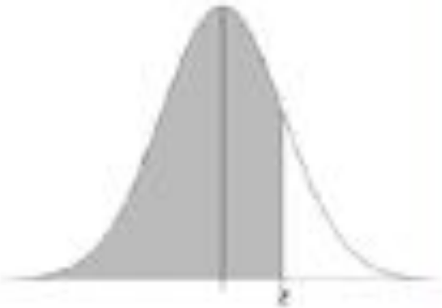
$$F(x) = \phi(x)$$



*This is the probability density function for the standard normal

Using Table of ϕ

Standard Normal Cumulative Probability Table



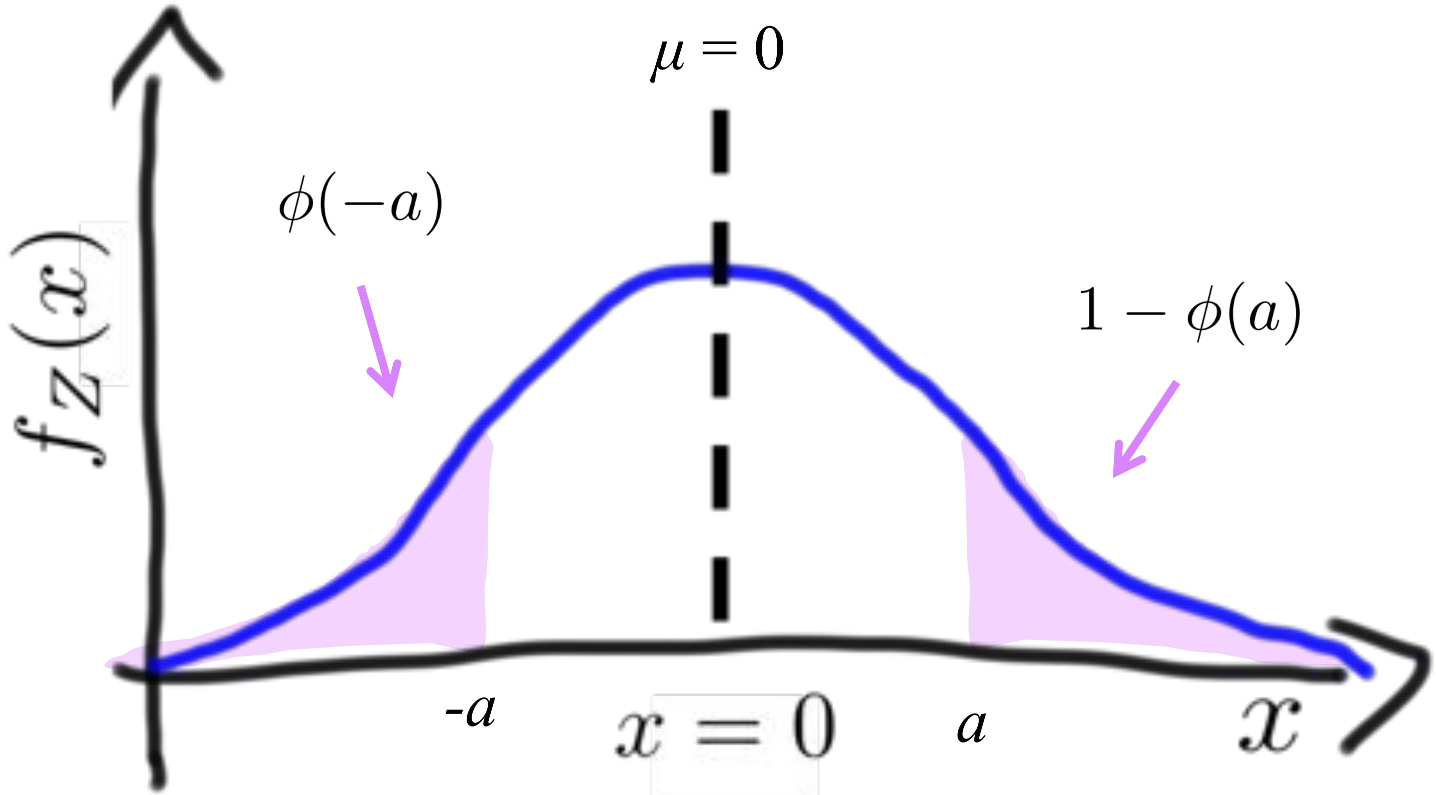
$\Phi(1.31) = 0.7054$

Cumulative probabilities for POSITIVE z-values are shown in the following table:

