CSE 312

Foundations of Computing II

Lecture 14: Quick wrapup of discrete RVs
Continuous RVs

no 8 pm office hours today

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Agenda

- Wrap-up of Discrete RVs
- Continuous Random Variables
- Probability Density Function
- Cumulative Distribution Function
- Expectation and Variance of continuous RVs

Poisson Random Variables

Definition. A **Poisson random variable** X with parameter $\lambda \geq 0$ is such that for all $i = 0,1,2,3 \ldots,$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

$i = 0, 1, \ldots$

General principle:

- Events happen at an average rate of λ per time unit
- Number of events happening at a time unit X is distributed according to Poi(λ)
- Poisson approximates Binomial when n is large, p is small, and np is moderate
- Sum of independent Poisson is still a Poisson

$X \sim Poi(\lambda_1)$
$Y \sim Poi(\lambda_2)$
$Z = X + Y \sim Poi(\lambda_1 + \lambda_2)$

Zoo of Random Variables🦍🐘🦁🐅🦓🐪🦒

$X \sim \text{Poisson}(\lambda)$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

$$E[X] = \lambda$$

$$\text{Var}(X) = \lambda$$

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

$$P(X = 1) = p, P(X = 0) = 1 - p$$

$$E[X] = p$$

$$\text{Var}(X) = p(1 - p)$$

$X \sim \text{Bin}(n, p)$

$$P(X = k) = \binom{n}{k} p^k (1 - p)^{n-k}$$

$$E[X] = np$$

$$\text{Var}(X) = np(1 - p)$$

$X \sim \text{Geo}(p)$

$$P(X = k) = (1 - p)^{k-1} p$$

$$E[X] = \frac{1}{p}$$

$$\text{Var}(X) = \frac{1 - p}{p^2}$$

$X \sim \text{NegBin}(r, p)$

$$P(X = k) = \binom{k - 1}{r - 1} p^r (1 - p)^{k-r}$$

$$E[X] = \frac{r}{p}$$

$$\text{Var}(X) = \frac{r(1 - p)}{p^2}$$

$X \sim \text{HypGeo}(N, K, n)$

$$P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$$

$$E[X] = n\frac{K}{N}$$

$$\text{Var}(X) = n\frac{K(N - K)(N - n)}{N^2(N - 1)}$$

r-1 H's in first k-1 trials.

T T T T T H T H T T T H

k

r = 3

Negative Binomial Random Variables

p, r

A discrete random variable X that models the number of independent trials $Y_i \sim \mathrm{Ber}(p)$ before seeing the r^{th} success.
Equivalently, $X = \sum_{i=1}^{r} Z_i$ where $Z_i \sim \mathrm{Geo}(p)$.
X is called a Negative Binomial random variable with parameters r, p.

Notation: $X \sim \boxed{\mathrm{NegBin}(r, p)}$

PMF: $P(X = k) = \binom{k-1}{r-1} p^{r-1} (1-p)^{(k-1)-(r-1)}$ $\quad p = \binom{k-1}{r-1} p^{r} (1-p)^{k-r}$

Expectation: $\mathbb{E}[X] = \frac{r}{p}$

Negative Binomial Random Variables

A discrete random variable X that models the number of independent trials $Y_i \sim \mathrm{Ber}(p)$ before seeing the r^{th} success.
Equivalently, $X = \sum_{i=1}^{r} Z_i$ where $\mathrm{Z}_i \sim \mathrm{Geo}(p)$.
X is called a Negative Binomial random variable with parameters r, p.

Notation: $X \sim \mathrm{NegBin}(r, p)$

PMF: $P(X = k) = \binom{k-1}{r-1} p^r (1-p)^{k-r}$

Expectation: $\mathbb{E}[X] = \frac{r}{p}$

Variance: $\mathrm{Var}(X) = \frac{r(1-p)}{p^2}$

Hypergeometric Random Variables

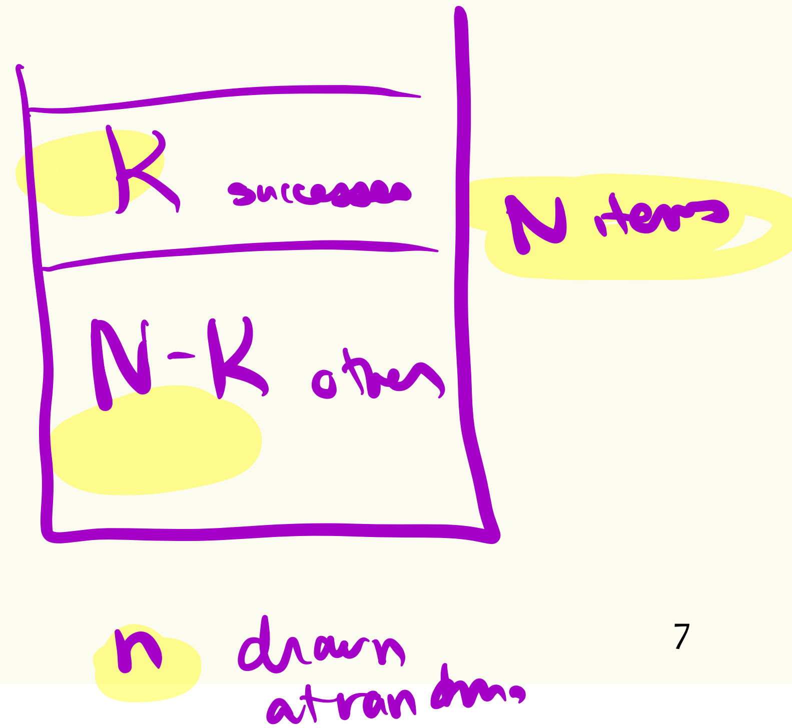
A discrete random variable X that models the number of successes in n draws (without replacement) from N items that contain K successes in total. X is called a Hypergeometric RV with parameters N, K, n.

Notation: $X \sim \text{HypGeo}(N, K, n)$

PMF: $P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$

Expectation: $\mathbb{E}[X] = n\frac{K}{N}$

Variance: $\text{Var}(X) = n\frac{K(N-K)(N-n)}{N^2(N-1)}$



Hope you enjoyed the zoo! 🦍🐘🦁🐅🦓🐪🦒

$X \sim \mathrm{Unif}(a, b)$

$$P(X = k) = \frac{1}{b - a + 1}$$

$$\mathbb{E}[X] = \frac{a + b}{2}$$

$$\mathrm{Var}(X) = \frac{(b - a)(b - a + 2)}{12}$$

$X \sim \mathrm{Ber}(p)$

$$P(X = 1) = p, P(X = 0) = 1 - p$$

$$\mathbb{E}[X] = p$$

$$\mathrm{Var}(X) = p(1 - p)$$

$X \sim \mathrm{Bin}(n, p)$

$$P(X = k) = \binom{n}{k} p^k (1 - p)^{n-k}$$

$$\mathbb{E}[X] = np$$

$$\mathrm{Var}(X) = np(1 - p)$$

$X \sim \mathrm{Geo}(p)$

$$P(X = k) = (1 - p)^{k-1} p$$

$$\mathbb{E}[X] = \frac{1}{p}$$

$$\mathrm{Var}(X) = \frac{1 - p}{p^2}$$

$X \sim \mathrm{NegBin}(r, p)$

$$P(X = k) = \binom{k - 1}{r -}$$

$$\mathbb{E}[X] = \frac{r}{p}$$

$$\mathrm{Var}(X) = \frac{r(1 - p}{p^2}$$

$X \sim \mathrm{HypGeo}(N, K, n)$

$$\frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$$

$$\frac{K(N - K)(N - n)}{N^2(N - 1)}$$

$X \sim \mathrm{Poisson}(\lambda)$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

$$E[X] = \lambda$$

$$\mathrm{Var}(X) = \lambda$$

Agenda

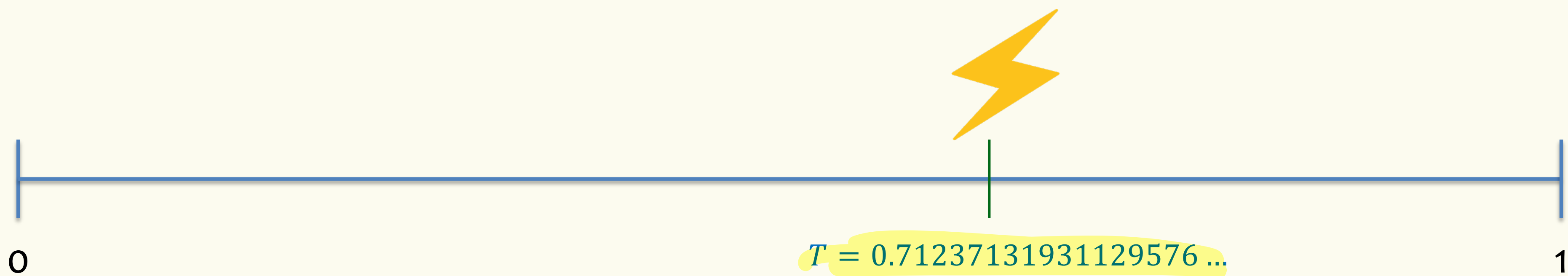
- Wrap-up of Poisson RVs
- Continuous Random Variables
- Probability Density Function
- Cumulative Distribution Function
- Expectation and Variance of continuous r.v.

