

Central Limit Theorem

CSE 312 26Su

Lecture 15

Logistics

- Midterm grades released
- Ed post later this afternoon for more info!
- Quiz on Friday
 - Discrete + Continuous RVs (lectures 10-14)
 - Midterm cheat sheet + distribution sheet + z-table

$$\sim \text{final} \\ = \text{avg}(\text{quiz}, \text{midterm})$$

incl. normal

midterm

Where Are We?

Last time:

- Zoo of continuous random variables



- Exponential distribution
- Normal distribution

Today:

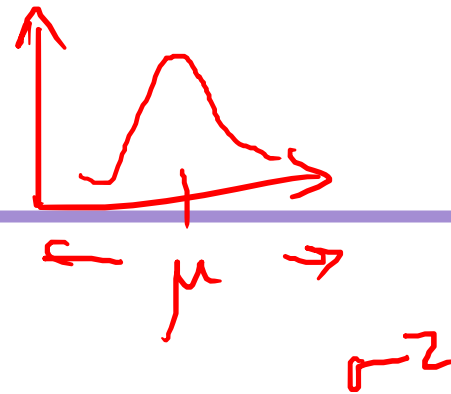
- Central Limit Theorem

Normal Distributions

A normal random variable $X \sim \mathcal{N}(\mu, \sigma^2)$ has two parameters:

- * $\mu = \mathbb{E}[X]$ is the mean
 - * $\sigma^2 = \text{Var}(X)$ is the variance ($\sigma = \sqrt{\text{Var}(X)}$ is *standard deviation*)
- and follows this *probability density function* (a bell curve!):

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



Normal Distributions

The CDF has no closed form, so instead, we have a table containing values of the CDF for a standard normal random variable $\mathcal{N}(0,1)$.

To find the probability of a normal RV $\underline{X} \sim \mathcal{N}(\mu, \sigma^2)$ being in some range...

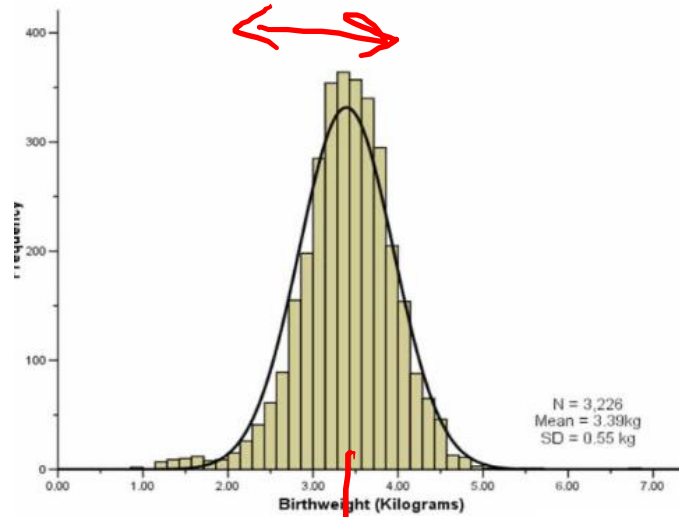
① **Standardize** the normal random variable: $\underline{Z} = \frac{X - \mu}{\sigma}$ $z \sim \mathcal{N}(0, 1)$

note: when we standardize, the numbers left are called z-scores (the number of standard deviations away from the mean (e.g., $\mathbb{P}(Z \geq 2)$ means we're finding probability of being more than 2 standard deviations away from the mean)

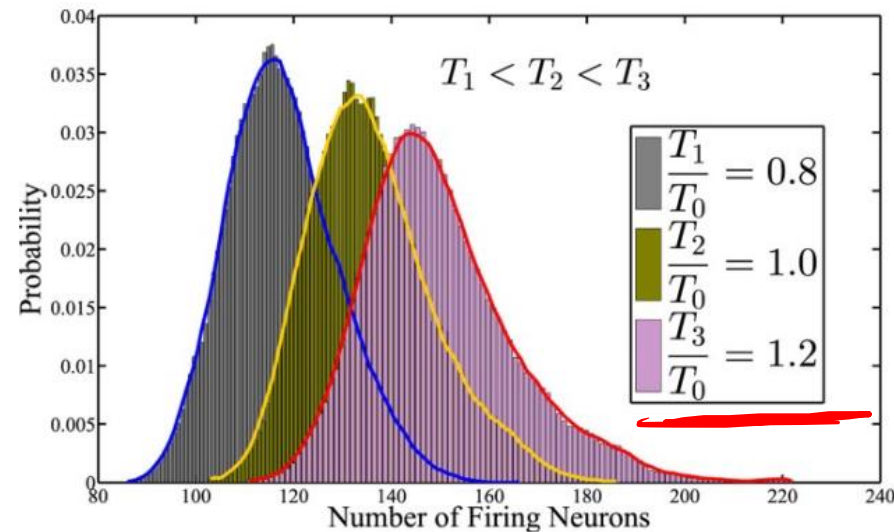
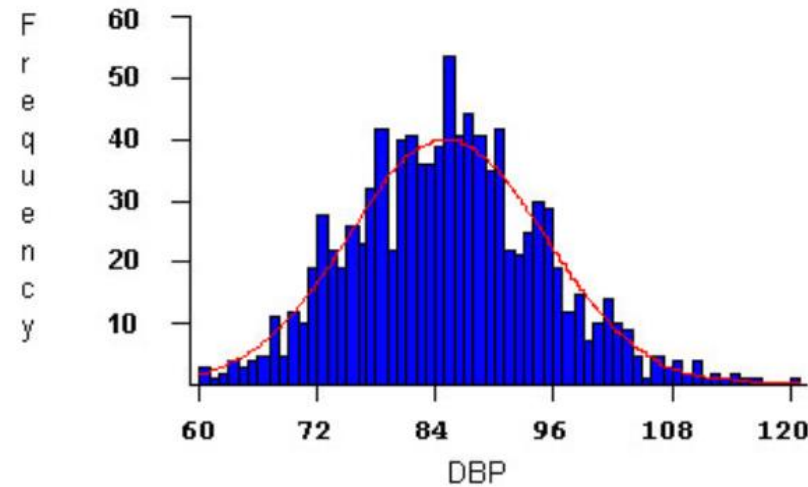
② Write probability expression in terms of $\Phi(z)$ = $\mathbb{P}(Z \leq z)$

③ Look up the value(s) in the table

Normal distributions show up everywhere!



3.5kg



But...why?

This is because of what we call, the ~~A~~ central limit theorem!

"The sum of any independent random variables approaches a normal distribution. ~~It becomes closer to normal as we sum more RVs together.~~"

More formally, the Central Limit Theorem!

This is because of what we call, the central limit theorem!

"The sum of **any** independent random variables **approaches** a normal distribution. It becomes closer to normal as we sum more RVs together."

i.i.d. = indpt. & identically dist.

Central Limit Theorem

$$E[X_i] = \mu \quad \text{Var}(X_i) = \sigma^2$$

If $X_1, X_2, \dots, X_n$ are i.i.d. random variables, each with mean μ and variance σ^2

$$\text{Let } Y_n = X_1 + X_2 + \dots + X_n$$

As $n \rightarrow \infty$, Y_n approaches a normal distribution $\mathcal{N}(n \cdot \mu, n \cdot \sigma^2)$

(i.e., CDF of Y_n converges to the CDF of $\mathcal{N}(n \cdot \mu, n \cdot \sigma^2)$)

$$\sum X_i$$

$$E[\sum X_i] = n \cdot \sum E[X_i]$$

$$\text{Var}(\sum X_i) = \sum \text{Var}(X_i)$$

What does i.i.d mean?

Independent and Identically Distributed (i.i.d)

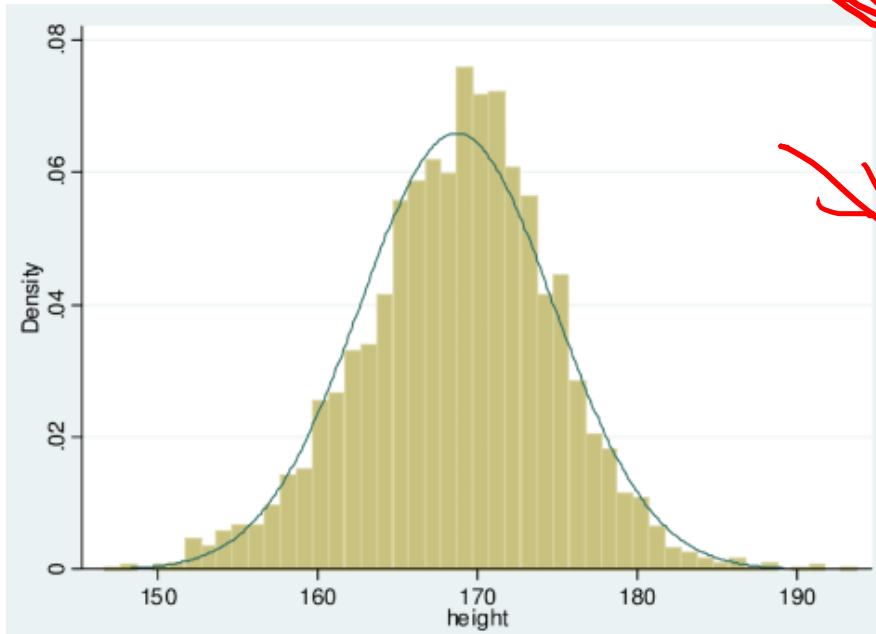
For random variables $X_1, X_2, \dots, X_n$ to be i.i.d., they must

- Be mutually independent
"knowing value of one random variable doesn't give us info about the value of others"
- All have the same PMF (if discrete) or PDF (if continuous)
"they follow the same probability distribution"

$$E[X_1] = E[X_2] = \dots = E[X_n]$$
$$\text{Var}(X_1) = \text{Var}(X_2) = \dots = \text{Var}(X_n)$$

CLT with ***RVs that are NOT i.i.d***

(R.A. Fisher (1918))



Height may be expressed as the *sum of many independent, random factors*

How much milk you drank per day as a child

Which variant of GH1 (a growth hormone) you have

How much protein/calcium/vitamins/minerals you had as a child

How many hours of sleep you averaged

How many hours of physical activity you averaged

$$\underline{H} = \underline{H_1} + \underline{H_2} + \dots + \underline{H_n} \rightarrow \underline{H \sim N(\dots)}$$

A version of CLT does work here! But it's outside the scope of this class.

CLT with RVs that are i.i.d

"number of firing neurons" – sum of indicator random variables for whether each neuron fired

$$X_i \sim \text{Ber}(p)$$

Assume: each neuron is independent, and has the same probability

"number of people who voted for someone" – sum of indicator random variables for (assume people are independent)

$$X_i \sim \text{Ber}(p)$$

Assume: each person makes independent, and has the same probability

"total amount invested in a year" – sum of random variables for amount invested each day (assume each investment is independent)

$$X_i \sim N$$

Assume: each day's investment is independent and follows the same distribution

We will use CLT in this class on problems like this.

A Sum of i.i.d Random Variables

If we have $X_1, X_2, \dots, X_n$ as i.i.d RVs each with mean μ and variance σ^2

$S_n = X_1 + X_2 + \dots + X_n$ is the sum of those RVs. Then...

> **Expectation.** *by linearity of expectation...*

$$\mathbb{E}[S_n] = \mathbb{E}[X_1 + X_2 + \dots + X_n] = \mathbb{E}[X_1] + \mathbb{E}[X_2] + \dots + \mathbb{E}[X_n] = n\mu$$

> **Variance.** *by linearity of variance because of independence*

$$\text{Var}(S_n) = \text{Var}(X_1 + X_2 + \dots + X_n) = \text{Var}(X_1) + \text{Var}(X_2) + \dots + \text{Var}(X_n) = n\sigma^2$$

$$\text{approx } S_n \sim N(\mathbb{E}[S_n], \text{Var}(S_n))$$

Proof of the CLT?

We're not going to cover the proof here.

How is the proof done?