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319

Symmetry of Phi

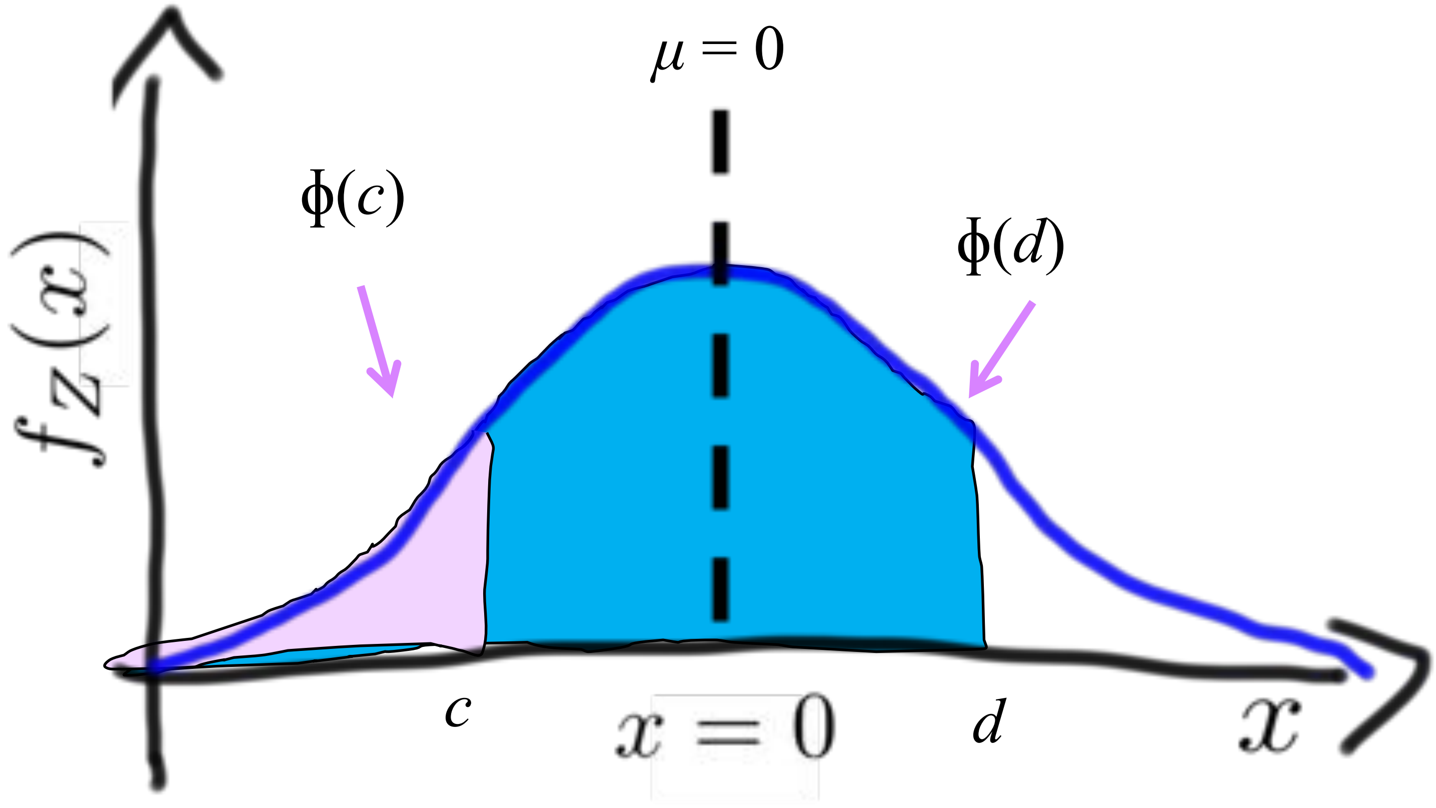
$$\phi(a) = 1 - \phi(a)$$



*This is the probability density function for the standard normal

Interval of Phi

$$P(c < Z < d) = \phi(d) - \phi(c)$$



Compute F(x) via Transform

Let $X \sim \mathcal{N}(\mu, \sigma^2)$ $\qquad Z = \frac{X - \mu}{\sigma}$

Use Z to compute $F(x)$

$$
\begin{aligned}
F_X(x) &= P(X \leq x) \\
&= P(X - \mu \leq x - \mu) \\
&= P\left(\frac{X - \mu}{\sigma} \leq \frac{x - \mu}{\sigma}\right) \\
&= P\left(Z \leq \frac{x - \mu}{\sigma}\right) \\
&= \Phi\left(\frac{x - \mu}{\sigma}\right)
\end{aligned}
$$

For normal distribution, F(x) is computed using the phi transform.