Often we want to model experiments where the outcome is <u>not</u> discrete.

Example – Lightning Strike

Lightning strikes a pole within a one-minute time frame

- T = time of lightning strike
- Every time within $[0,1]$ is equally likely
  - – Time measured with infinitesimal precision.

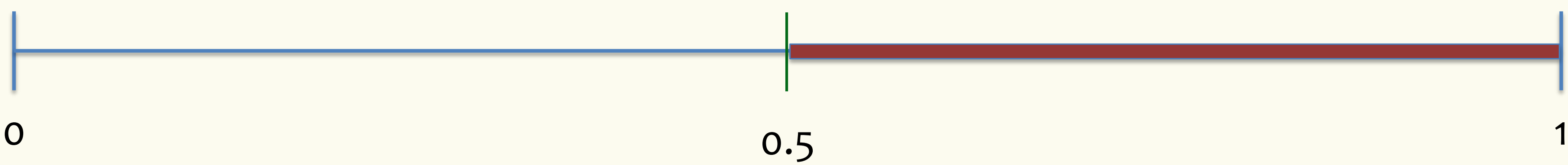


The outcome space is not discrete

Lightning strikes a pole within a one-minute time frame

- T = time of lightning strike
- Every point in time within $[0,1]$ is equally likely

$$P(T \geq 0.5) = \ 0.5$$



Lightning strikes a pole within a one-minute time frame

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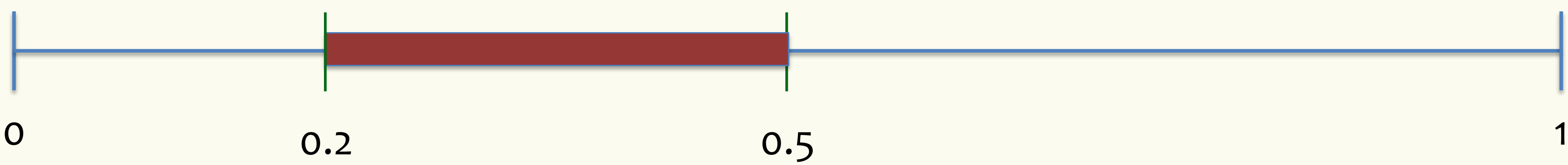
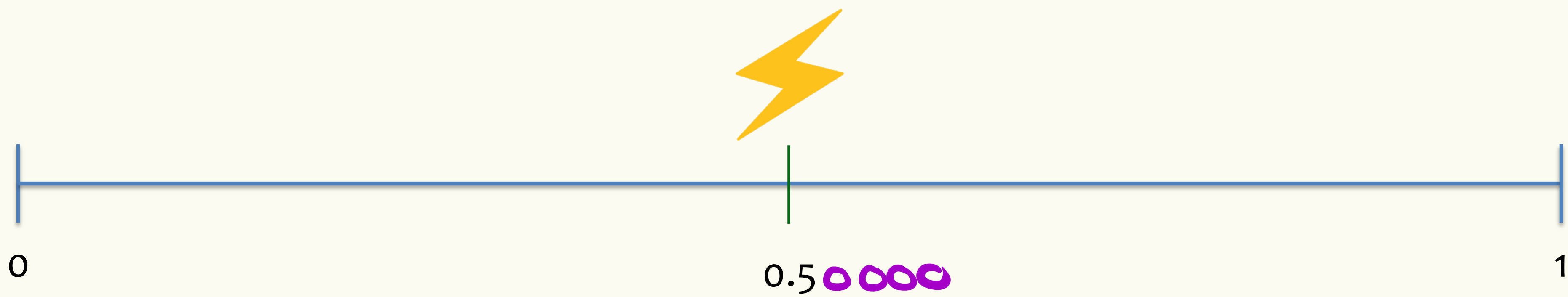


$P(0.2 \leq T \leq 0.5) =$ $0.5 - 0.2 = 0.3$

Lightning strikes a pole within a one-minute time frame

- T = time of lightning strike
- Every point in time within [0,1] is equally likely



$P(T = 0.5) = 0$

Bottom line

- This gives rise to a different type of random variable
- $P(T = x) = 0$ for all $x \in [0,1]$
- Yet, somehow we want
  - $P(T \in [0,1]) = 1$
  - $P(T \in [a, b]) = b - a$
  - …
- How do we model the behavior of T?

First try: A discrete approximation

Recall: Cumulative Distribution Function (CDF)

$p_X(x) = P(X = x)$

$\sum_{x \in \Omega_X} p_X(x) = 1$

$p_X(x) \geq 0 \ \forall x$

$F_X(x) = P(X \leq x)$

F_X monotone increasing from 0 to 1

$F_X(x) = \sum_{y \leq x} p_X(y)$

Probability Mass Function

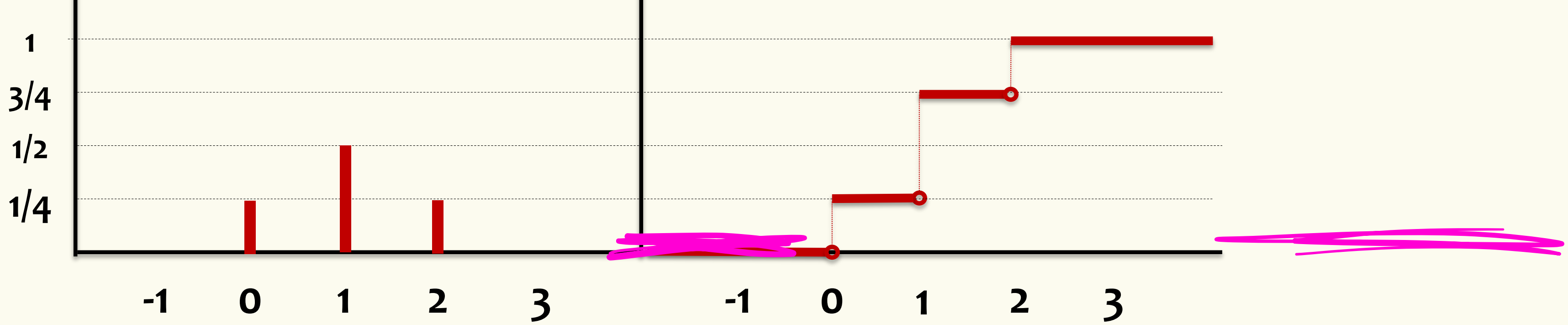
PMF

p_X

Cumulative Distribution Function

CDF

F_X



k

Poll: Given the CDF, how do you compute the pmf?