Step 1: Prove that for all positive integers k , $\mathbb{E}[(Y_n)^k] \rightarrow \mathbb{E}[Z^k]$

Step 2: Prove that if $\mathbb{E}[(Y_n)^k] = \mathbb{E}[Z^k]$ for all k then $F_{Y_n}(z) = F_Z(z)$

CDF is approx N

"Proof by example"



CLT says a sum of n i.i.d RVs approaches a normal distribution as n gets larger

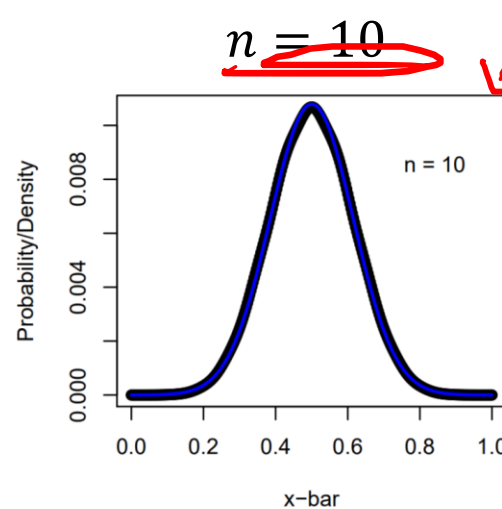
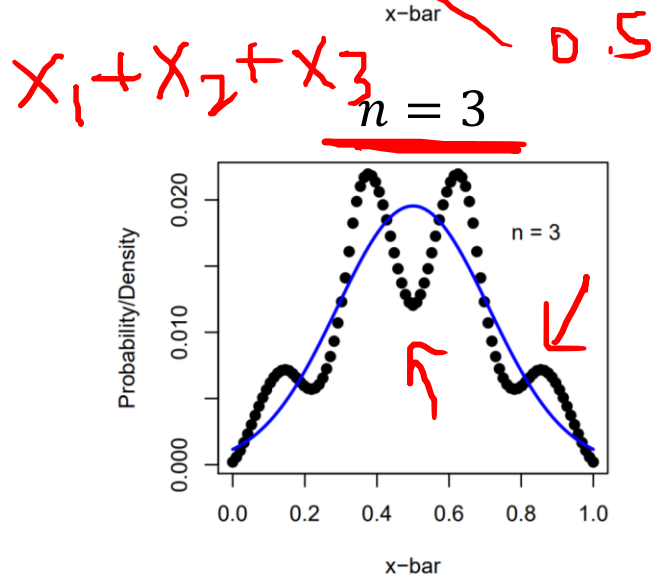
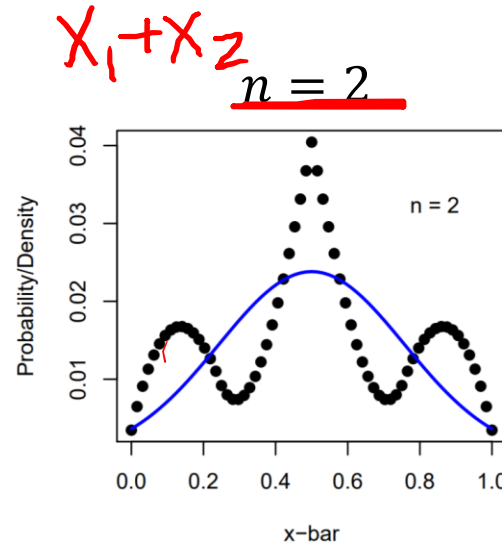
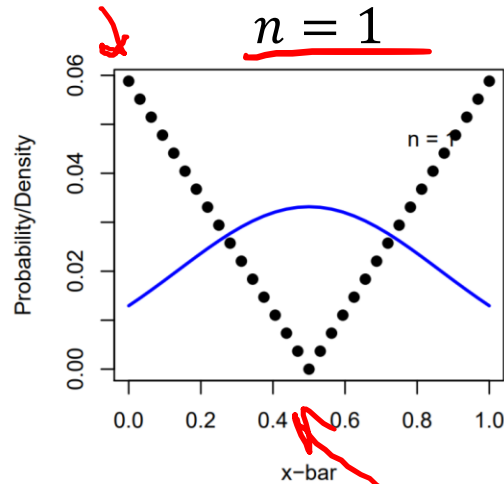
n is the number of i.i.d RVs summed

The **dotted lines** show an "empirical PMF" – a PMF estimated by running the experiment a large number of times.

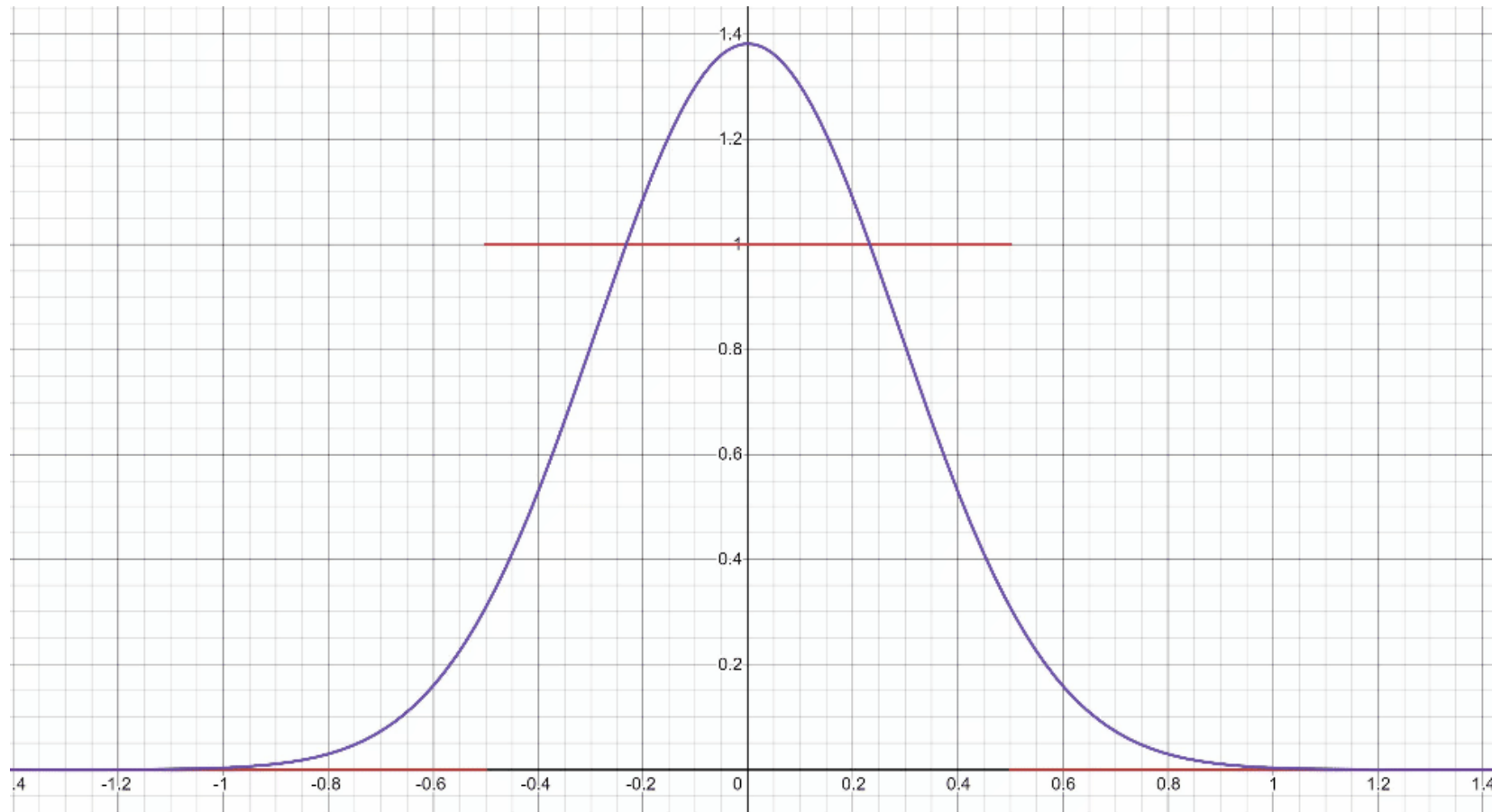
The **blue line** is the normal RV that the CLT predicts.

Shown are $n = 1, 2, 3, 10$

? dist. for X



"Proof by example" -- uniform



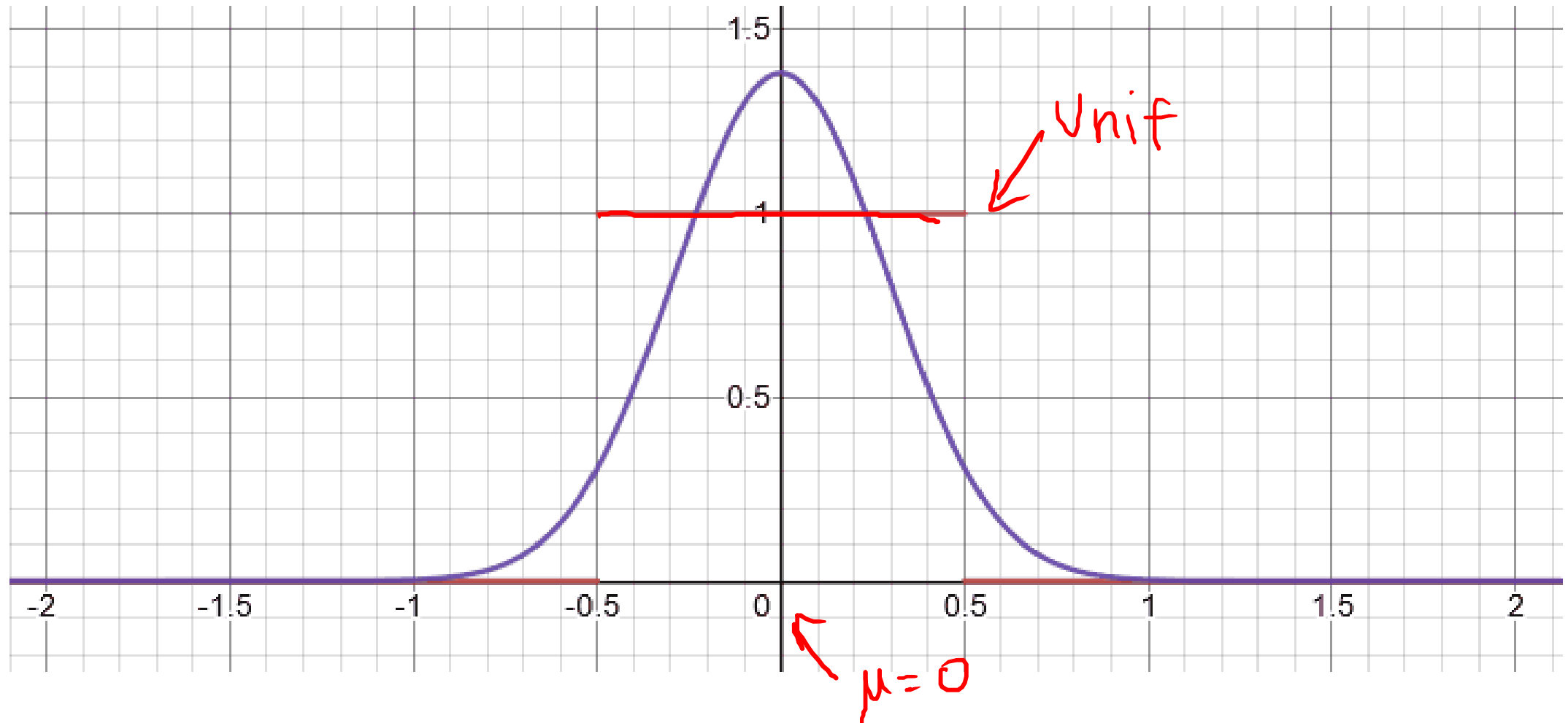
<https://www.desmos.com/calculator/2n2m05a9km>

"Proof by example" -- uniform

$n=1$
 $x_i \sim \text{Unif}(0,1)$

$$X = X_1$$

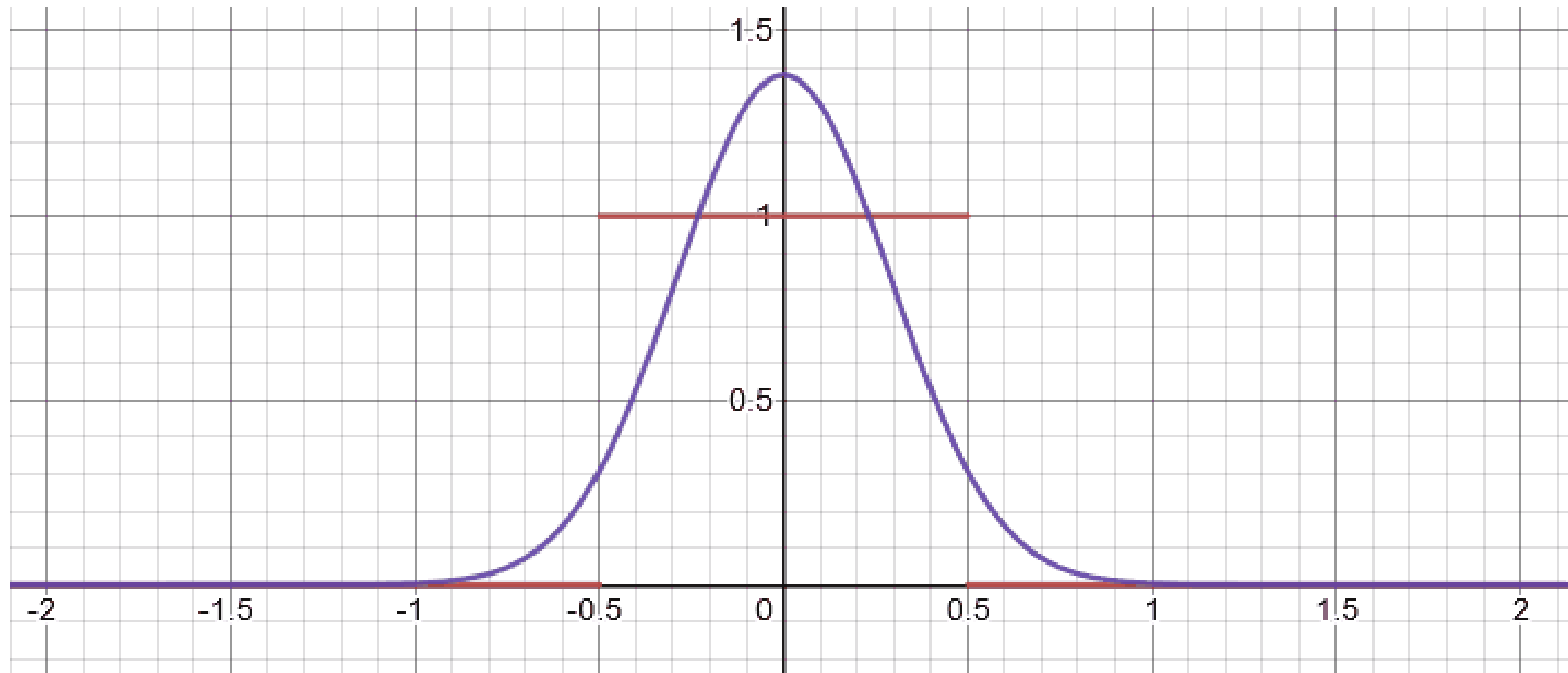
where each $X_i \sim \text{Unif}(0,1)$ and is independent