And here we are

$\mathcal{N}(\mu, \sigma^2)$

CDF of Standard Normal: A function that has been solved for numerically

$$F(x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

The cumulative density function (CDF) of any normal

Table of $\Phi(z)$ values in textbook, p. 201 and handout

Using Table of ϕ

Standard Normal Cumulative Probability Table

$\Phi(0.54) = 0.7054$

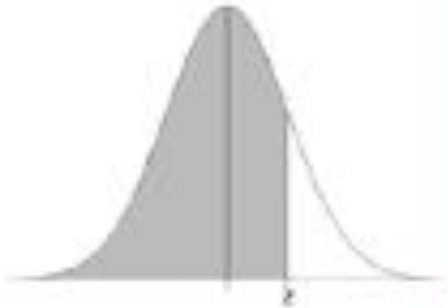


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Table is kinda old school

Using Programming Library

Every modern programming language has a normal library

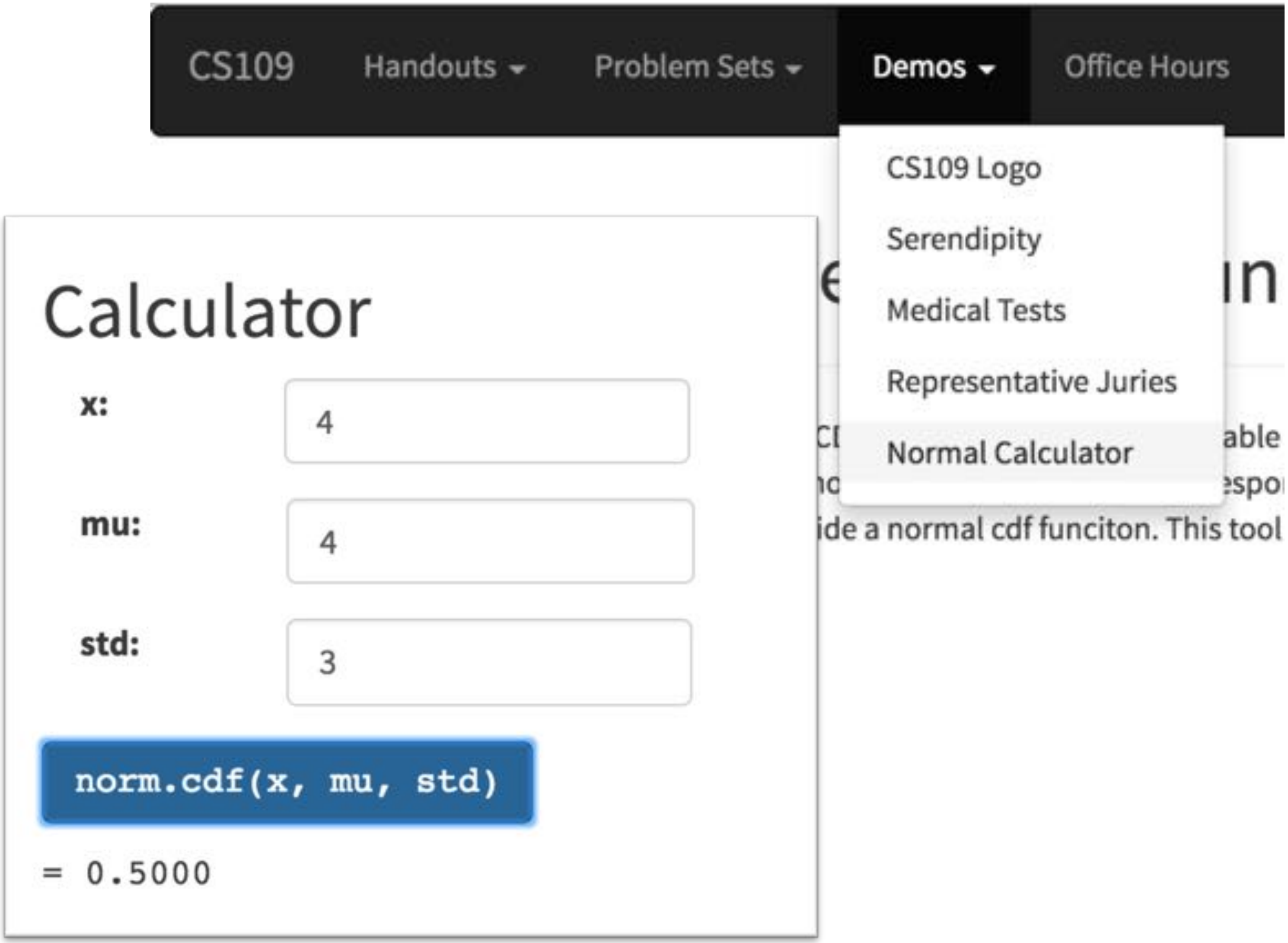
```
norm.cdf(x, mean, std)
```

$$= P(X < x) \text{ where } X \sim \mathcal{N}(\mu, \sigma^2)$$

$$= \Phi\left(\frac{x - \mu}{\sigma}\right)$$

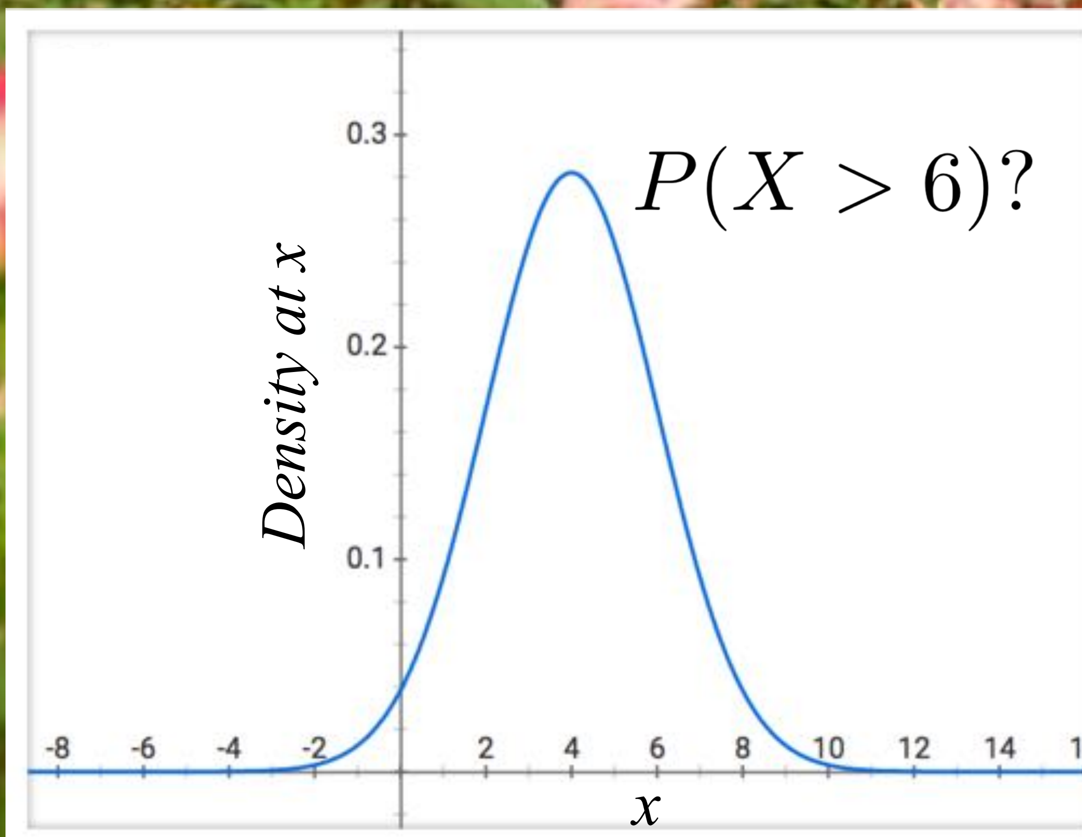
* This is from Python's scipy library

I made one for you



Flowers on a Rose Bush

$$X \sim N(\mu = 4, \sigma^2 = 2)$$



Flowers on a Rose Bush

flowers on a rose bush

$$X \sim N(\mu = 4, \sigma^2 = 2)$$

$$P(X > 6)?$$

$$P(X > 6) = F_X(6)$$

$$= \phi\left(\frac{6 - \mu}{\sigma}\right)$$

$$= \phi\left(\frac{6 - 4}{\sqrt{2}}\right)$$

$$\approx \phi(1.414)$$

$$\approx 0.921$$

For any normal:

$$F_X(x) = \phi\left(\frac{x - \mu}{\sigma}\right)$$

Get Your Gaussian On

- X ~ N(3, 16) $\mu = 3$ $\sigma^2 = 16$ $\sigma = 4$
  - What is P(X > 0)?