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$p_X(k) =$ $\Pr(X = k) =$

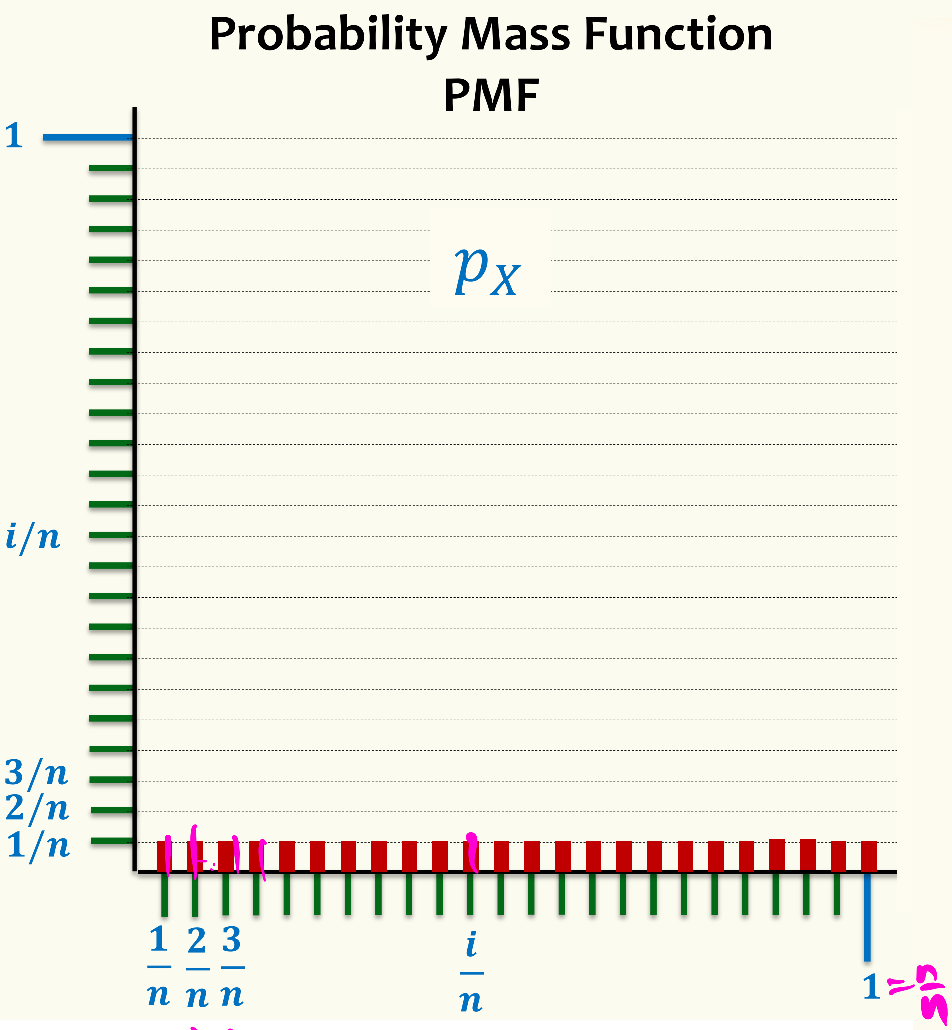
a. $F_X(k-1)$
b. $F_X(1) + F_X(2) + \cdots + F_X(k-1)$
c. $F_X(k) - F_X(k-1)$
d. I don't know.

$$F_X(k) = \sum_{x \le k} P(X = x)$$

$$F_X(k-1) = \sum_{x \le k-1} P(X = x)$$

$$F_X(w) = \sum_{x \le w} p_X(x)$$

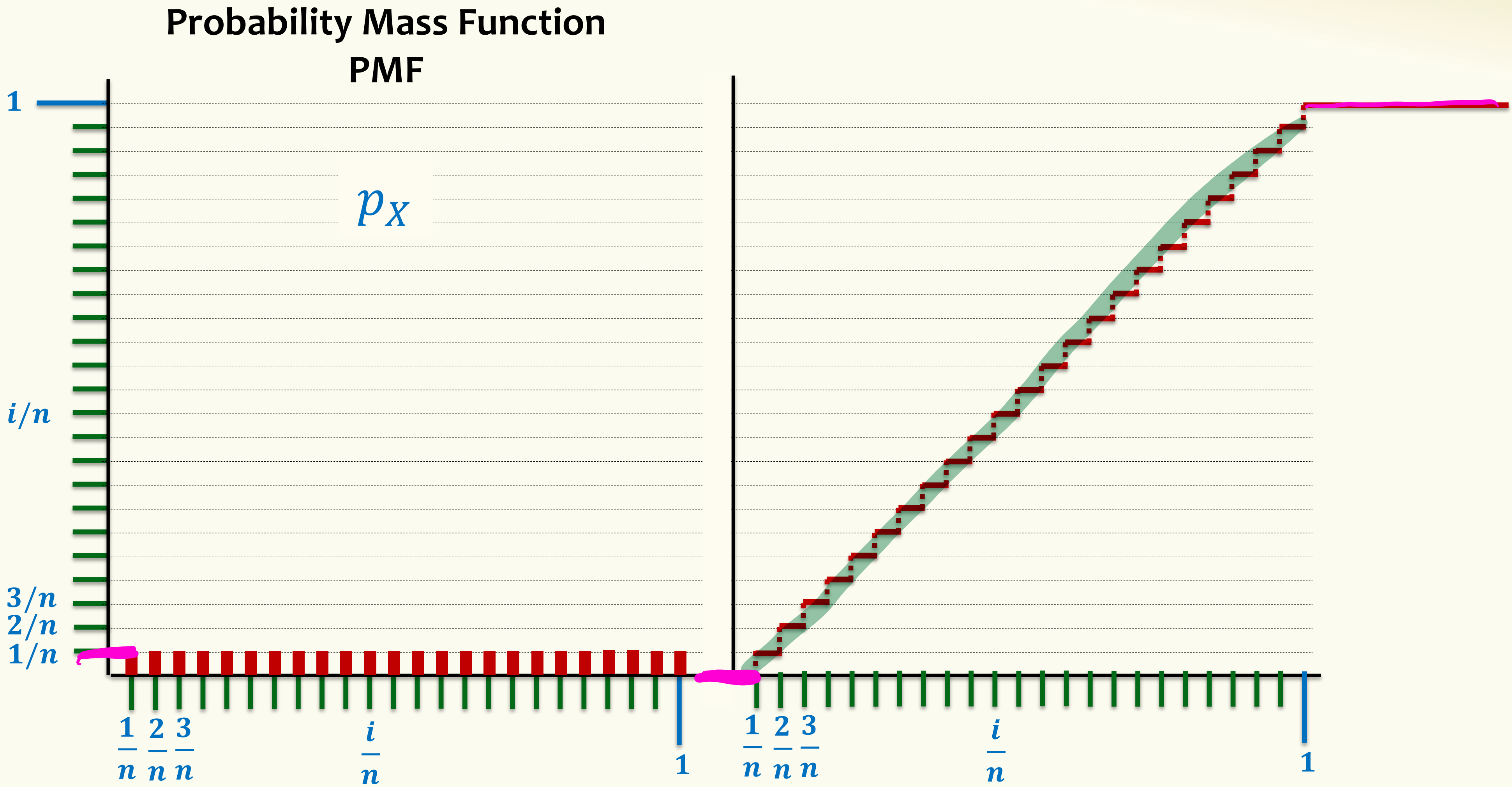
A Discrete Approximation



$$\Omega_X = \left\{\frac{1}{n}, \frac{2}{n}, \dots, \frac{n-1}{n}, \frac{n}{n}\right\}$$

$$F_X\left(\frac{i}{n}\right) = \frac{i}{n}.$$

A Discrete Approximation



$\{ 0 \qquad x<0$

$$\lim_{n\to\infty} F_X(x) = \begin{cases} x & 0 \le x \le 1 \\ 1 & x > 1 \end{cases}$$

$$\lim_{n\to\infty} P_X(x) = 0$$

$$p_X(k) = P(X=k) = \frac{F_X(k) - F_X(k-1)}{k-(k-1)}$$

$$F_X(x) = \sum_{\substack{w \in \Omega_X \\ w \leq x}} p_X(w)$$

probability density fn

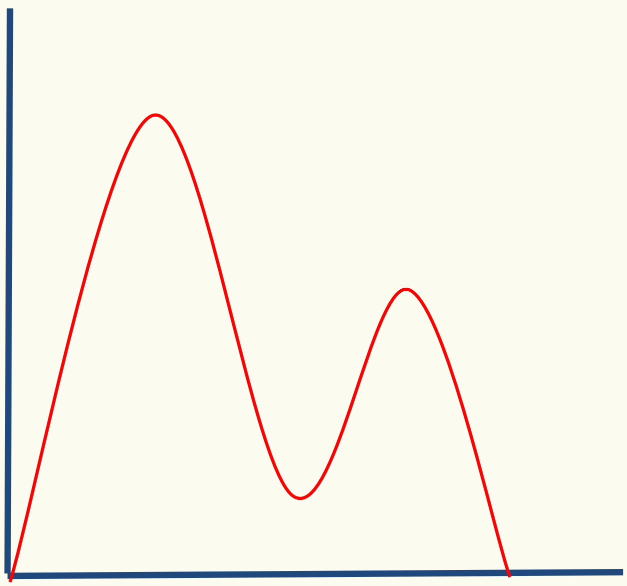
CDF

$$f_X(x) = \frac{d}{dx} F_X(x)$$

$$F_X(x) = \int_{-\infty}^{x} f_X(w)\,dw$$

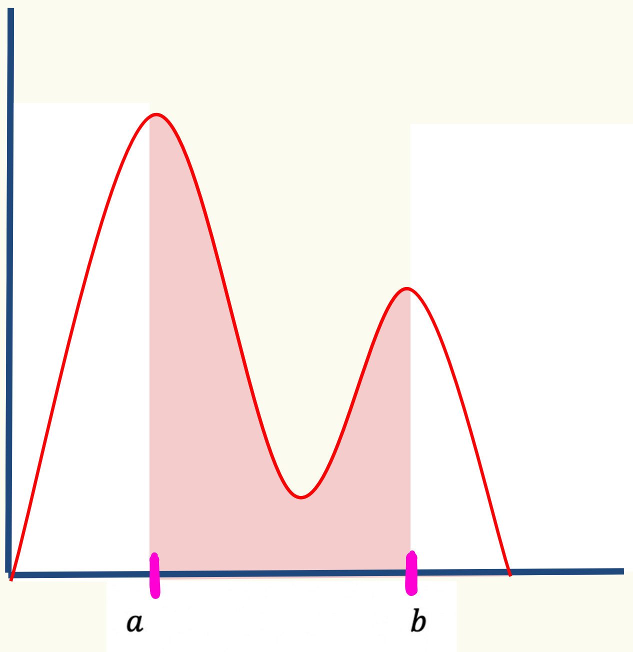
$= P(X \leq x)$

Definition. A **continuous random variable** X is defined by a **probability density function** (PDF) $f_X : \mathbb{R} \to \mathbb{R}$, such that