"Proof by example" -- uniform

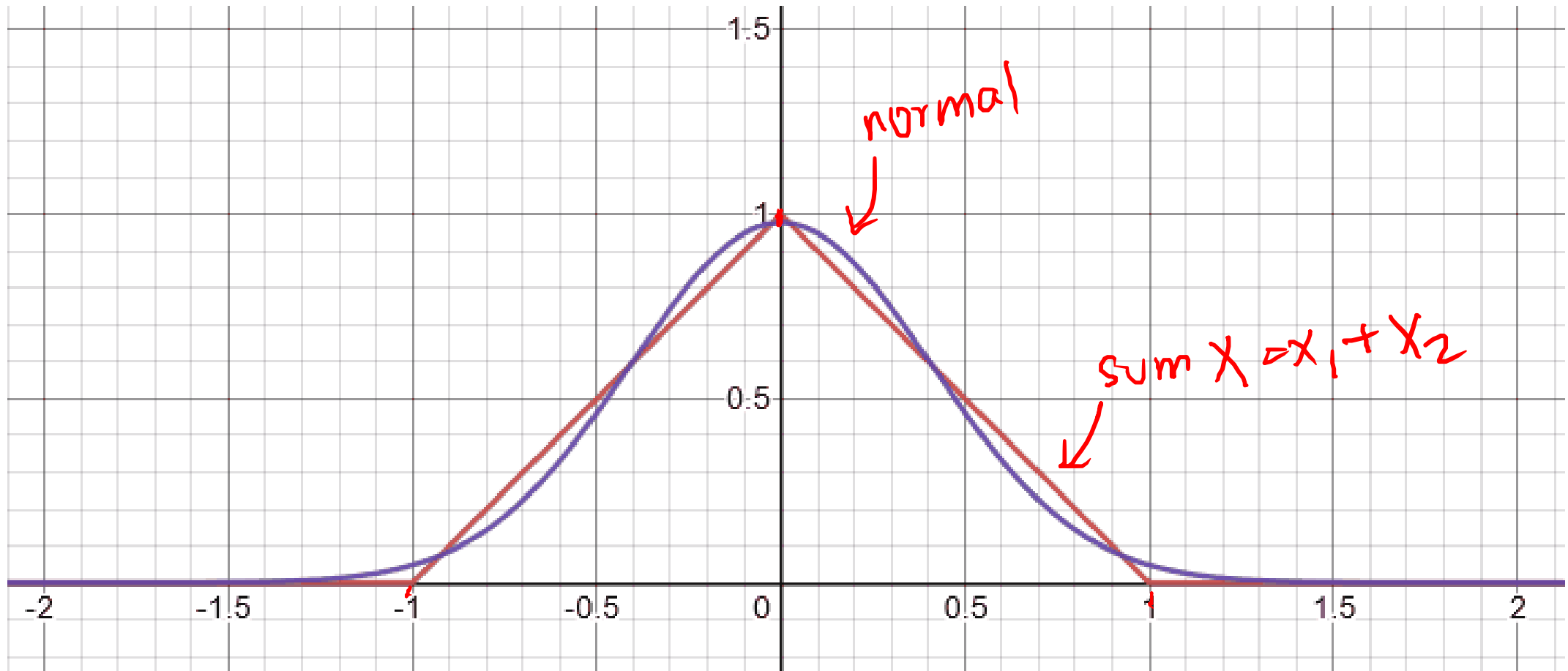
$$X = X_1$$

where each $X_i \sim \text{Unif}(0,1)$ and is independent



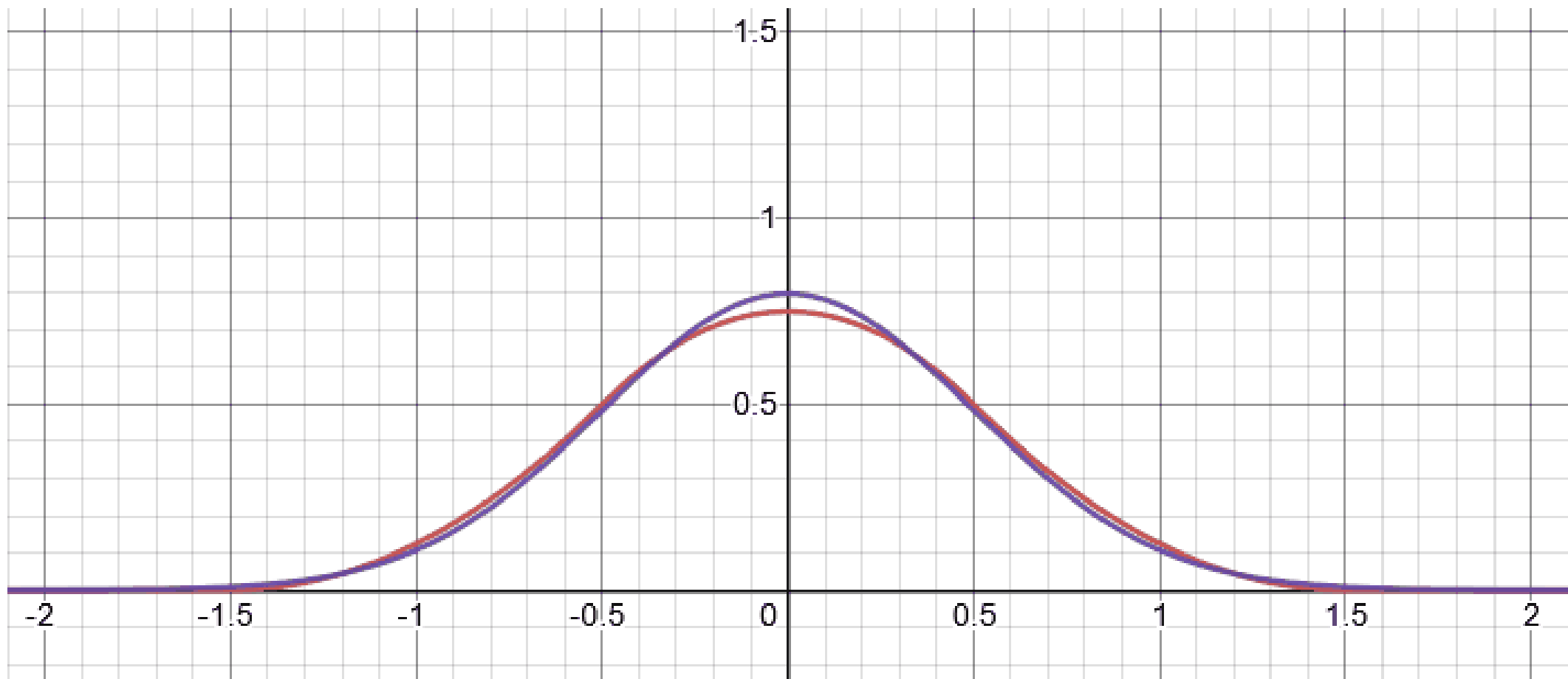
"Proof by example" -- uniform

$X = X_1 + X_2$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



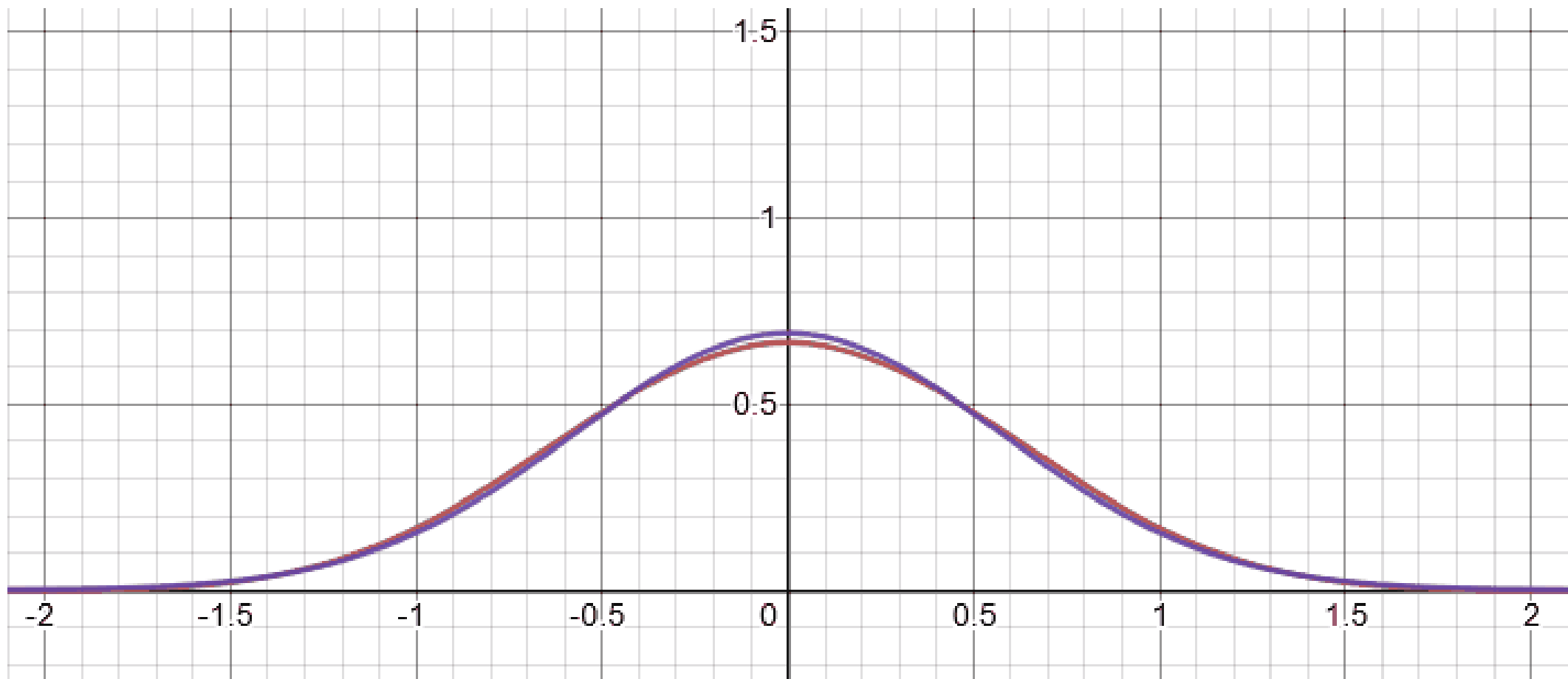
"Proof by example" -- uniform

$X = X_1 + X_2 + X_3$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



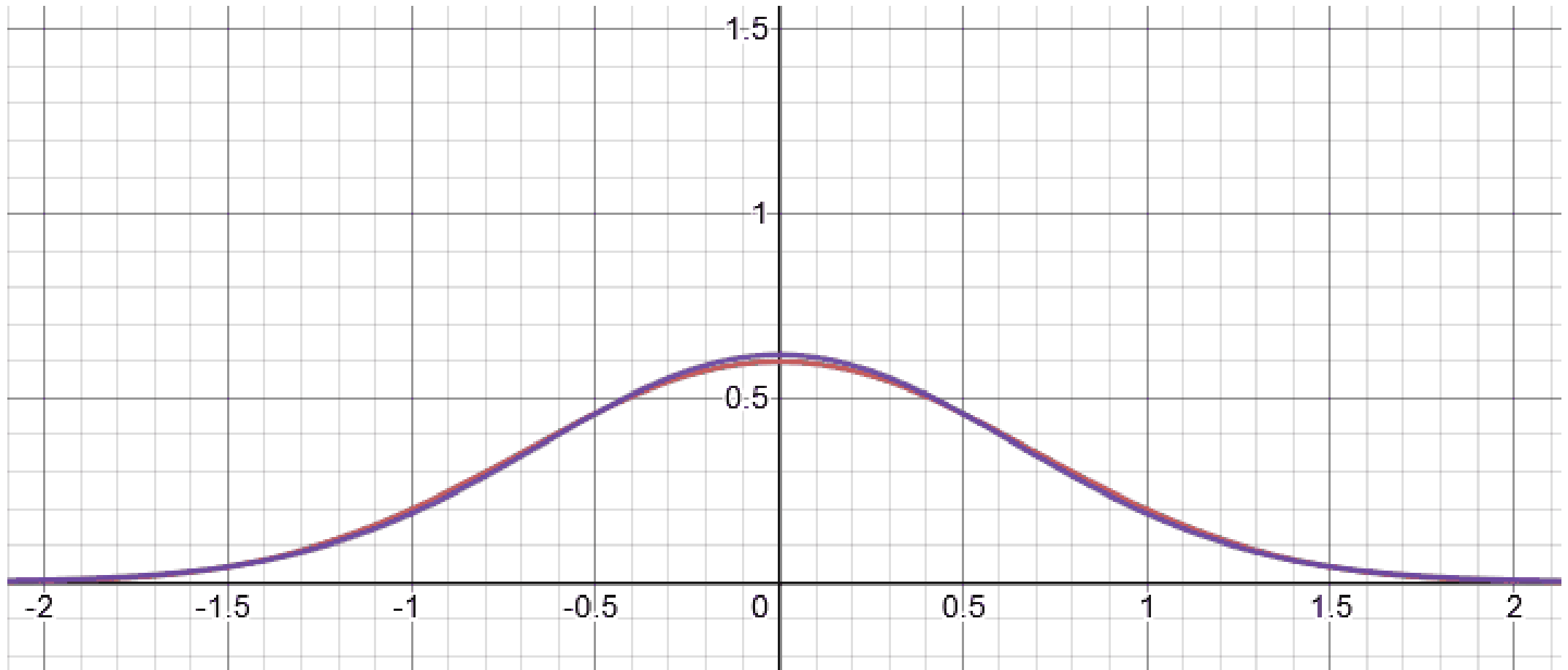
"Proof by example" -- uniform

$X = X_1 + X_2 + X_3 + X_4$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