$$P(X > 0) = P(\frac{X-3}{4} > \frac{0-3}{4}) = P(Z > -\frac{3}{4}) = 1 - P(Z \leq -\frac{3}{4})$$

$$1 - \Phi(-\frac{3}{4}) = 1 - (1 - \Phi(\frac{3}{4})) = \Phi(\frac{3}{4}) = 0.7734$$

  - What is P(2 < X < 5)?

$$P(2 < X < 5) = P(\frac{2-3}{4} < \frac{X-3}{4} < \frac{5-3}{4}) = P(-\frac{1}{4} < Z < \frac{2}{4})$$

$$\Phi(\frac{2}{4}) - \Phi(-\frac{1}{4}) = \Phi(\frac{1}{2}) - (1 - \Phi(\frac{1}{4})) = 0.6915 - (1 - 0.5987) = 0.2902$$

  - What is P(|X – 3| > 6)?

$$P(X < -3) + P(X > 9) = P(Z < \frac{-3-3}{4}) + P(Z > \frac{9-3}{4})$$

$$\Phi(-\frac{3}{2}) + (1 - \Phi(\frac{3}{2})) = 2(1 - \Phi(\frac{3}{2})) = 2(1 - 0.9332) = 0.1337$$

Noisy Wires

- Send voltage of 2 or -2 on wire (to denote 1 or 0)
  - X = voltage sent
  - R = voltage received = X + Y, where noise Y ~ N(0, 1)
  - Decode R: if (R ≥ 0.5) then 1, else 0
  - What is P(error after decoding | original bit = 1)?

$$P(2+Y<0.5)=P(Y<-1.5)=\Phi(-1.5)=1-\Phi(1.5)\approx 0.0668$$

  - What is P(error after decoding | original bit = 0)?

$$P(-2+Y\geq 0.5)=P(Y\geq 2.5)=1-\Phi(2.5)\approx 0.0062$$

Gaussian for uncertainty

ELO Ratings

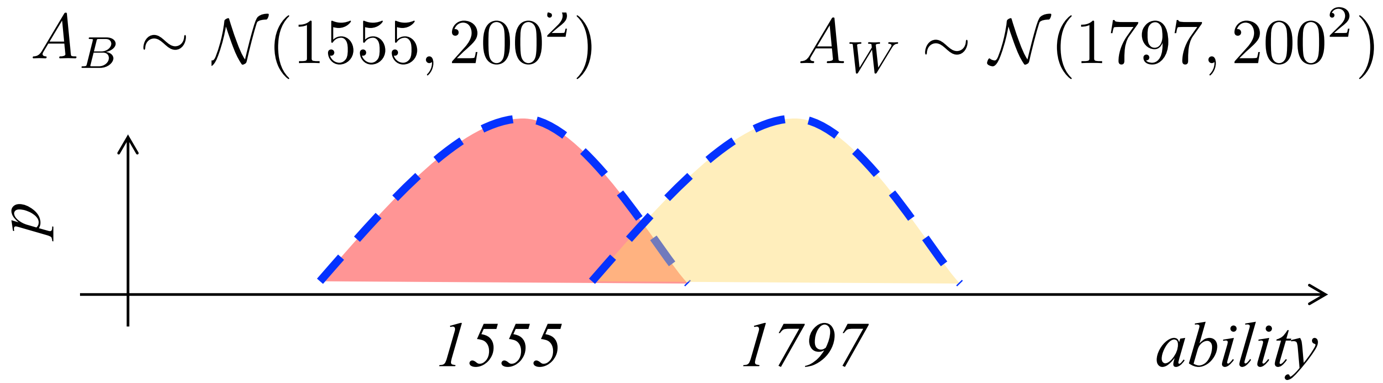
What is the probability that the Warriors win?
How do you model zero sum games?

ELO Ratings

How it works:

- Each team has an "ELO" score *S*, calculated based on their past performance.
- Each game, the team has ability $A \sim N(S, 200^2)$
- The team with the higher sampled ability wins.

Arpad Elo



$$P(\text{Warriors win}) = P(A_W > A_B)$$

ELO Ratings

```
from random import *

WARRIORS_ELO = 1797
OPPONENT_ELO = 1555
VAR = 200 * 200

nSuccess = 0
for i in range(NTRIALS):
    w = gauss(WARRIORS_ELO, VAR)
    b = gauss(OPPONENT_ELO, VAR)
    if w > b:
        nSuccess += 1

print float(nSuccess) / NTRIALS
```

ELO Ratings

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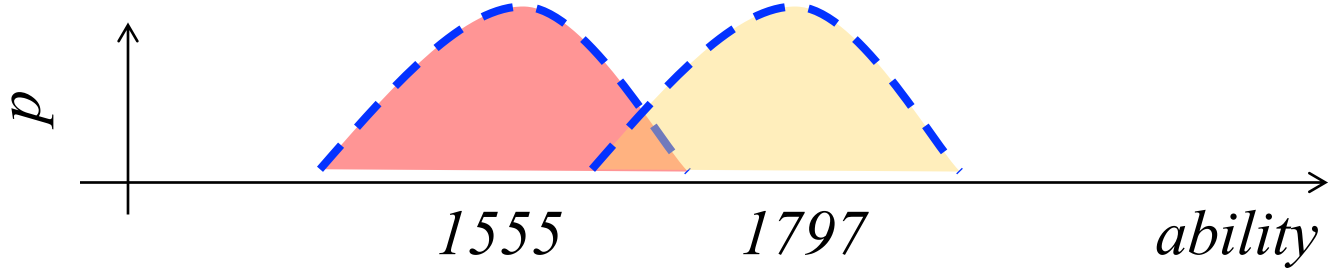
Arpad Elo