Non-negativity: $f_X(x) \geq 0$ for all $x \in \mathbb{R}$

Probability Density Function - Intuition

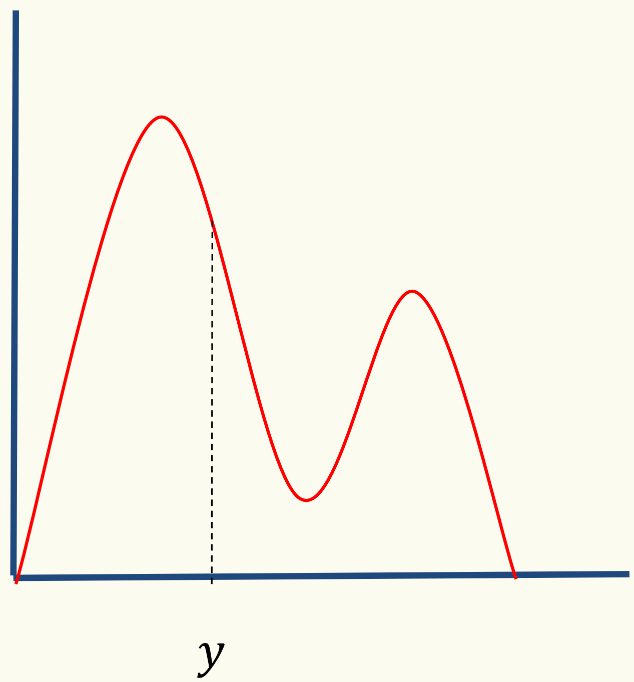


Non-negativity: $f_X(x) \geq 0$ for all $x \in \mathbb{R}$

Normalization: $\int_{-\infty}^{+\infty} f_X(x)\, \mathrm{d}x = 1$

$$P(a \leq X \leq b) = \int_a^b f_X(x)\, \mathrm{d}x$$

Probability Density Function - Intuition



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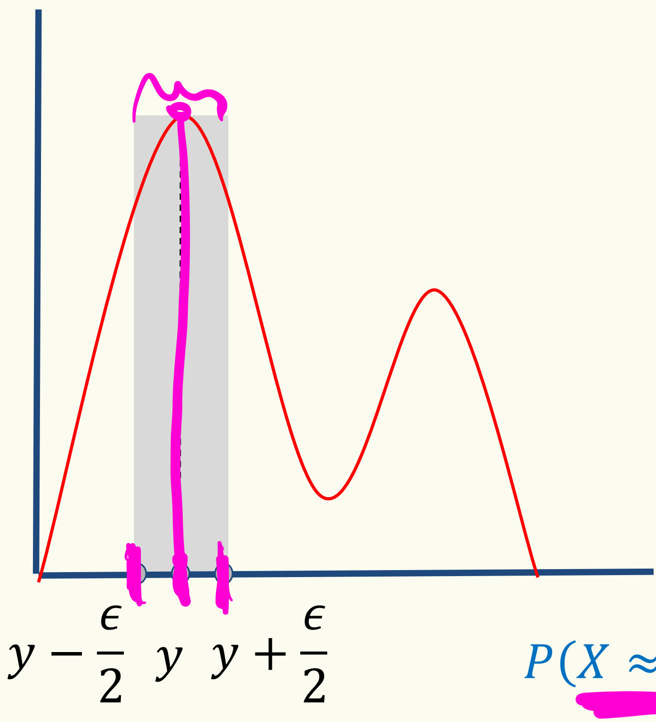
$$P(X = y) = P(y \leq X \leq y) = \int_y^y f_X(x)\,\mathrm{d}x = 0$$

Density ≠ Probability

$f_X(y) \neq 0 \qquad P(X = y) = 0$

Probability Density Function - Intuition



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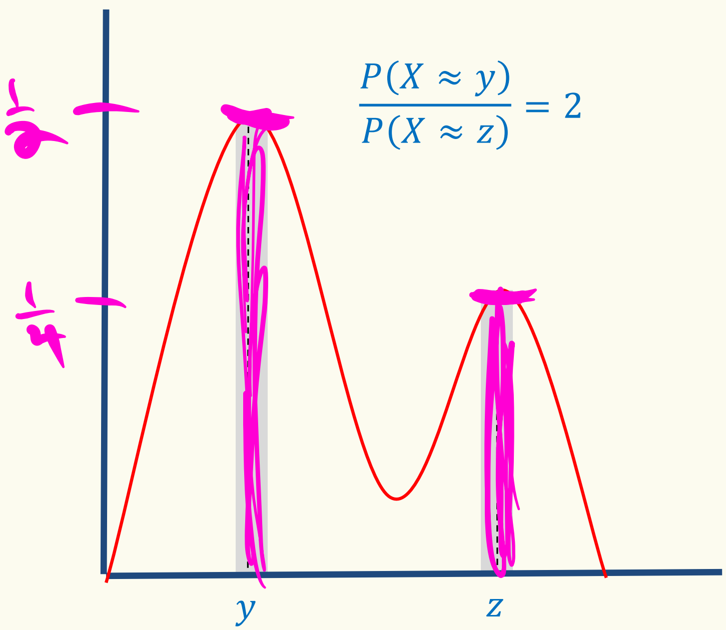
$$P(X = y) = P(y \leq X \leq y) = \int_y^y f_X(x)\,\mathrm{d}x = 0$$

$$P(X \approx y) \approx P\left(y - \frac{\epsilon}{2} \leq X \leq y + \frac{\epsilon}{2}\right) = \int_{y-\frac{\epsilon}{2}}^{y+\frac{\epsilon}{2}} f_X(x)\,\mathrm{d}x \approx \epsilon f_X(y)$$

What $f_X(x)$ measures: The local ***rate*** at which probability accumulates

Probability Density Function - Intuition



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$$\boxed{\frac{P(X \approx y)}{P(X \approx z)}} \approx \frac{\epsilon f_X(y)}{\epsilon f_X(z)} = \frac{f_X(y)}{f_X(z)}$$

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Normalization: $\int_{-\infty}^{+\infty} f_X(x)\,\mathrm{d}x = 1$

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$$\frac{P(X \approx y)}{P(X \approx z)} \approx \frac{\epsilon f_X(y)}{\epsilon f_X(z)} = \frac{f_X(y)}{f_X(z)}$$

$$F_X(x) = P(X \le x) = \begin{cases} 0 & x < 0 \\ x & 0 \le x \le 1 \\ 1 & x > 1 \end{cases}$$