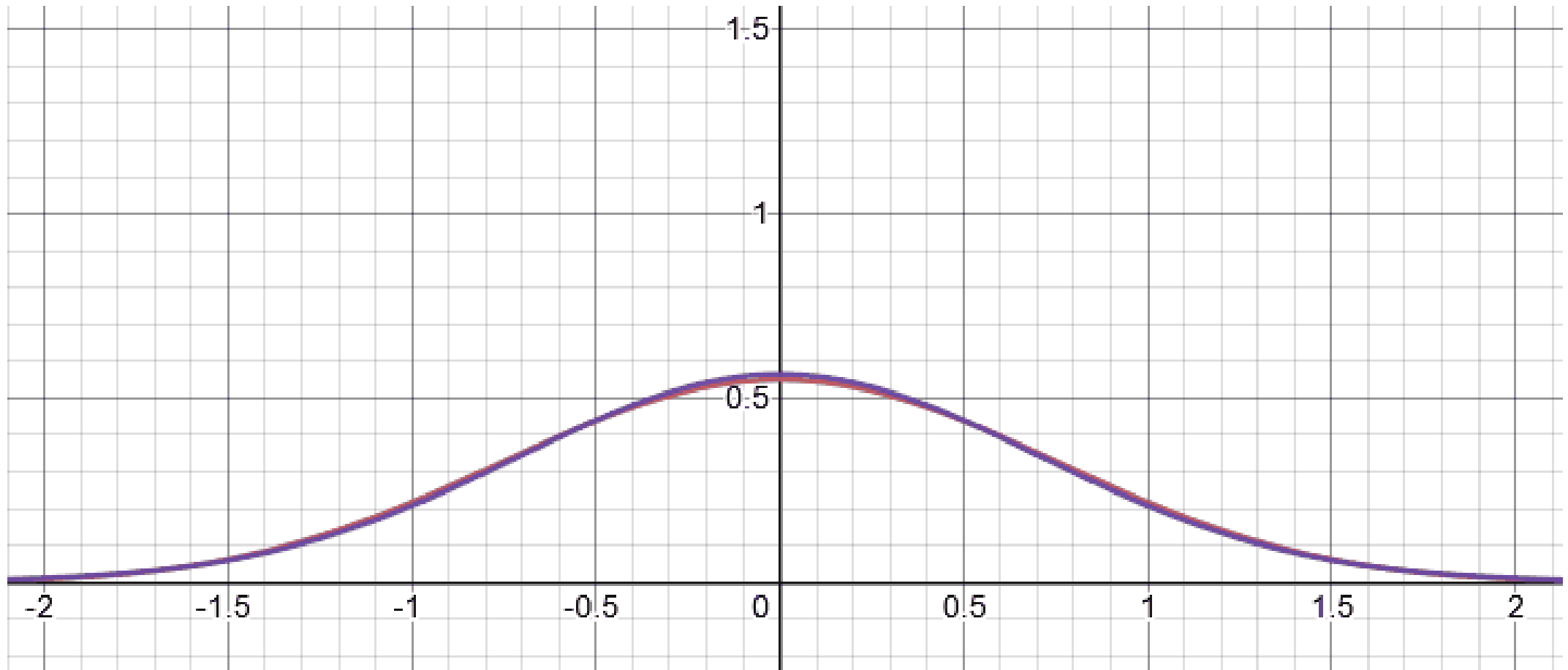
"Proof by example" -- uniform

$X = X_1 + X_2 + X_3 + X_4 + X_5$ ✓
where each $X_i \sim \text{Unif}(0,1)$ and is independent



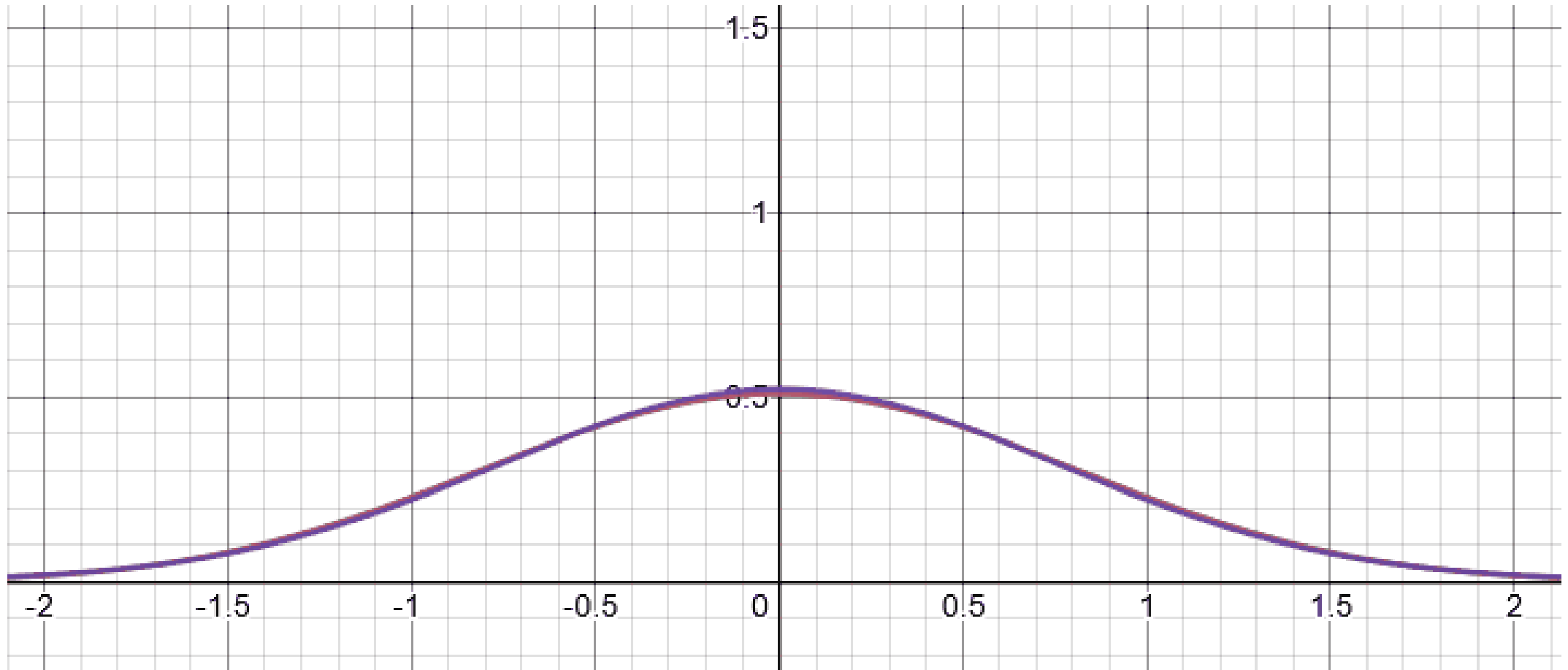
"Proof by example" -- uniform

$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



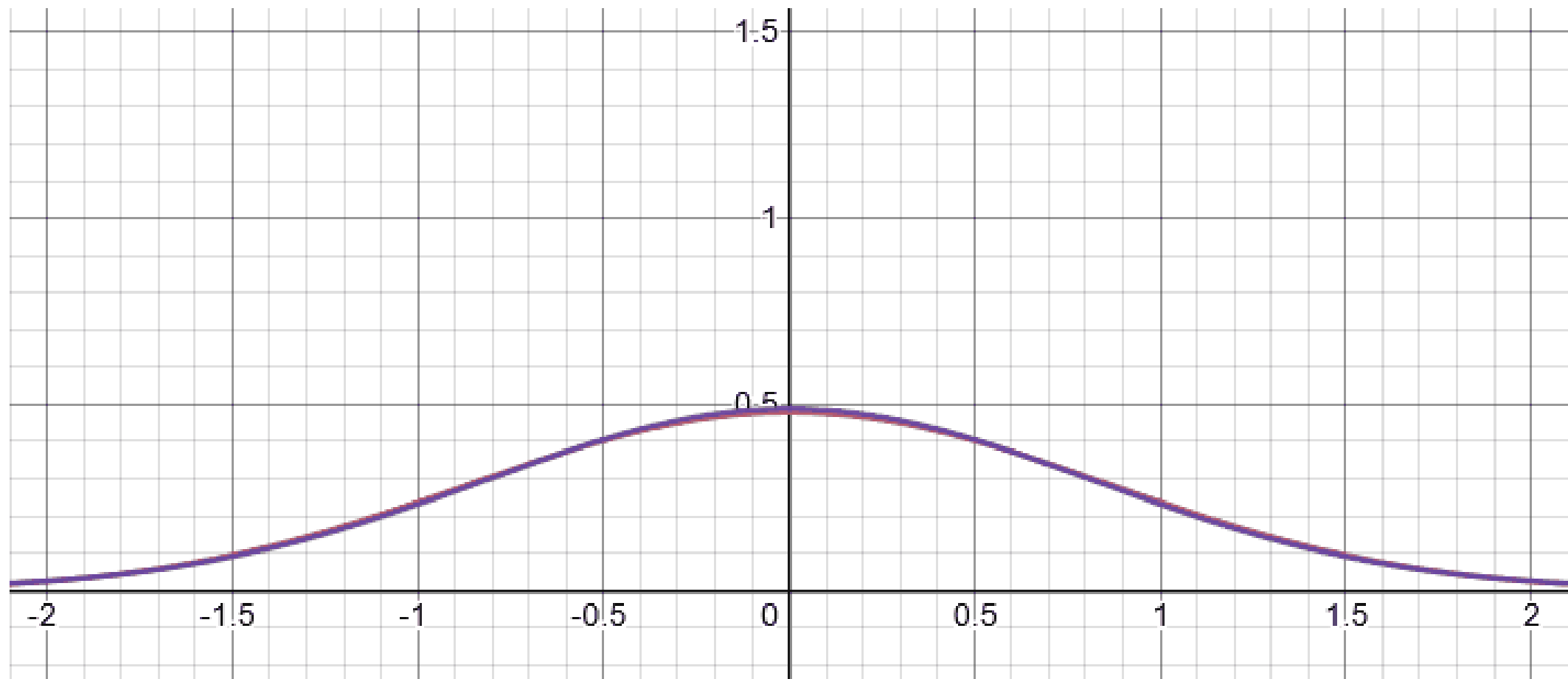
"Proof by example" -- uniform

$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



"Proof by example" -- uniform

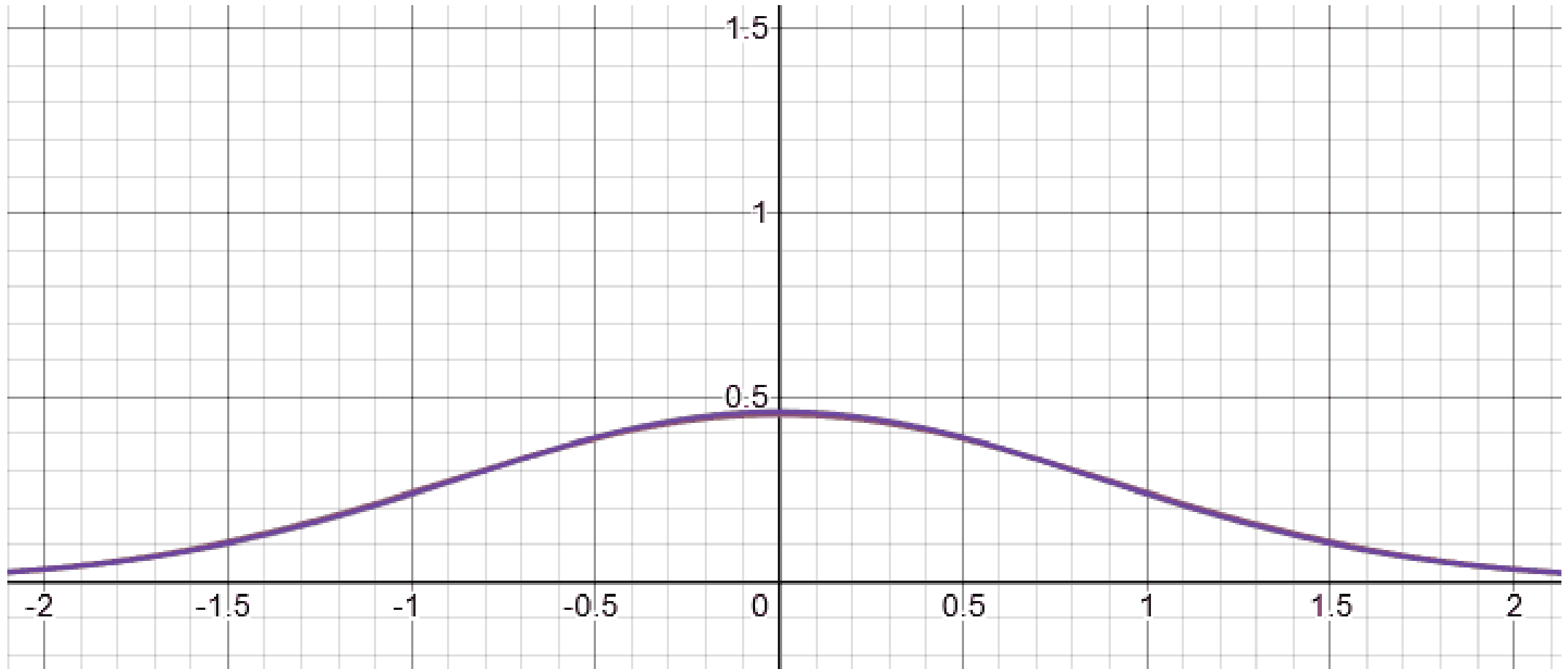
$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8$
where each $X_i \sim \text{Unif}(0,1)$ and is independent