$$A_B \sim \mathcal{N}(1555, 200^2) \qquad A_W \sim \mathcal{N}(1797, 200^2)$$



$$P(\text{Warriors win}) = P(A_W > A_B)$$
$$\approx 0.87$$

← Calculated via sampling

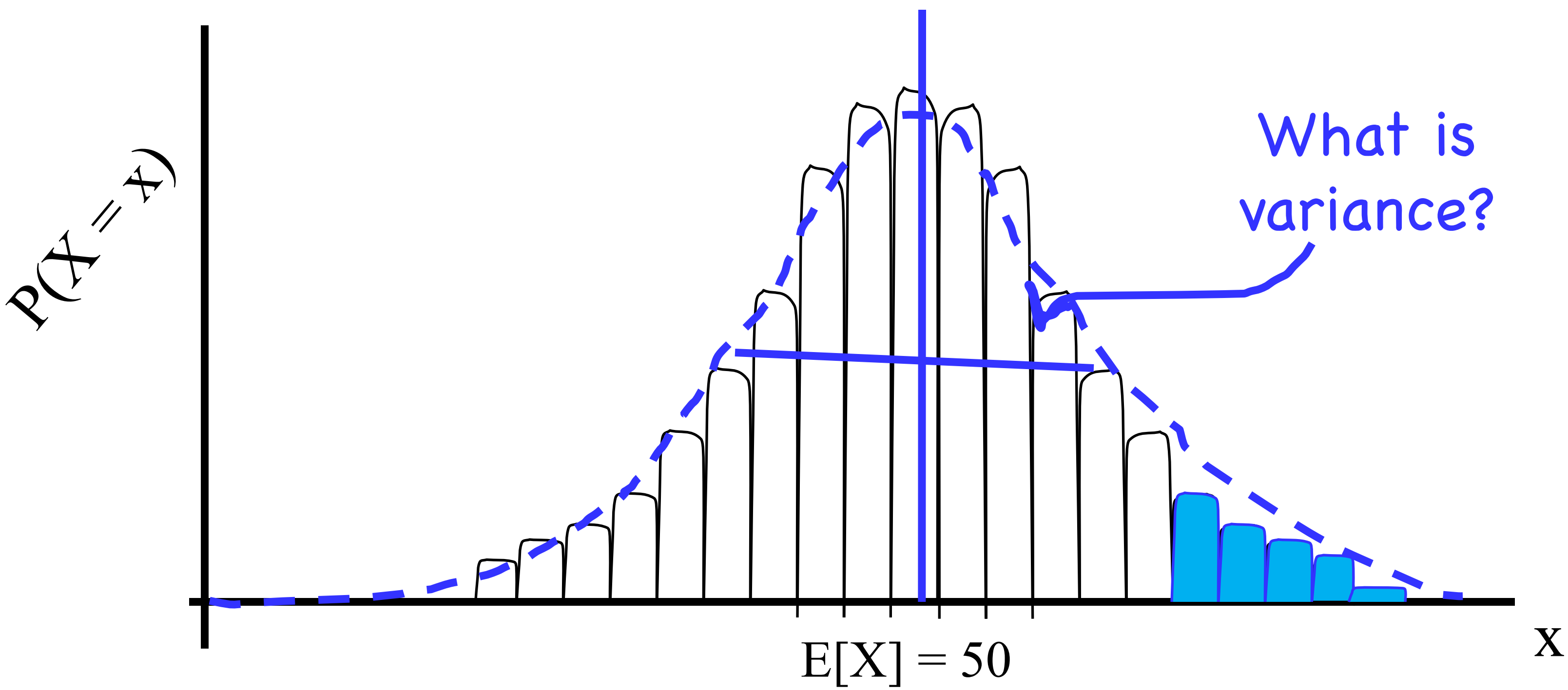
That's all folks!

If time…

Gaussian for a big number world

Website Testing

- 100 people are given a new website design
  - X = # people whose time on site increases
  - CEO will endorse new design if X ≥ 65 What is P(CEO endorses change| it has no effect)?
  - X ~ Bin(100, 0.5). Want to calculate P(X ≥ 65)



Website Testing

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  - CEO will endorse new design if X ≥ 65 What is P(CEO endorses change| it has no effect)?
  - X ~ Bin(100, 0.5). Want to calculate P(X ≥ 65)

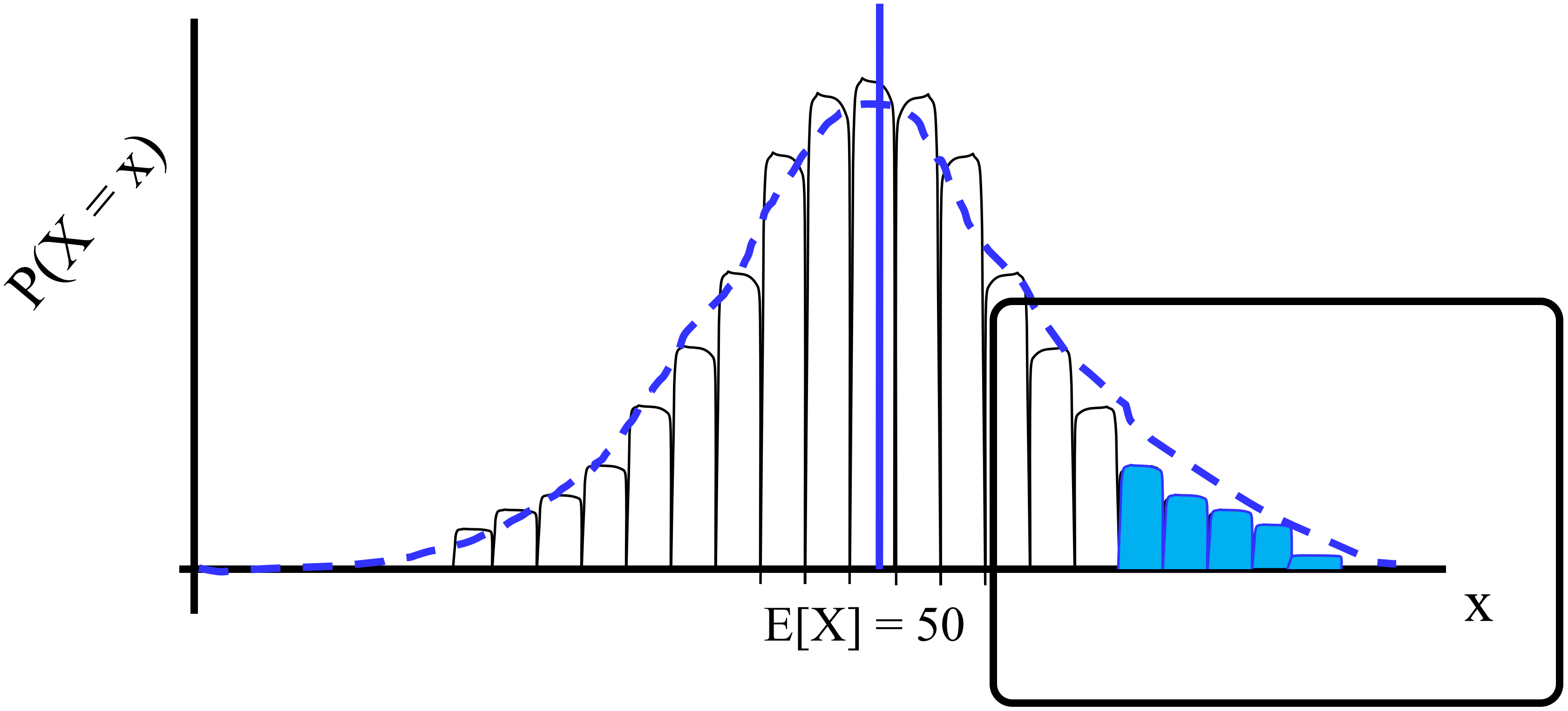
$$np = 50 \quad np(1-p) = 25 \quad \sqrt{np(1-p)} = 5$$