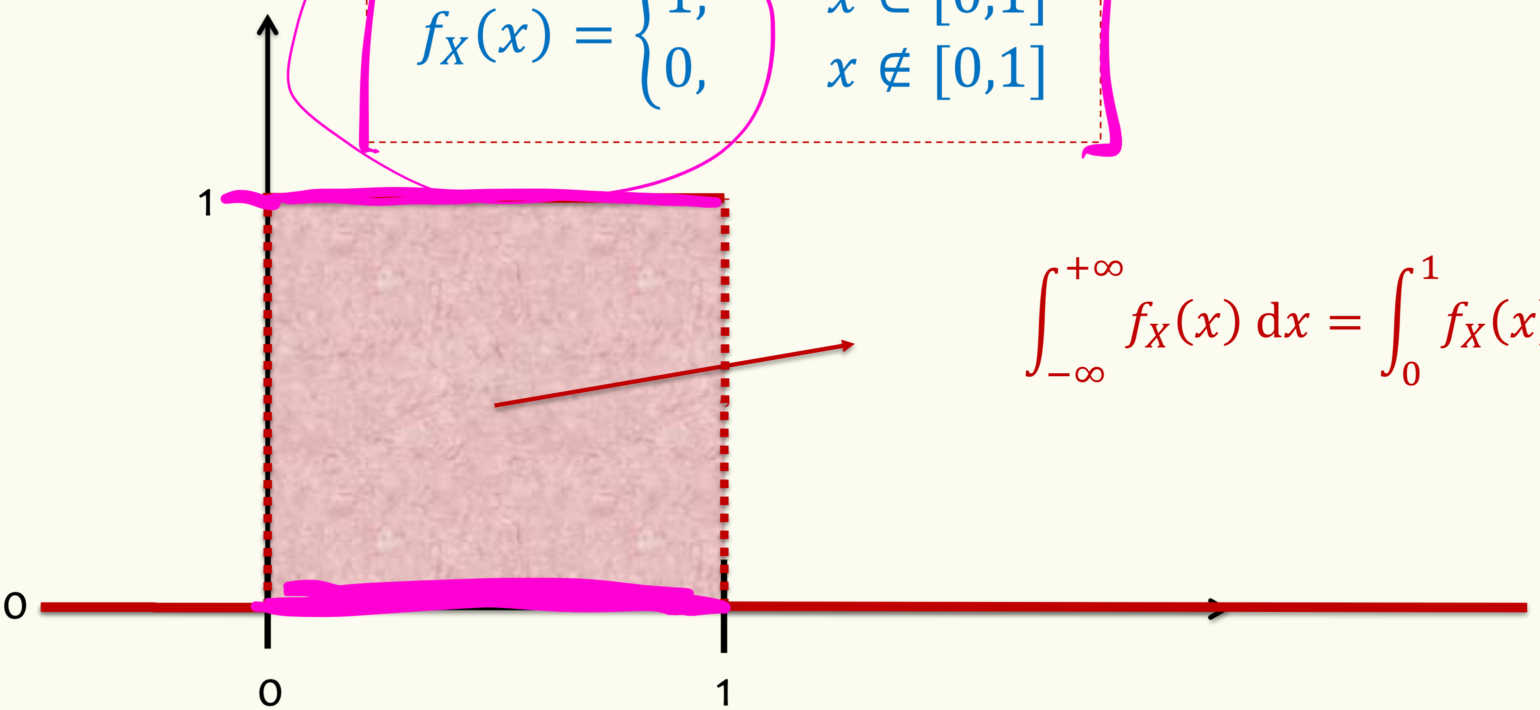
PDF of Uniform RV

$X \sim \text{Unif}(0,1)$

$$f_X(x) = \begin{cases} 1, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$

Non-negativity: $f_X(x) \ge 0$ for all $x \in \mathbb{R}$

Normalization: $\int_{-\infty}^{+\infty} f_X(x)\, \mathrm{d}x = 1$

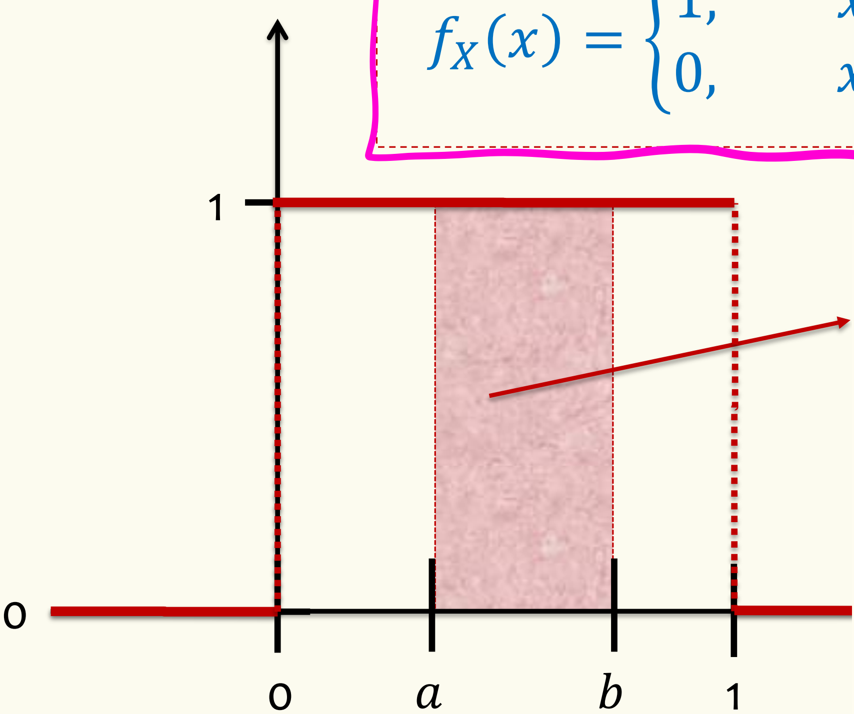


$$\int_{-\infty}^{+\infty} f_X(x)\, \mathrm{d}x = \int_0^1 f_X(x)\, \mathrm{d}x = 1 \cdot 1 = 1$$

Probability of Event

$X \sim \text{Unif}(0,1)$

$$f_X(x) = \begin{cases} 1, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$



Non-negativity: $f_X(x) \geq 0$ for all $x \in \mathbb{R}$

Normalization: $\int_{-\infty}^{+\infty} f_X(x)\,\mathrm{d}x = 1$

$$P(a \leq X \leq b) = \int_a^b \underbrace{f_X(x)\,\mathrm{d}x}_{1}$$

1. If $0 \leq a$ and $a \leq b \leq 1$
   $P(a \leq X \leq b) = b - a$
2. If $a < 0$ and $0 \leq b \leq 1$
   $P(a \leq X \leq b) = b$
3. If $a \geq 0$ and $b > 1$
   $P(a \leq X \leq b) = b - a$
4. If $a < 0$ and $b > 1$
   $P(a \leq X \leq b) = 1$

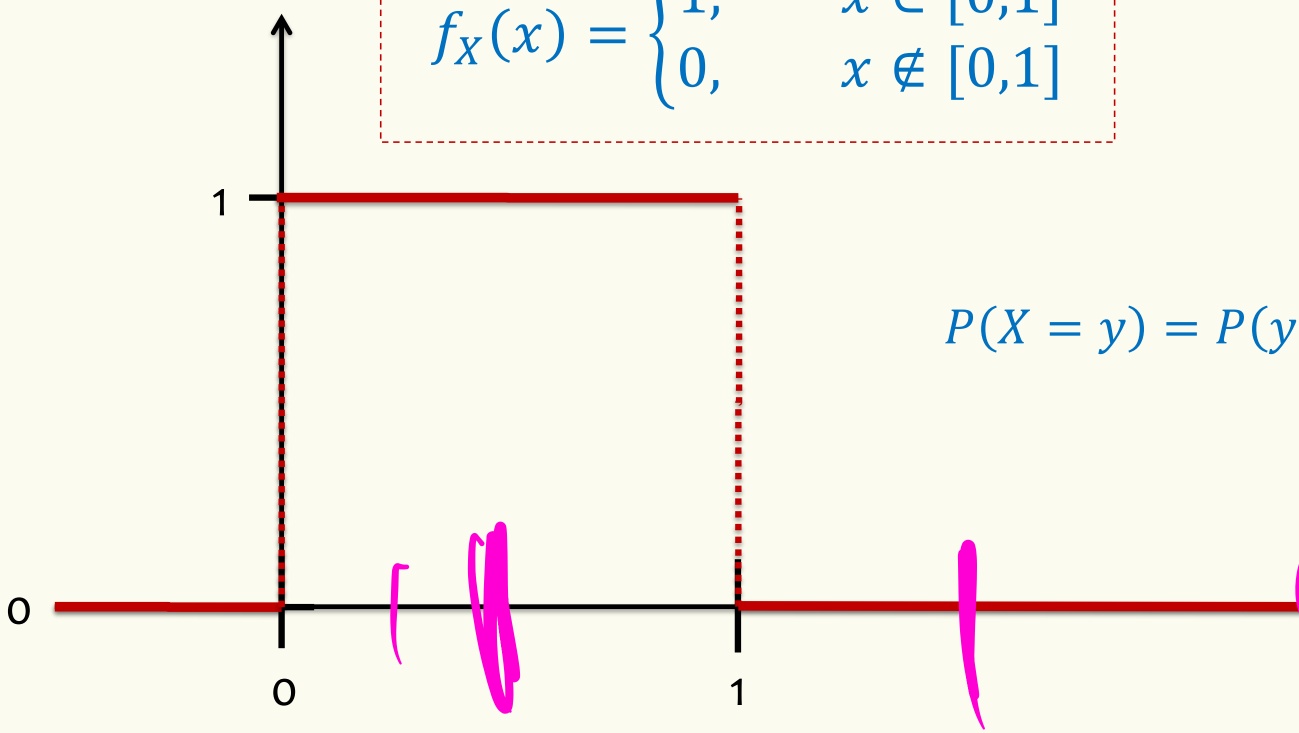
Poll: Slido.com/4694375

A. All of them are correct
B. Only 1, 2, 4 are right
C. Only 1 is right
D. Only 1 and 2 are right

Probability of Event

$X \sim \mathrm{Unif}(0,1)$

$$f_X(x) = \begin{cases} 1, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$