"Proof by example" -- uniform

$$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9$$

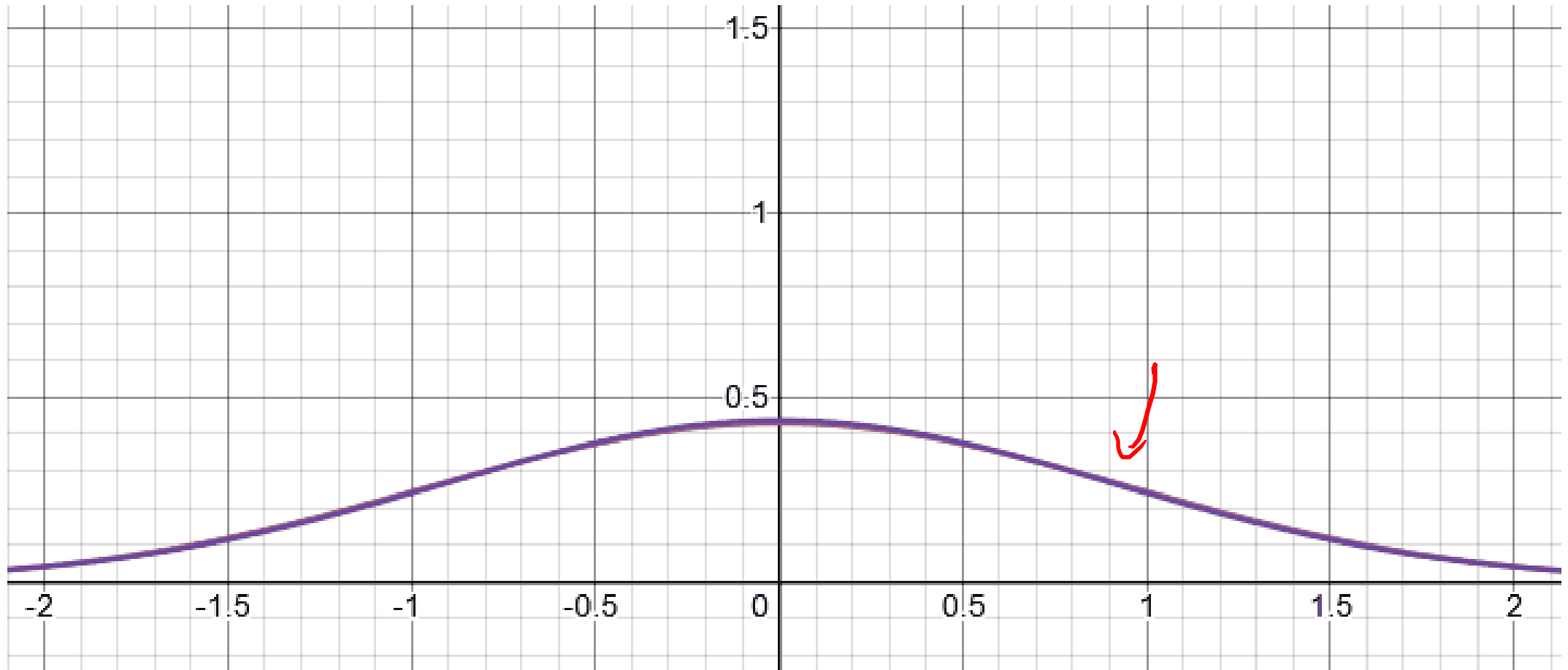
where each $X_i \sim \text{Unif}(0,1)$ and is independent



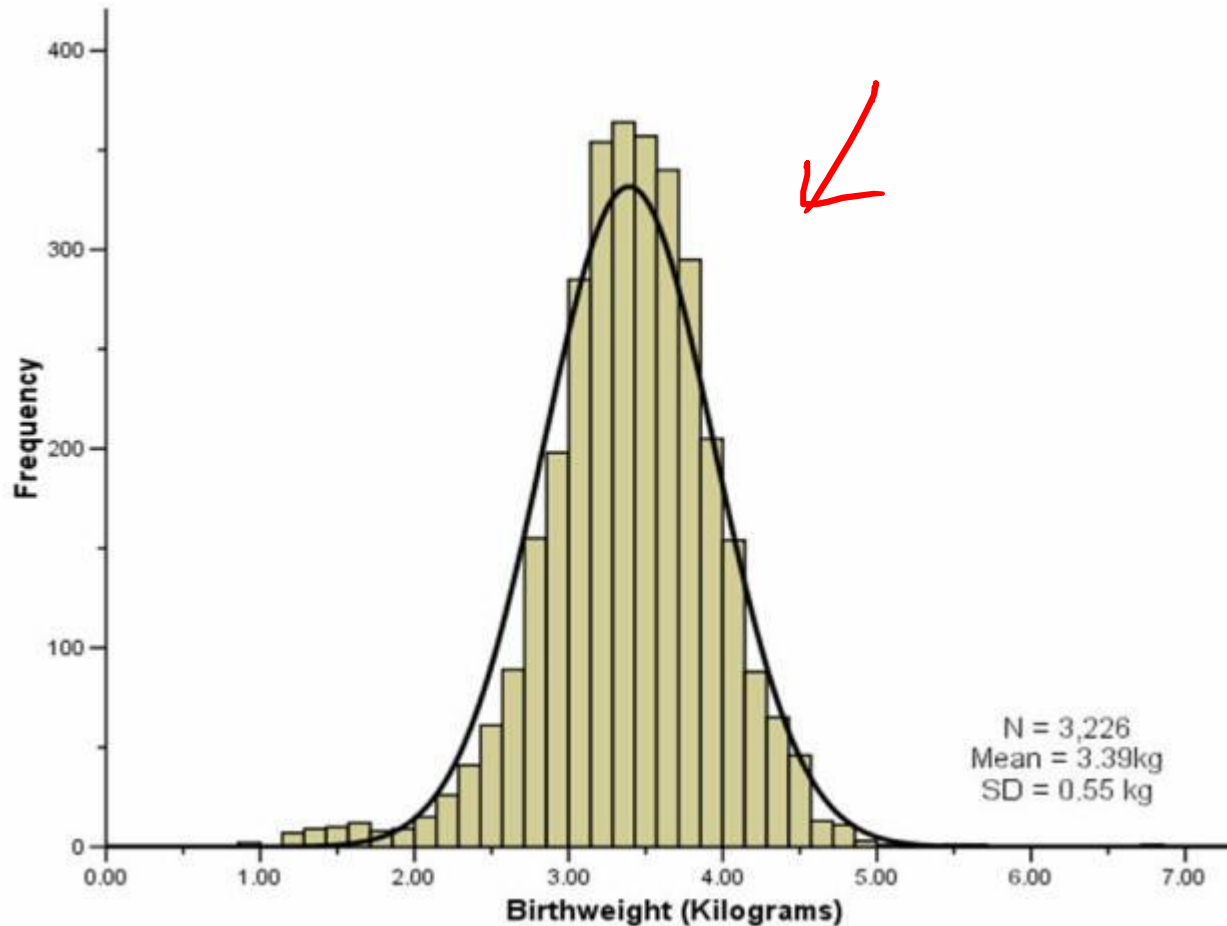
"Proof by example" -- uniform

$$X = X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10}$$

where each $X_i \sim \text{Unif}(0,1)$ and is independent



"Proof by real-world"



birthweight

A lot of real-world bell-curves can be explained as:

1. The random variable comes from a combination of independent factors.
2. The CLT says the distribution will become like a bell curve.

Theory vs. Practice

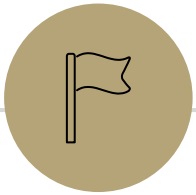
- > The formal theorem statement is "in the limit"

You might not get exactly a normal distribution for any finite n (e.g. if you sum discrete, the sum is always discrete and will be discontinuous for every finite n).

- 
- > In practice, the approximations get very accurate very quickly (at least with a few tricks we'll see soon).

They won't be exact (unless the X_i are normals) but it's close enough to use even with relatively small n .

$$\begin{aligned} n &> 20 \\ n &> 30 \end{aligned}$$



Using the Central Limit Theorem

Let's start with the case when we are using CLT to approximate a sum of continuous i.i.d random variables as normal

Outline of CLT steps

continuous X_i for now

1. Setup the problem (e.g., $X = \sum_{i=1}^n X_i$, X_i are i.i.d., and we want $\mathbb{P}(X \leq k)$)

Write event you are interested in, in terms of sum of random variables.

⚠ we're going to be adding one more step here when we talk about discrete RVs! ⚠

→ 2. Apply CLT (e.g., approx X as $Y \sim N(\overset{E[X]}{n\mu}, \overset{\text{Var}(X)}{n\sigma^2}) \rightarrow \mathbb{P}(X \leq k) \approx \mathbb{P}(Y \leq k)$
Approximate sum of RVs as normal with appropriate mean and variance

from here, we're working with a normal distribution, which we've worked with before!

3. Compute probability approximation using Phi table

> Standardize $(Z = \frac{Y - \mu}{\sigma}) \rightarrow \mathbb{P}(Y \leq k) = \mathbb{P}\left(\frac{Y - \mu}{\sigma} \leq \frac{k - \mu}{\sigma}\right) = \mathbb{P}\left(Z \leq \frac{k - \mu}{\sigma}\right)$

> Write in terms of $\Phi(z) = \mathbb{P}(Z \leq z)$

> Look up in table

Lightbulbs

$$X_i \sim \text{Exp}(1.8)$$

You buy lightbulbs that each burn out according to an exponential distribution with parameter of $\lambda = 1.8$ lightbulbs per year.

You buy a 10 pack of (independent) light bulbs. What is the probability that your 10-pack lasts at least 5 years?

Let X_i be the time it takes for lightbulb i to burn out.

Let X be the total time. Estimate $\mathbb{P}(X \geq 5)$.

Lightbulbs

$$X_i \sim \text{Exp}(1.8)$$
$$X = \sum_{i=1}^{10} X_i$$

$$\leftarrow E[X_i] = \frac{1}{1.8}$$
$$\text{Var}(X_i) = \frac{1}{1.8^2}$$

You buy lightbulbs that each burn out according to distribution $\text{Exp}(1.8)$ lightbulbs per year. Estimate the probability your 10-pack (independent) lasts at least 5 years?

1. Setup the Problem:

$$P(X \geq 5)$$

2. Apply CLT.

$$Y \approx N(E[X], \text{Var}(X))$$
$$Y \sim N\left(\frac{10}{1.8}, \frac{10}{1.8^2}\right)$$
$$= 10 \cdot \frac{1}{1.8} = 10 \cdot \frac{1}{1.8^2}$$

3. Compute Probability.

$$P(X \geq 5) \approx P(Y \geq 5) = P\left(\frac{Y - 10/1.8}{\sqrt{10/1.8^2}} \geq \frac{5 - 10/1.8}{\sqrt{10/1.8^2}}\right)$$
$$\sigma = \sqrt{\text{Var}(X)}$$
$$\approx \Phi(0.32)$$

$\Phi(0.32)$

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5	0.50399	0.50798	0.51197	0.51595	0.51994	0.52392	0.5279	0.53188	0.53586
0.1	0.53983	0.5438	0.54776	0.55172	0.55567	0.55962	0.56356	0.56749	0.57142	0.57535
0.2	0.57926	0.58317	0.58706	0.59095	0.59483	0.59871	0.60257	0.60642	0.61026	0.61409
0.3	0.61791	0.62172	0.62552	0.6293	0.63307	0.63683	0.64058	0.64431	0.64803	0.65173
0.4	0.65542	0.6591	0.66276	0.6664	0.67003	0.67364	0.67724	0.68082	0.68439	0.68793
0.5	0.69146	0.69497	0.69847	0.70194	0.7054	0.70884	0.71226	0.71566	0.71904	0.7224
0.6	0.72575	0.72907	0.73237	0.73565	0.73891	0.74215	0.74537	0.74857	0.75175	0.7549
0.7	0.75804	0.76115	0.76424	0.7673	0.77035	0.77337	0.77637	0.77935	0.7823	0.78524
0.8	0.78814	0.79103	0.79389	0.79673	0.79955	0.80234	0.80511	0.80785	0.81057	0.81327
0.9	0.81594	0.81859	0.82121	0.82381	0.82639	0.82894	0.83147	0.83398	0.83646	0.83891
1.0	0.84134	0.84375	0.84614	0.84849	0.85083	0.85314	0.85543	0.85769	0.85993	0.86214
1.1	0.86433	0.8665	0.86864	0.87076	0.87286	0.87493	0.87698	0.879	0.881	0.88298
1.2	0.88493	0.88686	0.88877	0.89065	0.89251	0.89435	0.89617	0.89796	0.89973	0.90147
1.3	0.9032	0.9049	0.90658	0.90824	0.90988	0.91149	0.91309	0.91466	0.91621	0.91774
1.4	0.91924	0.92073	0.9222	0.92364	0.92507	0.92647	0.92785	0.92922	0.93056	0.93189
1.5	0.93319	0.93448	0.93574	0.93699	0.93822	0.93943	0.94062	0.94179	0.94295	0.94408
1.6	0.9452	0.9463	0.94738	0.94845	0.9495	0.95053	0.95154	0.95254	0.95352	0.95449
1.7	0.95543	0.95637	0.95728	0.95818	0.95907	0.95994	0.9608	0.96164	0.96246	0.96327
1.8	0.96407	0.96485	0.96562	0.96638	0.96712	0.96784	0.96856	0.96926	0.96995	0.97062
1.9	0.97128	0.97193	0.97257	0.9732	0.97381	0.97441	0.975	0.97558	0.97615	0.9767
2.0	0.97725	0.97778	0.97831	0.97882	0.97932	0.97982	0.9803	0.98077	0.98124	0.98169
2.1	0.98214	0.98257	0.983	0.98341	0.98382	0.98422	0.98461	0.985	0.98537	0.98574
2.2	0.9861	0.98645	0.98679	0.98713	0.98745	0.98778	0.98809	0.9884	0.9887	0.98899
2.3	0.98928	0.98956	0.98983	0.9901	0.99036	0.99061	0.99086	0.99111	0.99134	0.99158
2.4	0.9918	0.99202	0.99224	0.99245	0.99266	0.99286	0.99305	0.99324	0.99343	0.99361
2.5	0.99379	0.99396	0.99413	0.9943	0.99446	0.99461	0.99477	0.99492	0.99506	0.9952
2.6	0.99534	0.99547	0.9956	0.99573	0.99585	0.99598	0.99609	0.99621	0.99632	0.99643
2.7	0.99653	0.99664	0.99674	0.99683	0.99693	0.99702	0.99711	0.9972	0.99728	0.99736
2.8	0.99744	0.99752	0.9976	0.99767	0.99774	0.99781	0.99788	0.99795	0.99801	0.99807
2.9	0.99813	0.99819	0.99825	0.99831	0.99836	0.99841	0.99846	0.99851	0.99856	0.99861
3.0	0.99865	0.99869	0.99874	0.99878	0.99882	0.99886	0.99889	0.99893	0.99896	0.999

Lightbulbs

True value (uses a distribution not in our zoo) is ≈ 0.58741

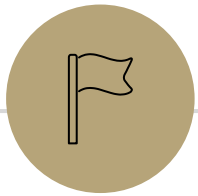
You buy lightbulbs that each burn out according to distribution $\text{Exp}(1.8)$ lightbulbs per year. Estimate the probability your 10-pack (independent) lasts at least 5 years?