  - Use Normal approximation: Y ~ N(50, 25)

$$P(Y \geq 65) = P(\frac{Y-50}{5} > \frac{65-50}{5}) = P(Z > 3) = 1 - \phi(3) \approx 0.0013$$

  - Using Binomial: $P(X \geq 65) \approx 0.0018$

Website Testing



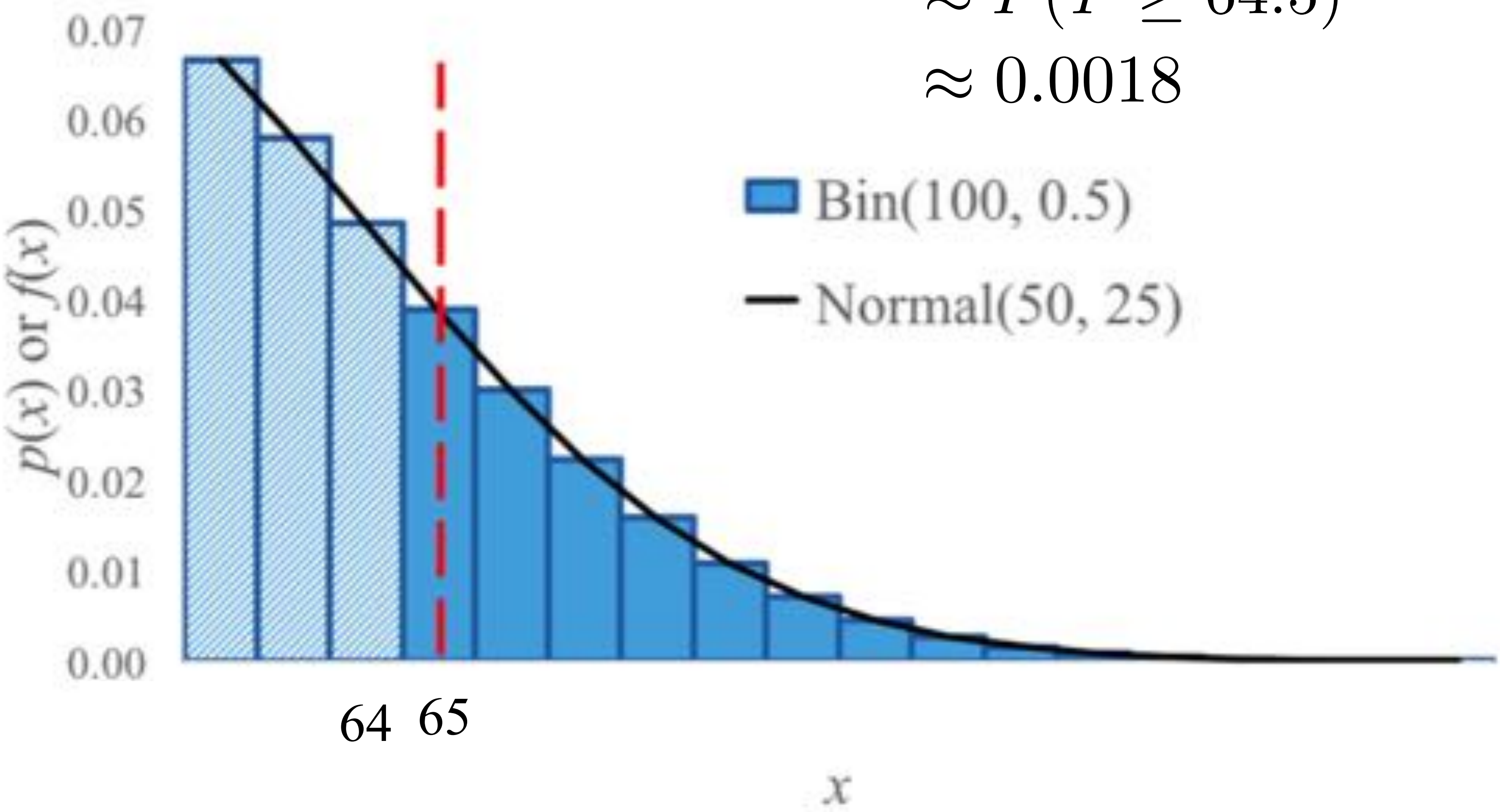
Continuity Correction

$$P(X \geq 65)$$

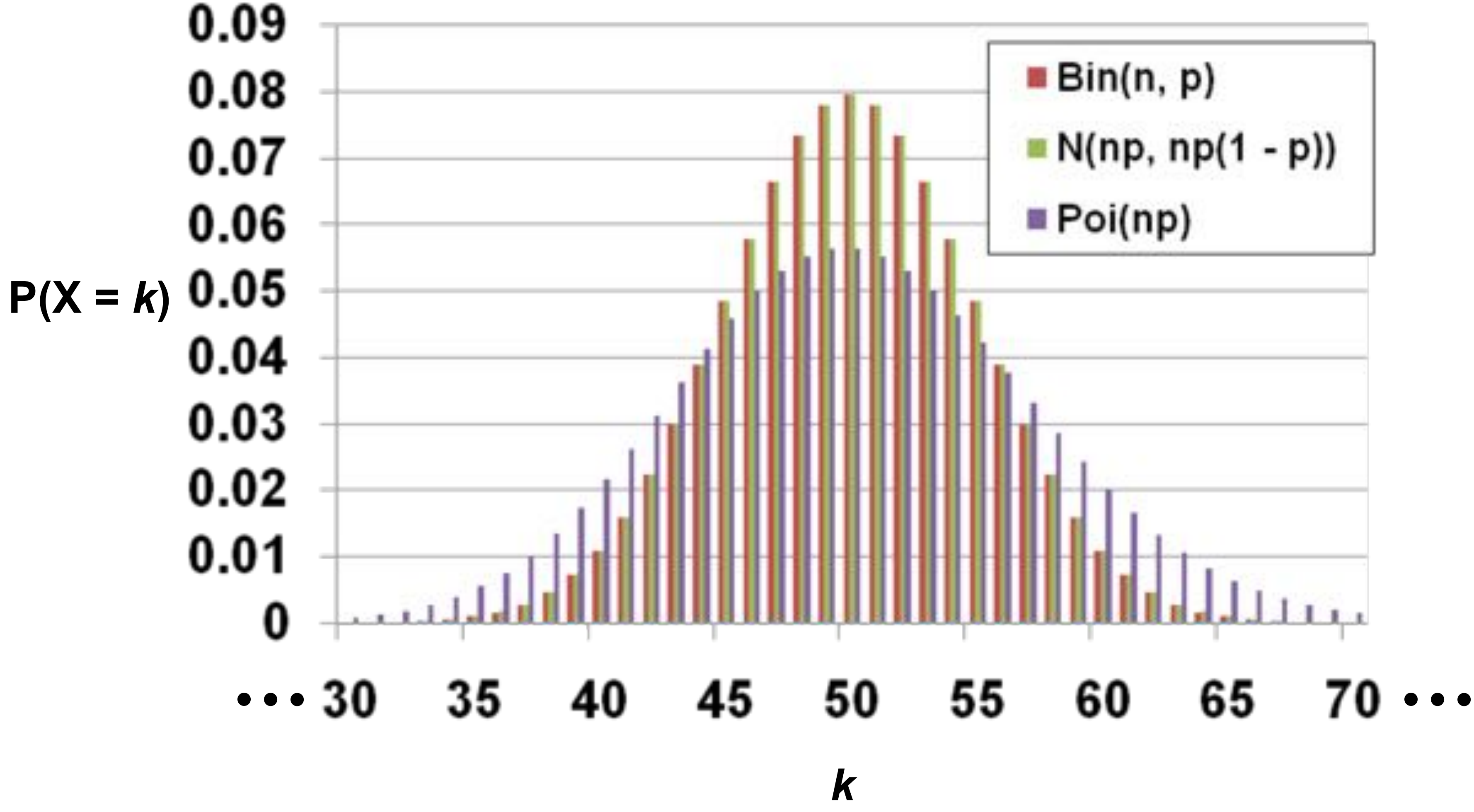
$$\approx P(Y \geq 64.5)$$

$$\approx 0.0018$$

What about 64.9?



Comparison when $n = 100$, $p = 0.5$



Normal Approximation of Binomial

- X ~ Bin(*n*, *p*)
  - E[X] = *np*   Var(X) = *np*(1 – *p*)
  - Poisson approx. good: *n* large (> 20), *p* small (< 0.05)
  - For large *n:* X ≈ Y ~ N(E[X], Var(X)) = N(*np*, *np*(1 – *p*))
  - Normal approx. good : Var(X) = *np*(1 – *p*) ≥ 10

$$P(X = k) \approx P\left(k - \frac{1}{2} < Y < k + \frac{1}{2}\right) = \Phi\left(\frac{k - np + 0.5}{\sqrt{np(1-p)}}\right) - \Phi\left(\frac{k - np - 0.5}{\sqrt{np(1-p)}}\right)$$

"Continuity correction"

Continuity Correction

Discrete (eg Binomial) probability question	Continuous (Normal) probability question
$x = 6$	$5.5 < x < 6.5$
$x >= 6$	$x > 5.5$
$x > 6$	$x > 6.5$
$x < 6$	$x < 5.5$
$x <= 6$	$x < 6.5$

Poll of polls?

French Elections:

Poll	Le Pen	Macron	Fillon	Hamon	Mélenchon	Other
Ipsos/CEVIPOF/LeMonde Apr 19 – Apr 20 2,048 Registered Voters	22	**24**	19	8	19	10
Elabe/BFMTV/L'Express Apr 19 – Apr 20 1,445 Registered Voters	22	**24**	20	7	20	9
OpinionWay/ORPI/Radio Classíque/Les Echos Apr 18 – Apr 20 2,269 Registered Voters	22	**23**	21	8	18	7
Harris/France Télévisions/L'emission Politique Apr 18 – Apr 20 962 Registered Voters	21	**25**	20	8	19	9
BVA/Orange/Presse Regionale Apr 18 – Apr 19 1,427 Registered Voters	23	**24**	19	9	19	8

Credit: fivethirtyeight.com

What is the probability that Le Pen / Macron wins?