Non-negativity: $f_X(x) \geq 0$ for all $x \in \mathbb{R}$

Normalization: $\int_{-\infty}^{+\infty} f_X(x)\,\mathrm{d}x = 1$

$$P(a \leq X \leq b) = \int_a^b f_X(x)\,\mathrm{d}x$$

$$P(X = y) = P(y \leq X \leq y) = \int_y^y f_X(x)\,\mathrm{d}x = 0$$

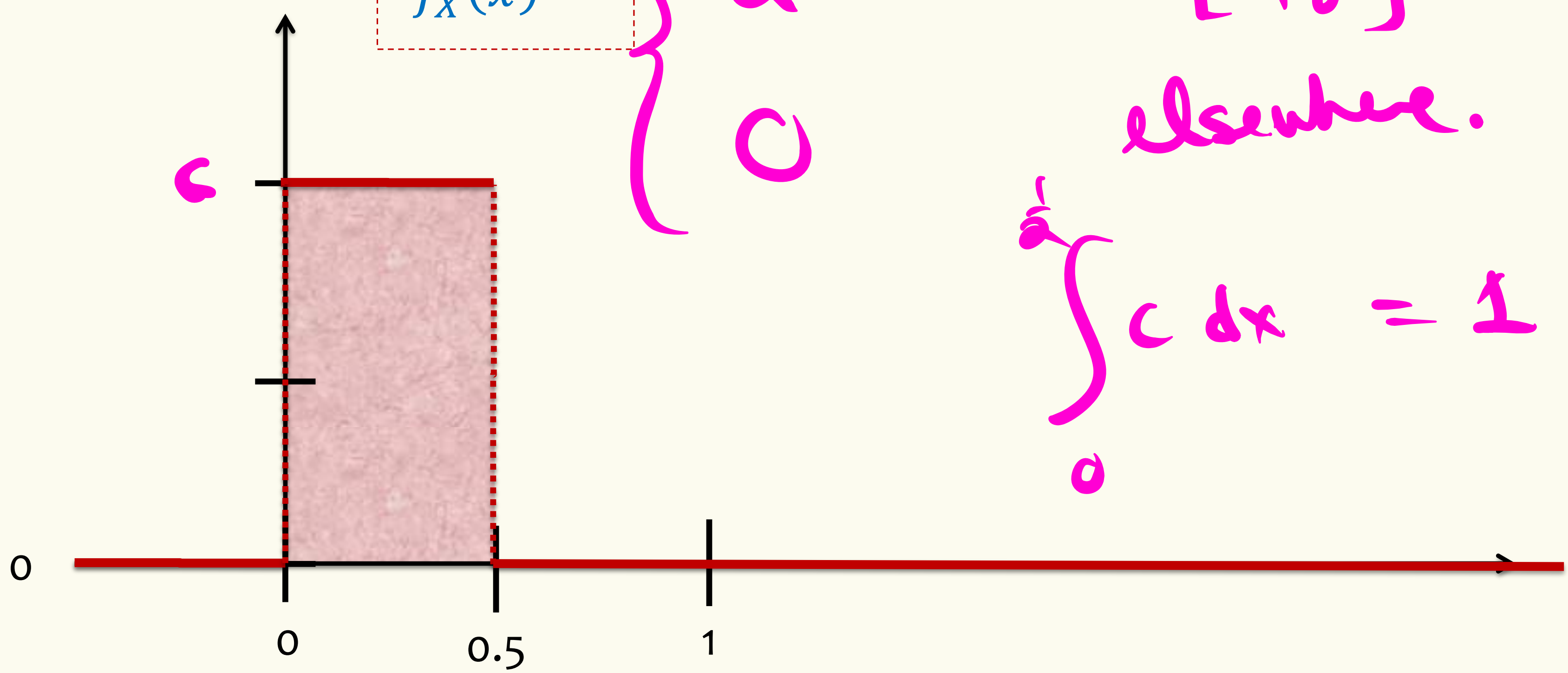
$$P(X \approx y) \approx \epsilon f_X(y) = \epsilon$$

$$\frac{P(X \approx y)}{P(X \approx z)} \approx \frac{\epsilon f_X(y)}{\epsilon f_X(z)} = \frac{f_X(y)}{f_X(z)}$$

PDF of Uniform RV

$X \sim \mathrm{Unif}(0,0.5)$

$$f_X(x) = \begin{cases} 2 & x \in [0, \tfrac{1}{2}] \\ 0 & \text{elsewhere.} \end{cases}$$



$$\int_0^{\frac{1}{2}} c \, dx = 1$$

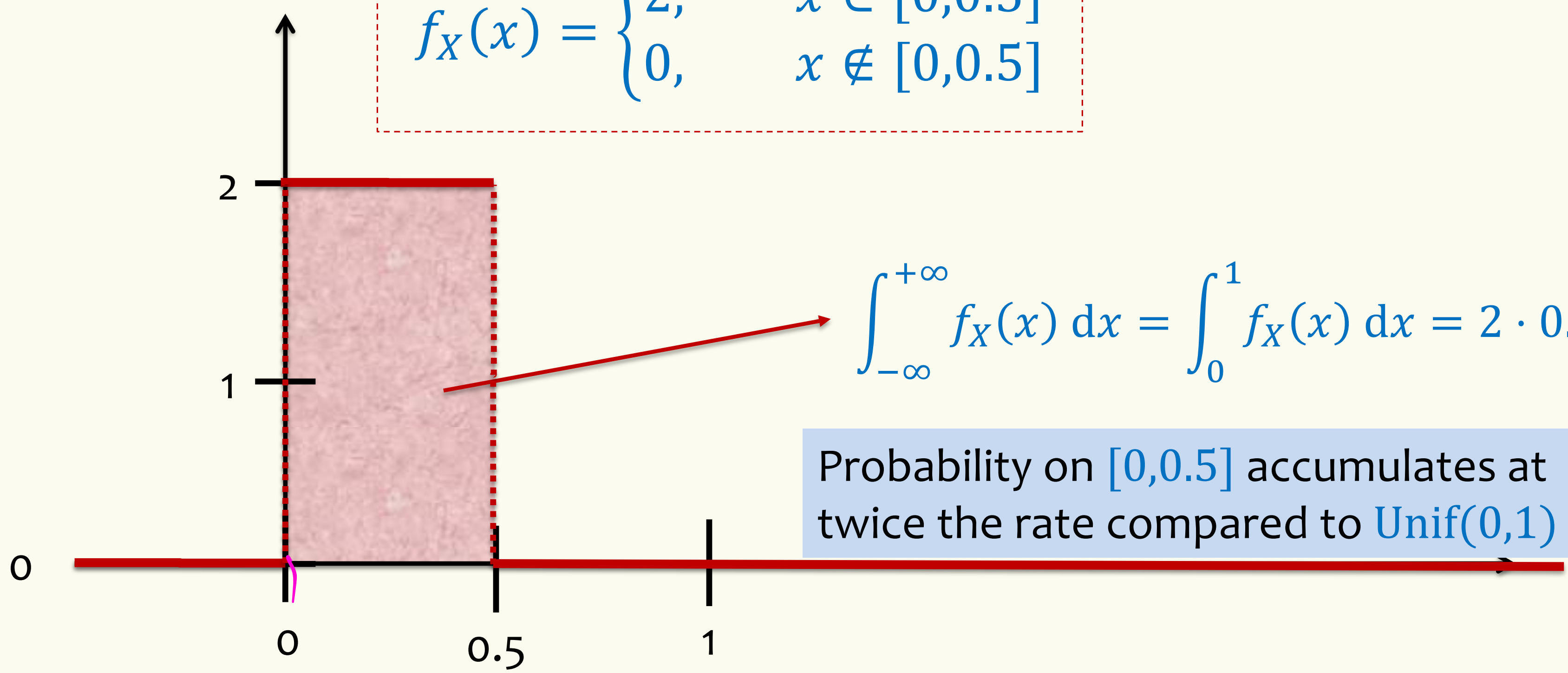
PDF of Uniform RV

$X \sim \text{Unif}(0,0.5)$

Density $\neq$ Probability

$f_X(x) \gg 1$ is possible!