1. Setup the Problem: Let X_i be the time it takes for lightbulb i to burn out. $X_i \sim \text{Exp}(1.8)$ and $\mu = \mathbb{E}[X_i] = \frac{1}{1.8}$ and $\sigma^2 = \text{Var}(X_i) = \frac{1}{1.8^2}$. Let X be the total time and $X = \sum_{i=1}^{10} X_i$. We are interested in $\mathbb{P}(X \geq 5)$.

2. Apply CLT. Because the X_i 's are i.i.d, we can apply CLT and X can be approximated by $Y \sim \mathcal{N}(10 \cdot \frac{1}{1.8}, 10 \cdot \frac{1}{1.8^2})$. $\mathbb{P}(X \geq 5) \approx \mathbb{P}(Y \geq 5)$

3. Compute Probability.

$$\begin{aligned}\mathbb{P}(Y \geq 5) &= \mathbb{P}\left(Z \geq \frac{5 - 10/1.8}{\sqrt{10}/1.8}\right) \text{ standardize} \\ &\approx \mathbb{P}(Z \geq -0.32) = \mathbb{P}(Z \leq 0.32) \text{ (symmetry)} \\ &= \Phi(0.32) \approx .62552 \text{ plug into z-table}\end{aligned}$$



Using the Central Limit Theorem

Now, let's try the case when we are using CLT to approximate a sum of discrete i.i.d random variables as normal

Factory Widgets 🕒

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%. $p = 0.05 = \text{failure}$

Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

no CLT

X - # of non-defective widgets

$X \sim \text{Bin}(1000, 0.95)$

$P(X \leq 940)$

Factory Widgets 🕒 - *Exact Answer*

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%.

Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

X is the number of non-defective widgets. Let $X \sim \text{Bin}(1000, .95)$

Our goal: $\mathbb{P}(X \leq 940)$?

That's a big summation: $\sum_{k=0}^{940} \binom{1000}{k} (.95)^k \cdot (.05)^{1000-k} \approx .08673$

Factory Widgets 🕒 - Exact Answer

→ Poi
 $E[X]$ limit
 $n \rightarrow \infty$

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→ Σ $n \rightarrow \infty$

What does the CLT give? Binomial is sum of i.i.d bernoullis -> can use CLT!

Factory Widgets 🕒 - CLT

$$X_i \sim \text{Ber}(0.95)$$
$$X_i = \begin{cases} 1 & \text{if non-defective} \\ 0 & \text{otherwise} \end{cases}$$

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%.

Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

1. Setup the Problem:

$$P(X \leq 940)$$

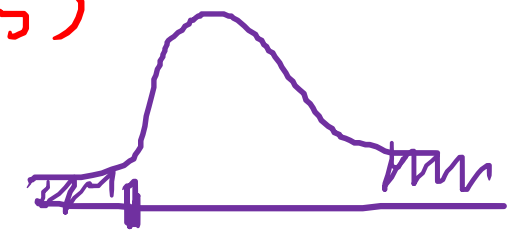
X - # of non-defective widgets

$$X = \sum_{i=1}^{1000} X_i$$
$$E[X_i] = 0.95$$
$$\text{Var}(X_i) = p \cdot (1-p) = 0.0475$$

2. Apply CLT.

$$\text{approx } X \text{ as } Y \sim N(E[X], \text{Var}(X))$$

3. Compute Probability. $N(1000 \cdot 0.95, 1000 \cdot 0.0475)$

$$P(X \leq 940) \approx P(Y \leq 940)$$
$$= P\left(Z \leq \frac{940 - 1000 \cdot 0.95}{\sqrt{1000 \cdot 0.0475}}\right) = P(Z \leq -2) = 1 - P(Z \geq 2) = 1 - \Phi(2)$$


Factory Widgets 🕒 - CLT

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%.

Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

1. Setup the Problem: X is the number of non-defective widgets.

$X = \sum_{i=1}^{1000} X_i$ where X_i is 1 if the i 'th widget is non-defective. **Goal:** $\mathbb{P}(X \leq 940)$

2. Apply CLT. X is sum of i.i.d RVs each with $\mu = \mathbb{E}[X_i] = p = .95$ and $\text{Var}(X_i) = p(1 - p) = .0475$, we can approximate X with $Y \sim \mathcal{N}(1000 \cdot 0.95, 1000 \cdot 0.0475)$. So, $\mathbb{P}(X \leq 940) \approx \mathbb{P}(Y \leq 940)$

3. Compute Probability.

$$\begin{aligned}\mathbb{P}(Y \leq 940) &= \mathbb{P}\left(Z \leq \frac{940 - 1000 \cdot 0.95}{\sqrt{1000 \cdot 0.0475}}\right) && \text{standardize} \\ &\approx \Phi(-1.45) = 1 - \Phi(1.45) && \text{write in terms of } \Phi \\ &\approx 1 - .92647 = \underline{.07353}. && \text{plug into z-table}\end{aligned}$$

Factory Widgets 🕒 - CLT

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3. Compute Probability.

$$\mathbb{P}(Y \leq 940) = \mathbb{P}\left(Z \leq \frac{940 - 1000 \cdot 0.95}{\sqrt{1000 \cdot 0.0475}}\right)$$

$$\approx \Phi(-1.45) = 1 - \Phi(1.45)$$

$$\approx 1 - .92647 = .07353.$$

standardize

write in terms of Φ

plug into z-table

The exact probability is .08673. We're off by ~1.3%!

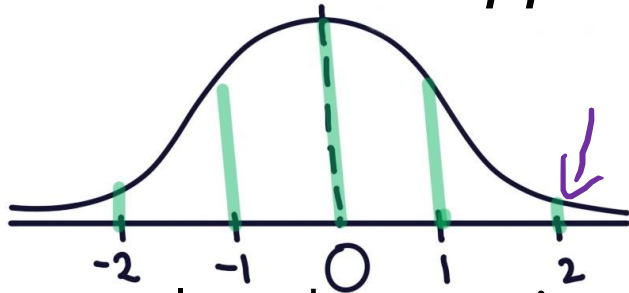
There's are some problems ☹️

When approximating a discrete distribution like binomial with a continuous normal distribution, there are some problems that arise!

> $\mathbb{P}(X = 2) > 0$ (we can use the binomial PMF).

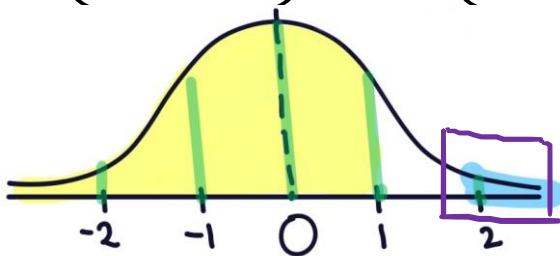
$Y \sim N(\mu, \sigma^2)$

But, when we approximate to the normal, continuous, Y , $\mathbb{P}(Y = 2) = 0$



> X only takes on integers, so $\mathbb{P}(X \leq 1) + \mathbb{P}(X \geq 2) = 1$.

But, when we approximate to the normal, continuous, Y ,
 $\mathbb{P}(Y \leq 1) + \mathbb{P}(Y \geq 2) < 1$



Continuity Correction

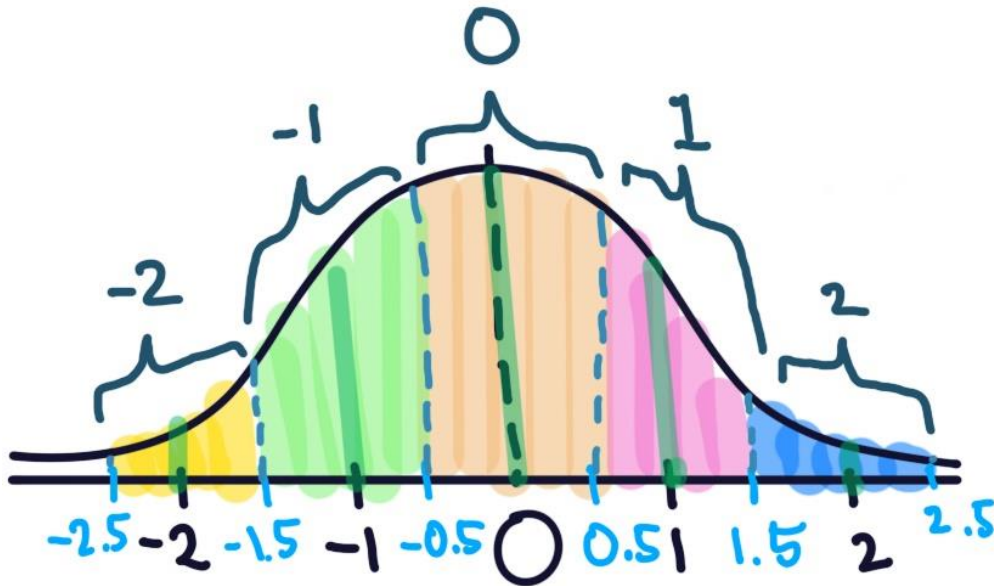
CLT to discrete RVS

The binomial distribution is discrete, but the normal is **continuous**.

Let's correct for that (called a "*continuity correction*")

★ Assign each value in the discrete range to a continuous interval

Here the support of X is $\{..., \underline{-2}, \underline{-1}, \underline{0}, \underline{1}, \underline{2}, ... \}$



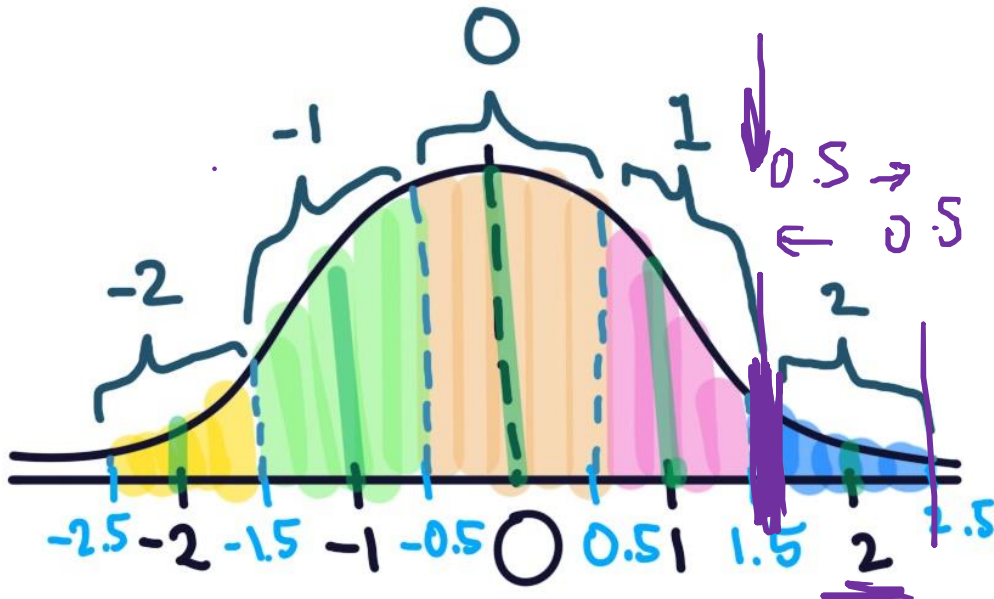
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★ Assign each value in the discrete range to a **continuous interval**

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e.g.,

$$\mathbb{P}(X = 2) \rightarrow P(1.5 < X < 2.5)$$

$$\mathbb{P}(X \geq 2) \rightarrow P(X \geq 1.5)$$

$$\mathbb{P}(X > 1) \rightarrow P(X \geq 1.5)$$

$$\mathbb{P}(X \leq 1) \rightarrow P(X \leq 1.5)$$

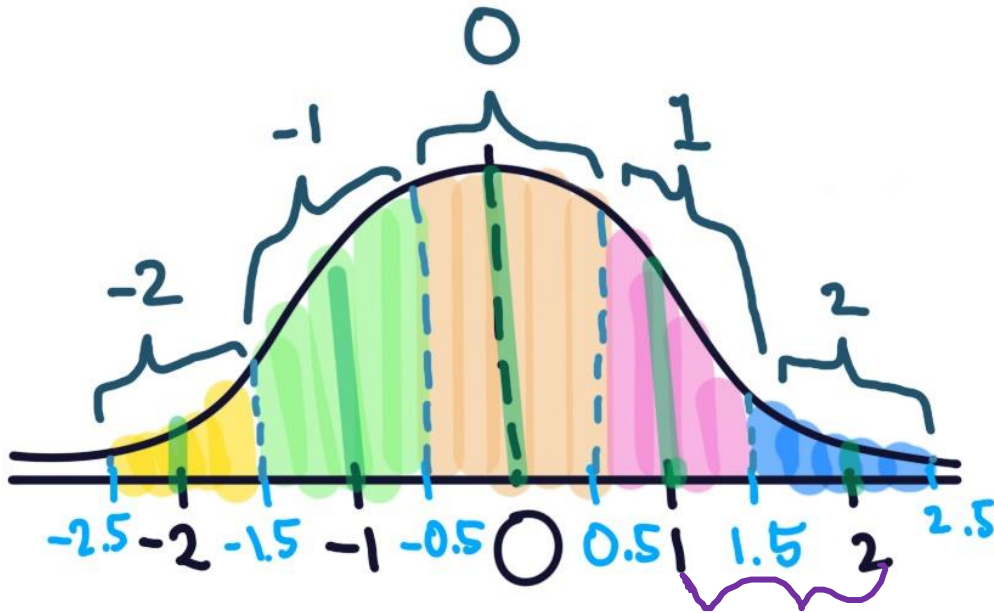
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e.g.,

$$\mathbb{P}(X = 2) \rightarrow \mathbb{P}(1.5 \leq X \leq 2.5)$$

$$\mathbb{P}(X \geq 2) \rightarrow \mathbb{P}(X \geq 1.5)$$

$$\mathbb{P}(X > 1) \rightarrow \mathbb{P}(X \geq 1.5)$$

$$\mathbb{P}(X \leq 1) \rightarrow \mathbb{P}(X \leq 1.5)$$

Continuity Correction

The binomial distribution is **discrete**, but the normal is **continuous**.