Binomial Looks Gaussian

There is a deep reason for the Binomial/Normal approximation…

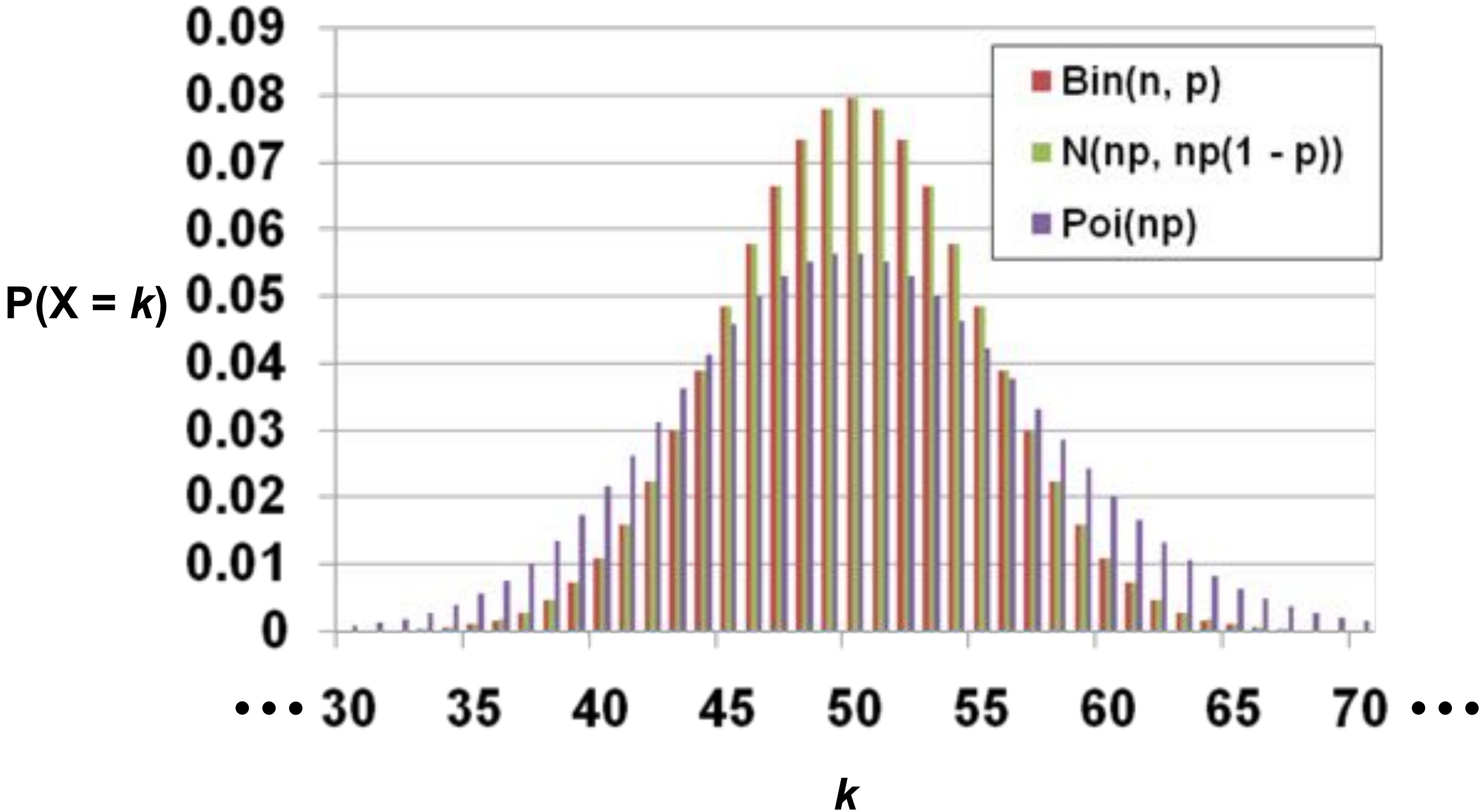
Normal Approximation of Binomial

- X ~ Bin(*n*, *p*)
  - E[X] = *np* Var(X) = *np*(1 – *p*)
  - Poisson approx. good: *n* large (> 20), *p* small (< 0.05)
  - For large *n:* X ≈ Y ~ N(E[X], Var(X)) = N(*np*, *np*(1 – *p*))
  - Normal approx. good : Var(X) = *np*(1 – *p*) ≥ 10

$$P(X=k)\approx P\left(k-\frac{1}{2}<Y<k+\frac{1}{2}\right)=\Phi\left(\frac{k-np+0.5}{\sqrt{np(1-p)}}\right)-\Phi\left(\frac{k-np-0.5}{\sqrt{np(1-p)}}\right)$$

"Continuity correction"

Comparison when $n = 100$, $p = 0.5$



Stanford Admissions

- Stanford accepts 2480 students
  - Each accepted student has 68% chance of attending
  - X = # students who will attend.   X ~ Bin(2480, 0.68)
  - What is P(X > 1745)?

$$np = 1686.4 \quad np(1-p) \approx 539.65 \quad \sqrt{np(1-p)} \approx 23.23$$

  - Use Normal approximation: Y ~ N(1686.4, 539.65)

$$P(X > 1745) \approx P(Y > 1745.5)$$

$$P(Y > 1745.5) = P\left(\frac{Y - 1686.4}{23.23} > \frac{1745.5 - 1686.4}{23.23}\right) = 1 - \Phi(2.54) \approx 0.0055$$

  - Using Binomial:

$$P(X > 1745) \approx 0.0053$$

Changes in Stanford Admissions

- Stanford Daily, March 28, 2014

  "Class of 2018 Admit Rates Lowest in University History" by Alex Zivkovic

  "Fewer students were admitted to the Class of 2018 than the Class of 2017, due to the increase in Stanford's yield rate which has increased over 5 percent in the past four years, according to Colleen Lim M.A. '80, Director of Undergraduate Admission."