$$f_X(x) = \begin{cases} 2, & x \in [0,0.5] \\ 0, & x \notin [0,0.5] \end{cases}$$



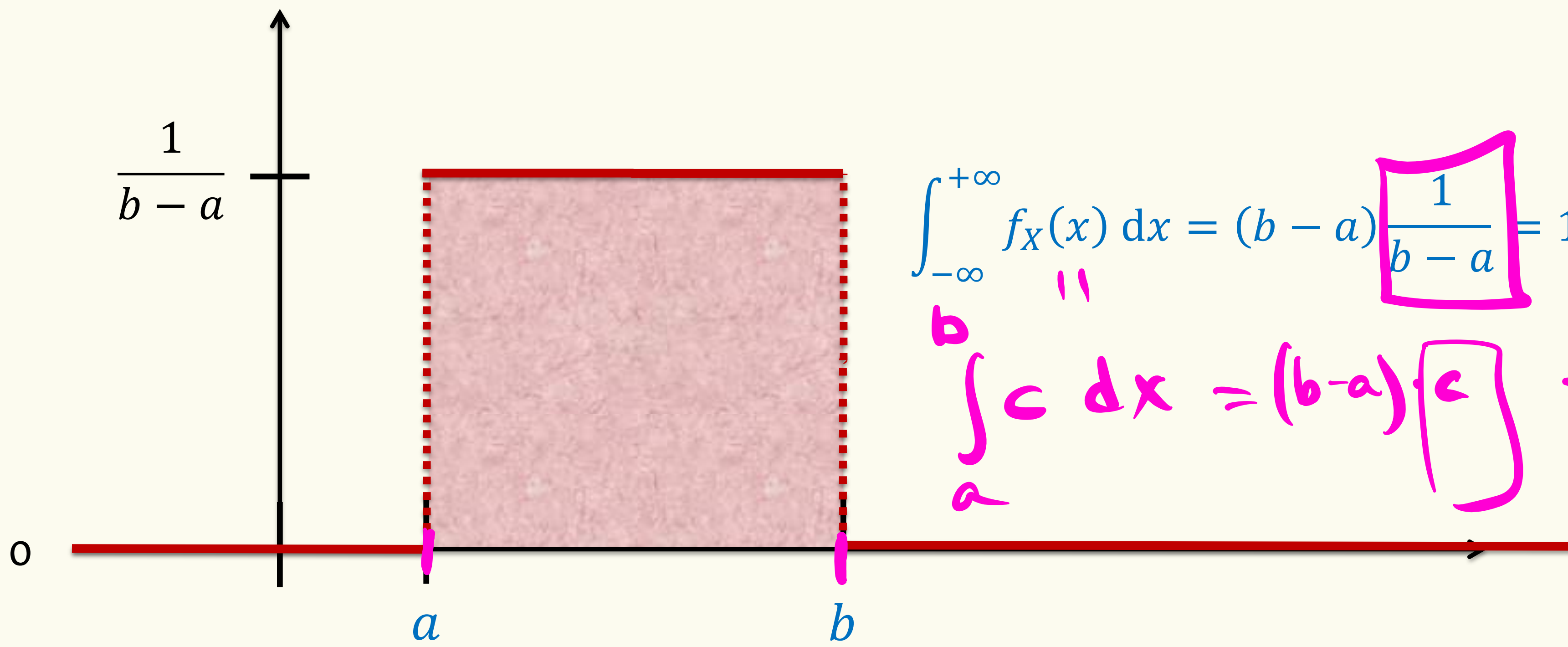
$$\int_{-\infty}^{+\infty} f_X(x)\, \mathrm{d}x = \int_0^1 f_X(x)\, \mathrm{d}x = 2 \cdot 0.5 = 1$$

Probability on $[0,0.5]$ accumulates at twice the rate compared to $\text{Unif}(0,1)$

Uniform Distribution

$X \sim \mathrm{Unif}(a, b)$

$$f_X(x) = \begin{cases} \dfrac{1}{b-a} & x \in [a,b] \\ 0 & \text{else} \end{cases}$$



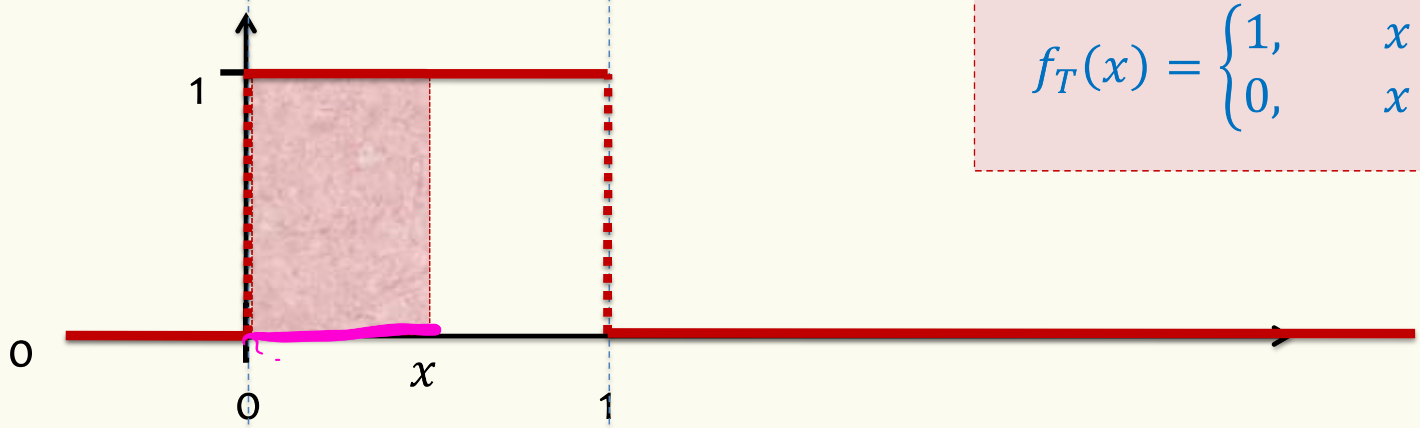
$$\int_{-\infty}^{+\infty} f_X(x)\,\mathrm{d}x = (b-a)\boxed{\frac{1}{b-a}} = 1$$

$$= \int_a^b c\,dx = (b-a)\boxed{c} = 1$$

Example. $\boxed{T \sim \mathrm{Unif}(0,1)}$

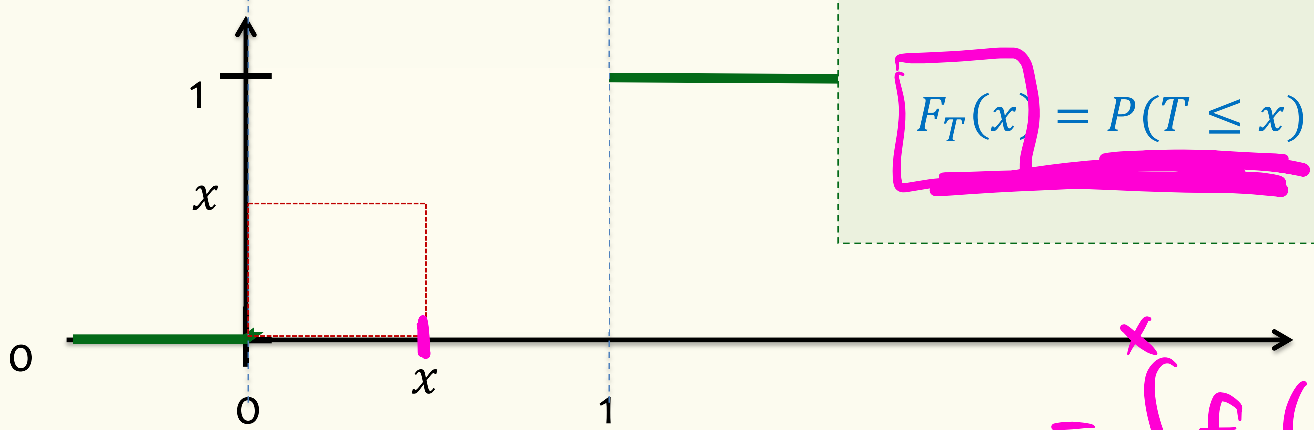
Probability Density Function

$$f_T(x) = \begin{cases} 1, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$