Let's correct for that (called a "*continuity correction*")

★ Assign each value in the discrete range to a continuous interval

Here the support of X is $\{..., \underline{-2}, \underline{5}, \underline{12}, \underline{19} ... \}$

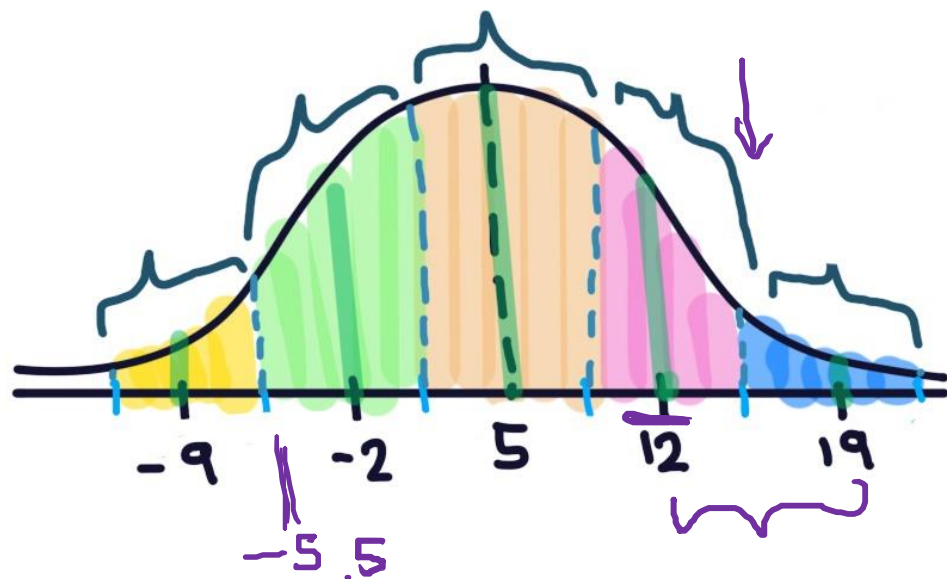
e.g.,

$$\underline{\mathbb{P}(X = -2)} \rightarrow$$

$$\mathbb{P}(X \geq 5) \rightarrow$$

$$\mathbb{P}(X < 12) \rightarrow$$

$$\mathbb{P}(X \geq 0) \rightarrow$$



Fill out the poll everywhere:
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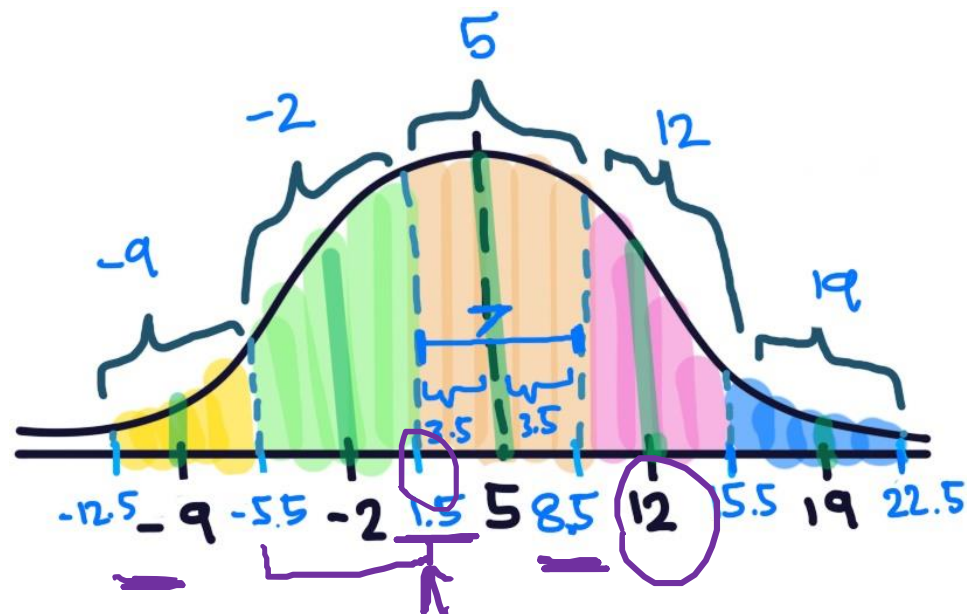
Continuity Correction

The binomial distribution is **discrete**, but the normal is **continuous**.

Let's correct for that (called a "**continuity correction**")

★ Assign each value in the discrete range to a continuous interval

Here the support of X is $\{\dots, -2, 5, 12, 19 \dots\}$



e.g.,

$$\mathbb{P}(X = -2) \rightarrow \mathbb{P}(-5.5 \leq x \leq 1.5)$$

$$\mathbb{P}(X \geq 5) \rightarrow \mathbb{P}(x \geq 1.5)$$

$$\mathbb{P}(X < 12) \rightarrow \mathbb{P}(x \leq 8.5)$$

$$\mathbb{P}(X \geq 0) \rightarrow \mathbb{P}(x \geq 1.5)$$

$$= \mathbb{P}(x > 1.5)$$

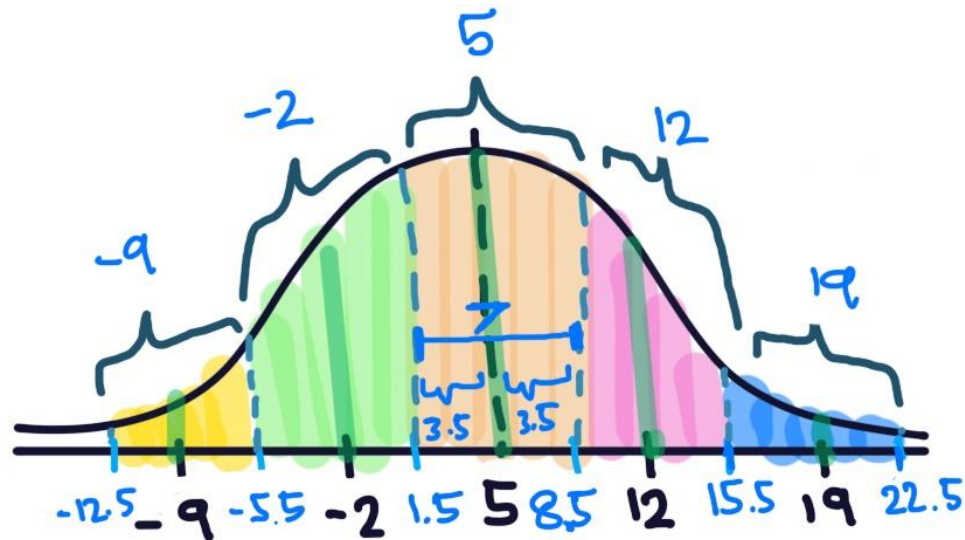
Continuity Correction

The binomial distribution is **discrete**, but the normal is **continuous**.

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$$\mathbb{P}(X \geq 0) \rightarrow \mathbb{P}(X \geq 1.5)$$

Outline of CLT steps

1. **Setup the problem** (e.g., $X = \sum_{i=1}^n X_i$, X_i are i.i.d., and we want $\mathbb{P}(X \leq k)$)

Write event you are interested in, in terms of sum of random variables.

→ ★ Apply **continuity correction** here if RVs are discrete.

2. **Apply CLT** (e.g., approx X as $Y \sim N(n\mu, n\sigma^2)$ -> $\mathbb{P}(X \leq k) \approx \mathbb{P}(Y \leq k)$)

Approximate sum of RVs as normal with appropriate mean and variance

from here, we're working with a normal distribution, which we've worked with before!

3. **Compute probability approximation using Phi table**

> **Standardize** ($Z = \frac{Y - \mu}{\sigma}$) -> $\mathbb{P}(Y \leq k) = \mathbb{P}\left(\frac{Y - \mu}{\sigma} \leq \frac{k - \mu}{\sigma}\right) = \mathbb{P}\left(Z \leq \frac{k - \mu}{\sigma}\right)$

> **Write in terms of $\Phi(z)$** = $\mathbb{P}(Z \leq z)$

> **Look up in table**

Factory Widgets 🕒 - CLT

Where to apply continuity correction?

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%.

Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

1. Setup the Problem: X is the number of non-defective widgets.

$X = \sum_{i=1}^{1000} X_i$ where X_i is 1 if the i 'th widget is non-defective. **Goal:** $\mathbb{P}(X \leq 940)$

2. Apply CLT. X is sum of i.i.d RVs each with $\mu = \mathbb{E}[X_i] = p = .95$ and $\text{Var}(X_i) = p(1 - p) = .0475$, we can approximate X with $Y \sim \mathcal{N}(1000 \cdot 0.95, 1000 \cdot 0.0475)$. So, $\mathbb{P}(X \leq 940) \approx \mathbb{P}(Y \leq 940)$

3. Compute Probability.

$$\begin{aligned}\mathbb{P}(Y \leq 940) &= \mathbb{P}\left(Z \leq \frac{940 - 1000 \cdot 0.95}{\sqrt{1000 \cdot 0.0475}}\right) && \text{standardize} \\ &\approx \Phi(-1.45) = 1 - \Phi(1.45) && \text{write in terms of } \Phi \\ &\approx 1 - .92647 = .07353. && \text{plug into z-table}\end{aligned}$$

Factory Widgets - CLT with continuity correction

Suppose you are managing a factory, that produces widgets. Each widget produced is defective (independently) with probability 5%. Your factory will produce 1000 (possibly defective) widgets. What is the probability of producing at most 940 non-defective widgets?

1. **Setup the Problem:** X is the number of non-defective widgets.

$X = \sum_{i=1}^{1000} X_i$ where X_i is 1 if the i 'th widget is non-defective. We want to find $\mathbb{P}(X \leq 940)$.

Because X is discrete, we use continuity correction: $\mathbb{P}(X \leq 940) = \mathbb{P}(X \leq 940.5)$

2. **Apply CLT.** X is sum of i.i.d RVs each with $\mu = \mathbb{E}[X_i] = p = .95$ and $\text{Var}(X_i) = p(1 - p) = .0475$, we can approximate X with $Y \sim \mathcal{N}(1000 \cdot 0.95, 1000 \cdot 0.0475)$.

So, $\mathbb{P}(X \leq 940.5) \approx \mathbb{P}(Y \leq 940.5)$

3. **Compute Probability.**

$$\begin{aligned}\mathbb{P}(Y \leq 940.5) &= \mathbb{P}\left(Z \leq \frac{940.5 - 1000 \cdot 0.95}{\sqrt{1000 \cdot 0.0475}}\right) \\ &\approx \Phi(-1.38) = 1 - \Phi(1.38) \\ &\approx 1 - .91621 = \underline{\underline{.08379}}.\end{aligned}$$

standardize

*write in terms of Φ
plug into z-table*

The exact probability is .08673. Still an approximation, but very close now! :D

What if we are asked something like...

> How people need to be surveyed to draw conclusion about [something to do with a sum of i.i.d RVs] with probability?

> How many trials should we do till the average amount from the trials [sum of i.i.d RVs] is away from the mean with probability?

$$\rightarrow P(|X - \mu| \leq d) > \text{ probability}$$

> What should the standard deviation be in order for the probability of [something to do with a sum of i.i.d. RVs] to be ?

↙ We will follow the exact same process as before for using CLT! Except now, we'll end up with something like $\mathbb{P}(Y \leq \underline{c}) = 0.96$ where we need to solve for c

Cereal

$$E[X_i] = 500$$
$$\text{Var}(X_i) = 100$$

A cereal company claims that their boxes contain an average of 500 grams of cereal with a variance of 100 grams. To test this claim, you take a random sample of n boxes. You want to determine the sample size n such that the probability of the sample mean being within 2 grams of the true mean (i.e., between 498 grams and 502 grams) is at least 95%.

1. Setup the Problem.

$$\text{Let } \bar{X} = \text{avg of } X_i = \frac{1}{n} \sum_{i=1}^n X_i$$

$$P(498 \leq \bar{X} \leq 502) \geq 0.95$$

2. Apply CLT

3. Compute Probability

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1. Setup the Problem.

Let X_i be the weight of the i th box weighed. The sample mean is $\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i = \sum_{i=1}^n \left(\frac{X_i}{n}\right)$

Goal: $\mathbb{P}(498 \leq \bar{X} \leq 502) \geq 0.95$

2. Apply CLT

3. Compute Probability

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Goal: $\mathbb{P}(498 \leq \bar{X} \leq 502) \geq 0.95$

2. Apply CLT

$\bar{X}$ is a sum of i.i.d random variables each with $\mu = E \left[\frac{X_i}{n} \right] = \frac{500}{n}$ and $\sigma^2 = Var \left(\frac{X_i}{n} \right) = \frac{100}{n^2}$

Let $Y \sim \mathcal{N} \left(n \cdot \frac{500}{n}, n \cdot \frac{100}{n^2} \right) = \mathcal{N} \left(500, \frac{100}{n} \right) \rightarrow$ By CLT, $\mathbb{P}(498 \leq \bar{X} \leq 502) \approx \mathbb{P}(498 \leq Y \leq 502)$

3. Compute Probability

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Goal: $\mathbb{P}(498 \leq \bar{X} \leq 502) \geq 0.95$

2. Apply CLT

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Let $Y \sim \mathcal{N} \left(n \cdot \frac{500}{n}, n \cdot \frac{100}{n^2} \right) = \mathcal{N} \left(500, \frac{100}{n} \right) \rightarrow$ By CLT, $\mathbb{P}(498 \leq \bar{X} \leq 502) \approx \mathbb{P}(498 \leq Y \leq 502)$

3. Compute Probability

$$\mathbb{P}(498 \leq Y \leq 502) = \mathbb{P} \left(\frac{498-500}{\sqrt{100/n}} \leq Z \leq \frac{502-500}{\sqrt{100/n}} \right) = \mathbb{P} \left(\frac{-2}{10/\sqrt{n}} \leq Z \leq \frac{2}{10/\sqrt{n}} \right) \quad \text{standardize}$$

Cereal

A cereal company claims that their boxes contain an average of 500 grams of cereal with a variance of 100 grams. To test this claim, you take a random sample of n boxes. You want to determine the sample size n such that the probability of the sample mean being within 2 grams of the true mean (i.e., between 498 grams and 502 grams) is at least 95%.