Cumulative Distribution Function

$$\boxed{F_T(x)} = P(T \le x) = \begin{cases} 0 & x \le 0 \\ x & 0 \le x \le 1 \\ 1 & 1 \le x \end{cases}$$



$$= \int_{-\infty}^{x} f_T(x)\,dx$$

$$= \int^{x} 1\,dx = x$$

Cumulative Distribution Function

Definition. The **cumulative distribution function (cdf)** of X is

$$F_X(a) = P(X \leq a) = \int_{-\infty}^{a} f_X(x)\,\mathrm{d}x$$

By the fundamental theorem of Calculus $f_X(x) = \frac{d}{dx} F_X(x)$

Cumulative Distribution Function

Definition. The **cumulative distribution function (cdf)** of X is

$$F_X(a) = P(X \leq a) = \int_{-\infty}^{a} f_X(x)\, \mathrm{d}x$$

By the fundamental theorem of Calculus $f_X(x) = \frac{d}{dx} F_X(x)$

Therefore: $P(X \in [a, b]) = F_X(b) - F_X(a) = \int_a^b f_X(x)\, dx$

F_X is monotone increasing, since $f_X(x) \geq 0$. That is $F_X(c) \leq F_X(d)$ for $c \leq d$

$\lim_{a \to -\infty} F_X(a) = P(X \leq -\infty) = 0 \quad \lim_{a \to +\infty} F_X(a) = P(X \leq +\infty) = 1$

From Discrete to Continuous

	Discrete	Continuous
PMF/PDF	$\boxed{p_X(x) = P(X = x)}$	$\boxed{f_X(x)} \neq P(X = x) = 0$
CDF	$\boxed{F_X(x) = \sum_{t \leq x} p_X(t)}$	$\boxed{F_X(x)} = \int_{-\infty}^{x} f_X(t)\, dt$
Normalization	$\boxed{\sum_{x} p_X(x) = 1}$	$\boxed{\int_{-\infty}^{\infty} f_X(x)\, dx = 1}$
Expectation	$\mathbb{E}[g(X)] = \sum_{x \in \Omega_X} g(x)\, p_X(x)$	$\mathbb{E}[g(X)] = \int_{-\infty}^{\infty} g(x)\, f_X(x)\, dx$

LOTUS

$$f_X(x) = \begin{cases} cx & 0 \leq x \leq 2 \end{cases}$$

$$\int_0^2 cx\, dx = 1$$

Agenda

$$\Pr\left(\tfrac{1}{2} \le X \le 1\right) = \int_{1/2}^{1} \boxed{\tfrac{1}{2}x}\, dx$$

$$c \left.\frac{x^2}{2}\right|_0^2 = c \cdot \frac{2^2}{2} = 1$$

$$c = \frac{1}{2}$$

- Wrap-up of Poisson RVs
- Continuous Random Variables
- Probability Density Function
- Cumulative Distribution Function
- Expectation and Variance of continuous r.v.

Expectation of a Continuous RV

Definition. The **expected value** of a continuous RV X is defined as

$$\mathbb{E}[X] = \int_{-\infty}^{+\infty} f_X(x) \cdot x \, \mathrm{d}x$$

Fact. $\mathbb{E}[aX + bY + c] = a\mathbb{E}[X] + b\mathbb{E}[Y] + c$

Proof follows same ideas as discrete case

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Proofs follow same ideas as discrete case

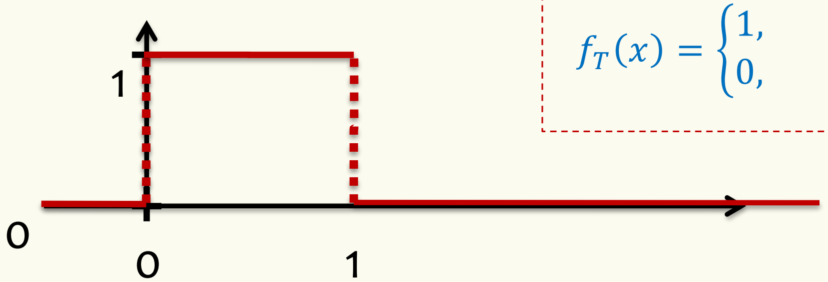
Definition. The **variance** of a continuous RV X is defined as

$$\mathrm{Var}(X) = \int_{-\infty}^{+\infty} f_X(x) \cdot (x - \mathbb{E}[X])^2 \, \mathrm{d}x = \mathbb{E}[X^2] - \mathbb{E}[X]^2$$

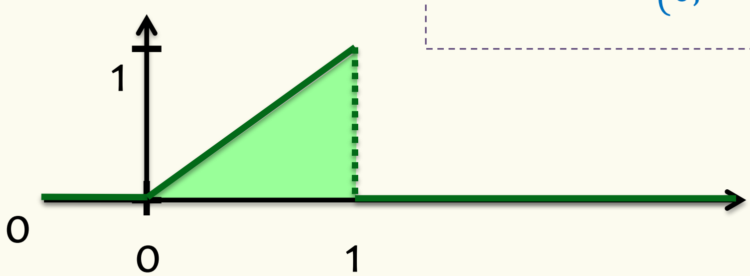
Expectation of a Continuous RV

Definition.
$$\mathbb{E}[X] = \int_{-\infty}^{+\infty} f_X(x) \cdot x \, \mathrm{d}x$$

Example. $T \sim \mathrm{Unif}(0,1)$



$$f_T(x) = \begin{cases} 1, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$



$$f_T(x) \cdot x = \begin{cases} x, & x \in [0,1] \\ 0, & x \notin [0,1] \end{cases}$$

$$\mathbb{E}[T] = \underbrace{\frac{1}{2} 1^2}_{\text{Area of triangle}} = \frac{1}{2}$$

Uniform Density – Expectation

$$f_X(x) = \begin{cases} \dfrac{1}{b-a} & x \in [a,b] \\ 0 & \text{else} \end{cases}$$

$X \sim \mathrm{Unif}(a,b)$

$$\mathbb{E}[X] =$$

Uniform Density – Expectation

$X \sim \mathrm{Unif}(a, b)$

$$f_X(x) = \begin{cases} \frac{1}{b-a} & x \in [a, b] \\ 0 & \text{else} \end{cases}$$

$$\mathbb{E}[X] = \int_{-\infty}^{+\infty} f_X(x) \cdot x \, \mathrm{d}x$$

$$= \frac{1}{b-a} \int_a^b x \, \mathrm{d}x \quad = \frac{1}{b-a} \left(\frac{x^2}{2} \right) \Bigg|_a^b = \frac{1}{b-a} \left(\frac{b^2 - a^2}{2} \right)$$

$$= \frac{(b-a)(a+b)}{2(b-a)} \quad = \frac{a+b}{2}$$

Uniform Density – Variance

$$f_X(x) = \begin{cases} \frac{1}{b-a} & x \in [a, b] \\ 0 & \text{else} \end{cases}$$

$X \sim \mathrm{Unif}(a, b)$

$\mathbb{E}[X^2] =$

Uniform Density – Variance

$$f_X(x) = \begin{cases} \dfrac{1}{b-a} & x \in [a,b] \\ 0 & \text{else} \end{cases}$$

$X \sim \text{Unif}(a, b)$

$$\mathbb{E}[X^2] = \int_{-\infty}^{+\infty} f_X(x) \cdot x^2 \, \mathrm{d}x$$

$$= \frac{1}{b-a} \int_a^b x^2 \, \mathrm{d}x = \frac{1}{b-a} \left(\frac{x^3}{3} \right) \Bigg|_a^b = \frac{b^3 - a^3}{3(b-a)}$$

$$= \frac{(b-a)(b^2 + ab + a^2)}{3(b-a)} = \frac{b^2 + ab + a^2}{3}$$

Uniform Density – Variance

$$\mathbb{E}[X^2] = \frac{b^2 + ab + a^2}{3} \qquad \mathbb{E}[X] = \frac{a+b}{2}$$

$X \sim \text{Unif}(a, b)$

$$\begin{aligned}
\text{Var}(X) &= \mathbb{E}[X^2] - \mathbb{E}[X]^2 \\
&= \frac{b^2 + ab + a^2}{3} - \frac{a^2 + 2ab + b^2}{4} \\
&= \frac{4b^2 + 4ab + 4a^2}{12} - \frac{3a^2 + 6ab + 3b^2}{12} \\
&= \frac{b^2 - 2ab + a^2}{12} = \frac{(b-a)^2}{12}
\end{aligned}$$

Uniform Distribution Summary

$X \sim \text{Unif}(a, b)$

$$f_X(x) = \begin{cases} \dfrac{1}{b-a} & x \in [a, b] \\ 0 & \text{else} \end{cases}$$

$$F_X(y) = \begin{cases} 0 & x < a \\ \dfrac{x-a}{b-a} & x \in [a, b] \\ 1 & x > b \end{cases}$$

$$\mathbb{E}[X] = \frac{a+b}{2}$$

$$\text{Var}(X) = \frac{(b-a)^2}{12}$$