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Let $Y \sim \mathcal{N}\left(n \cdot \frac{500}{n}, n \cdot \frac{100}{n^2}\right) = \mathcal{N}\left(500, \frac{100}{n}\right) \rightarrow$ By CLT, $\mathbb{P}(498 \leq \bar{X} \leq 502) \approx \mathbb{P}(498 \leq Y \leq 502)$

3. Compute Probability

$$\mathbb{P}(\mathbf{498} \leq \mathbf{Y} \leq \mathbf{502}) = \mathbb{P}\left(\frac{498-500}{\sqrt{100/n}} \leq Z \leq \frac{502-500}{\sqrt{100/n}}\right) = \mathbb{P}\left(\frac{-2}{10/\sqrt{n}} \leq Z \leq \frac{2}{10/\sqrt{n}}\right) \text{ *standardize*}$$

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3. Compute Probability

$$\begin{aligned} \mathbb{P}(498 \leq Y \leq 502) &= \mathbb{P}\left(\frac{498-500}{\sqrt{100/n}} \leq Z \leq \frac{502-500}{\sqrt{100/n}}\right) = \mathbb{P}\left(\frac{-2}{10/\sqrt{n}} \leq Z \leq \frac{2}{10/\sqrt{n}}\right) && \text{standardize} \\ &= \Phi\left(\frac{2}{10/\sqrt{n}}\right) - (1 - \Phi\left(\frac{2}{10/\sqrt{n}}\right)) = 2\Phi\left(\frac{2}{10/\sqrt{n}}\right) - 1 && \text{write in terms of } \Phi \\ &\geq 0.95 \end{aligned}$$

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...

Let $Y \sim \mathcal{N}\left(n \cdot \frac{500}{n}, n \cdot \frac{100}{n^2}\right) = \mathcal{N}\left(500, \frac{100}{n}\right) \rightarrow$ By CLT, $\mathbb{P}(498 \leq \bar{X} \leq 502) \approx \mathbb{P}(498 \leq Y \leq 502)$

3. Compute Probability

$$\begin{aligned} \mathbb{P}(498 \leq Y \leq 502) &= \mathbb{P}\left(\frac{498-500}{\sqrt{100/n}} \leq Z \leq \frac{502-500}{\sqrt{100/n}}\right) = \mathbb{P}\left(\frac{-2}{10/\sqrt{n}} \leq Z \leq \frac{2}{10/\sqrt{n}}\right) && \text{standardize} \\ &= \Phi\left(\frac{2}{10/\sqrt{n}}\right) - (1 - \Phi\left(\frac{2}{10/\sqrt{n}}\right)) = 2\Phi\left(\frac{2}{10/\sqrt{n}}\right) - 1 && \text{write in terms of } \Phi \\ &\geq 0.95 \end{aligned}$$

Doing some algebra...

$$2\Phi\left(\frac{2}{10/\sqrt{n}}\right) - 1 \geq 0.95 \text{ with some algebra, we get } \Phi\left(\frac{2}{10/\sqrt{n}}\right) \geq 0.975$$

reverse table lookup: what can we plug into the z-table to get $\Phi(z) \geq 0.975$?

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5	0.50399	0.50798	0.51197	0.51595	0.51994	0.52392	0.5279	0.53188	0.53586
0.1	0.53983	0.5438	0.54776	0.55172	0.55567	0.55962	0.56356	0.56749	0.57142	0.57535
0.2	0.57926	0.58317	0.58706	0.59095	0.59483	0.59871	0.60257	0.60642	0.61026	0.61409
0.3	0.61791	0.62172	0.62552	0.6293	0.63307	0.63683	0.64058	0.64431	0.64803	0.65173
0.4	0.65542	0.6591	0.66276	0.6664	0.67003	0.67364	0.67724	0.68082	0.68439	0.68793
0.5	0.69146	0.69497	0.69847	0.70194	0.7054	0.70884	0.71226	0.71566	0.71904	0.7224
0.6	0.72575	0.72907	0.73237	0.73565	0.73891	0.74215	0.74537	0.74857	0.75175	0.7549
0.7	0.75804	0.76115	0.76424	0.7673	0.77035	0.77337	0.77637	0.77935	0.7823	0.78524
0.8	0.78814	0.79103	0.79389	0.79673	0.79955	0.80234	0.80511	0.80785	0.81057	0.81327
0.9	0.81594	0.81859	0.82121	0.82381	0.82639	0.82894	0.83147	0.83398	0.83646	0.83891
1.0	0.84134	0.84375	0.84614	0.84849	0.85083	0.85314	0.85543	0.85769	0.85993	0.86214
1.1	0.86433	0.8665	0.86864	0.87076	0.87286	0.87493	0.87698	0.879	0.881	0.88298
1.2	0.88493	0.88686	0.88877	0.89065	0.89251	0.89435	0.89617	0.89796	0.89973	0.90147
1.3	0.9032	0.9049	0.90658	0.90824	0.90988	0.91149	0.91309	0.91466	0.91621	0.91774
1.4	0.91924	0.92073	0.9222	0.92364	0.92507	0.92647	0.92785	0.92922	0.93056	0.93189
1.5	0.93319	0.93448	0.93574	0.93699	0.93822	0.93943	0.94062	0.94179	0.94295	0.94408
1.6	0.9452	0.9463	0.94738	0.94845	0.9495	0.95053	0.95154	0.95254	0.95352	0.95449
1.7	0.95543	0.95637	0.95728	0.95818	0.95907	0.95994	0.9608	0.96164	0.96246	0.96327
1.8	0.96407	0.96485	0.96562	0.96638	0.96712	0.96784	0.96856	0.96926	0.96995	0.97062
1.9	0.97128	0.97193	0.97257	0.9732	0.97381	0.97441	0.975	0.97558	0.97615	0.9767
2.0	0.97725	0.97778	0.97831	0.97882	0.97932	0.97982	0.9803	0.98077	0.98124	0.98169
2.1	0.98214	0.98257	0.983	0.98341	0.98382	0.98422	0.98461	0.985	0.98537	0.98574
2.2	0.9861	0.98645	0.98679	0.98713	0.98745	0.98778	0.98809	0.9884	0.9887	0.98899
2.3	0.98928	0.98956	0.98983	0.9901	0.99036	0.99061	0.99086	0.99111	0.99134	0.99158
2.4	0.9918	0.99202	0.99224	0.99245	0.99266	0.99286	0.99305	0.99324	0.99343	0.99361
2.5	0.99379	0.99396	0.99413	0.9943	0.99446	0.99461	0.99477	0.99492	0.99506	0.9952
2.6	0.99534	0.99547	0.9956	0.99573	0.99585	0.99598	0.99609	0.99621	0.99632	0.99643
2.7	0.99653	0.99664	0.99674	0.99683	0.99693	0.99702	0.99711	0.9972	0.99728	0.99736
2.8	0.99744	0.99752	0.9976	0.99767	0.99774	0.99781	0.99788	0.99795	0.99801	0.99807
2.9	0.99813	0.99819	0.99825	0.99831	0.99836	0.99841	0.99846	0.99851	0.99856	0.99861
3.0	0.99865	0.99869	0.99874	0.99878	0.99882	0.99886	0.99889	0.99893	0.99896	0.999

Cereal

A cereal company claims that their boxes contain an average of 500 grams of cereal with a variance of 100 grams. To test this claim, you take a random sample of n boxes. You want to determine the sample size n such that the probability of the sample mean being within 2 grams of the true mean (i.e., between 498 grams and 502 grams) is at least 95%.

...

Let $Y \sim \mathcal{N}\left(n \cdot \frac{500}{n}, n \cdot \frac{100}{n^2}\right) = \mathcal{N}\left(500, \frac{100}{n}\right) \rightarrow$ By CLT, $\mathbb{P}(498 \leq \bar{X} \leq 502) \approx \mathbb{P}(498 \leq Y \leq 502)$

3. Compute Probability

$$\begin{aligned} \mathbb{P}(498 \leq Y \leq 502) &= \mathbb{P}\left(\frac{498-500}{\sqrt{100/n}} \leq Z \leq \frac{502-500}{\sqrt{100/n}}\right) = \mathbb{P}\left(\frac{-2}{10/\sqrt{n}} \leq Z \leq \frac{2}{10/\sqrt{n}}\right) && \text{standardize} \\ &= \Phi\left(\frac{2}{10/\sqrt{n}}\right) - (1 - \Phi\left(\frac{2}{10/\sqrt{n}}\right)) = 2\Phi\left(\frac{2}{10/\sqrt{n}}\right) - 1 && \text{write in terms of } \Phi \\ &\geq 0.95 \end{aligned}$$

Doing some algebra...

$$2\Phi\left(\frac{2}{10/\sqrt{n}}\right) - 1 \geq 0.95 \text{ with some algebra, we get } \Phi\left(\frac{2}{10/\sqrt{n}}\right) \geq 0.975$$

reverse table lookup: what can we plug into the z-table to get $\Phi(z) \geq 0.975$?

$$\frac{2}{10/\sqrt{n}} \geq 1.96 \rightarrow \text{solve the inequality} \rightarrow n \geq 97$$

Some more practice with that **reverse z-table lookup step!**

- > What value of c such that $\Phi(c) = 0.76$?
- > What condition on c so that $\Phi(c) \geq 0.94$?
- > What condition on c so that $\Phi(c) \leq \text{ick } 0.94$?

once we have that expression, we solve for whatever we're interested in c !

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5	0.50399	0.50798	0.51197	0.51595	0.51994	0.52392	0.5279	0.53188	0.53586
0.1	0.53983	0.5438	0.54776	0.55172	0.55567	0.55962	0.56356	0.56749	0.57142	0.57535
0.2	0.57926	0.58317	0.58706	0.59095	0.59483	0.59871	0.60257	0.60642	0.61026	0.61409
0.3	0.61791	0.62172	0.62552	0.6293	0.63307	0.63683	0.64058	0.64431	0.64803	0.65173
0.4	0.65542	0.6591	0.66276	0.6664	0.67003	0.67364	0.67724	0.68082	0.68439	0.68793
0.5	0.69146	0.69497	0.69847	0.70194	0.7054	0.70884	0.71226	0.71566	0.71904	0.7224
0.6	0.72575	0.72907	0.73237	0.73565	0.73891	0.74215	0.74537	0.74857	0.75175	0.7549
0.7	0.75804	0.76115	0.76424	0.7673	0.77035	0.77337	0.77637	0.77935	0.7823	0.78524
0.8	0.78814	0.79103	0.79389	0.79673	0.79955	0.80234	0.80511	0.80785	0.81057	0.81327
0.9	0.81594	0.81859	0.82121	0.82381	0.82639	0.82894	0.83147	0.83398	0.83646	0.83891
1.0	0.84134	0.84375	0.84614	0.84849	0.85083	0.85314	0.85543	0.85769	0.85993	0.86214
1.1	0.86433	0.8665	0.86864	0.87076	0.87286	0.87493	0.87698	0.879	0.881	0.88298
1.2	0.88493	0.88686	0.88877	0.89065	0.89251	0.89435	0.89617	0.89796	0.89973	0.90147
1.3	0.9032	0.9049	0.90658	0.90824	0.90988	0.91149	0.91309	0.91466	0.91621	0.91774
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1.6	0.9452	0.9463	0.94738	0.94845	0.9495	0.95053	0.95154	0.95254	0.95352	0.95449
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2.3	0.98928	0.98956	0.98983	0.9901	0.99036	0.99061	0.99086	0.99111	0.99134	0.99158
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2.5	0.99379	0.99396	0.99413	0.9943	0.99446	0.99461	0.99477	0.99492	0.99506	0.9952
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2.8	0.99744	0.99752	0.9976	0.99767	0.99774	0.99781	0.99788	0.99795	0.99801	0.99807
2.9	0.99813	0.99819	0.99825	0.99831	0.99836	0.99841	0.99846	0.99851	0.99856	0.99861
3.0	0.99865	0.99869	0.99874	0.99878	0.99882	0.99886	0.99889	0.99893	0.99896	0.999

Some more practice with that **reverse z-table lookup step!**

> What value of c such that $\Phi(c) = 0.76$?

$c \approx 0.53$ (it's an estimate, it gives us a value that's pretty close to 0.76)

some write this as $\Phi^{-1}(0.76) \approx 0.53$

> What condition on c so that $\Phi(c) \geq 0.94$?

$\Phi(1.56) = 0.94062$. 1.56 is the first value that gives us a value ≥ 0.94

So, if $c \geq 1.56$, $\Phi(c) \geq 0.94$

> What condition on c so that $\Phi(c) \leq 0.94$?

Now, if we want the probability ≤ 0.94 , $c \leq 1.55$ because $\Phi(1.55) = 0.93943$

if we said $c \leq 1.56$ that would include $\Phi(1.56) = 0.94062 > 0.94$ and values that give probability between 0.94 and 0.94062

once we have that expression, we solve for whatever we're interested in c !

When to use CLT

Use the CLT when:

- The random variable you're interested in is the sum of independent random variables.
- The random variable you're interested in does not have an easily accessible or easy to use pmf/pdf (or the question you're asking doesn't lend it self to easily using the pmf/pdf)
- You only need an approximate answer, and the sum is of at least a moderate number of random variables.