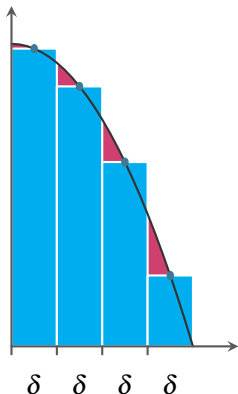


Survey

Fill it out!!

tinyurl.com/cs70-survey

Calculus



Riemann Sum/Integral: $\int_a^b f(x)dx = \lim_{\delta \rightarrow 0} \sum_i \delta f(a_i)$

“Area is defined as rectangles and add up some thin ones.”

Derivative (Rate of change):

$$F'(x) = \lim_{h \rightarrow 0} \frac{F(x+h) - F(x)}{h}.$$

“Rise over run of close together points.”

Fundamental Theorem: $F(b) - F(a) = \int_a^b F'(x)dx.$

“Area ($F(\cdot)$) under $f(x)$ grows at x , $F'(x)$, by $f(x)$ ”

Thus $F'(x) = f(x).$

CS70: Continuous Probability.

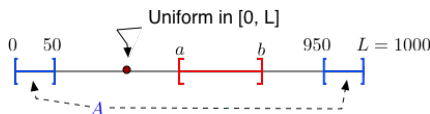
Continuous Probability 1

1. Examples
2. Events
3. Continuous Random Variables

Uniformly at Random in $[0, 1]$.

Choose a real number X , uniformly at random in $[0, 1]$.

What is the probability that X is exactly equal to $1/3$? Well, ..., 0.



What is the probability that X is exactly equal to 0.6? Again, 0.

In fact, for any $x \in [0, 1]$, one has $\Pr[X = x] = 0$.

How should we then describe 'choosing uniformly at random in $[0, 1]$ '?

Here is the way to do it:

$$\Pr[X \in [a, b]] = b - a, \forall 0 \leq a \leq b \leq 1.$$

Makes sense: $b - a$ is the fraction of $[0, 1]$ that $[a, b]$ covers.

$$F_X(x) = \Pr[X \leq x]$$

.

$$f_X(x) = \lim_{\delta \rightarrow 0} \Pr[X \in (x, x + \delta)]$$

What is true?

(A) $F_X(x) = \int_{-\infty}^{\infty} f_X(y) dy$

(B) $\int_{-\infty}^{\infty} f_X(x) = 1$

(C) $F_X(x) = \int_{-\infty}^x f(y) dy.$

(D) $f(x) = F'_X(x).$

(E) $\int_{-\infty}^{\infty} F_X(x) dx = 1.$

(F) $\int_{-\infty}^{\infty} xf(x) dx = \int_{-\infty}^{\infty} (1 - F(x)) dx.$

(A) False. limits wrong. (B) cuz probability distribution.

(C) “sums up probability of rectangles”, e.g. calculus.

(D) calculus, fundamental theorem.

(F) is true since $\int_{-\infty}^{\infty} xf(x) dx = \int_{-\infty}^{\infty} F(x) dx = E[X].$

Next lecture.

Uniformly at Random in $[0, 1]$.

Let $[a, b]$ denote the **event** that the point X is in the interval $[a, b]$.

$$Pr[[a, b]] = \frac{\text{length of } [a, b]}{\text{length of } [0, 1]} = \frac{b - a}{1} = b - a.$$

Intervals like $[a, b] \subseteq \Omega = [0, 1]$ are **events**.

More generally, events in this space are **unions of intervals**.

Example: the event A - “within 0.2 of 0 or 1” is $A = [0, 0.2] \cup [0.8, 1]$.

Thus,

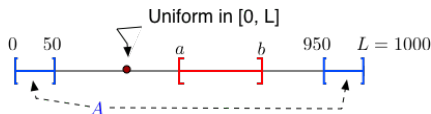
$$Pr[A] = Pr[[0, 0.2]] + Pr[[0.8, 1]] = 0.4.$$

More generally, if A_n are pairwise disjoint intervals in $[0, 1]$, then

$$Pr[\cup_n A_n] := \sum_n Pr[A_n].$$

Many subsets of $[0, 1]$ are of this form. Thus, the probability of those sets is well defined. We call such sets **events**.

Uniformly at Random in $[0, 1]$.



Note: A **radical** change in approach.

Finite prob. space: $\Omega = \{1, 2, \dots, N\}$, with $Pr[\omega] = p_\omega$.

$\implies Pr[A] = \sum_{\omega \in A} p_\omega$ for $A \subset \Omega$.

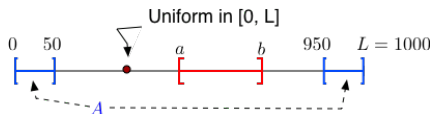
Continuous space: e.g., $\Omega = [0, 1]$,

$Pr[\omega]$ is typically 0.

Instead, start with $Pr[A]$ for some events A .

Event A = interval, or union of intervals.

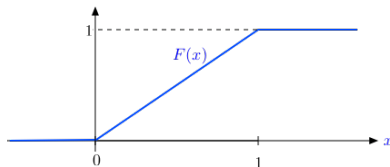
Uniformly at Random in $[0, 1]$.



$Pr[X \leq x] = x$ for $x \in [0, 1]$. Also, $Pr[X \leq x] = 0$ for $x < 0$.

$Pr[X \leq x] = 1$ for $x > 1$.

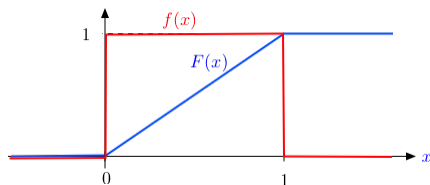
Define $F(x) = Pr[X \leq x]$.



Then we have $Pr[X \in (a, b)] = Pr[X \leq b] - Pr[X \leq a] = F(b) - F(a)$.

Thus, $F(\cdot)$ specifies the probability of all the events!

Uniformly at Random in $[0, 1]$.



$$Pr[X \in (a, b]] = Pr[X \leq b] - Pr[X \leq a] = F(b) - F(a).$$

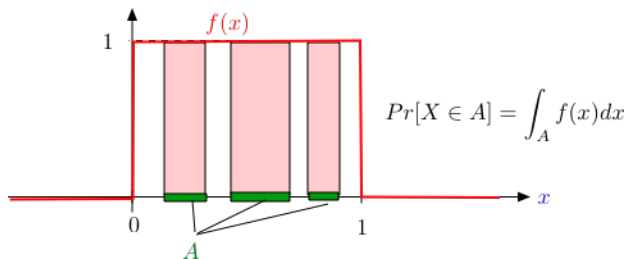
An alternative view is to define $f(x) = \frac{d}{dx} F(x) = 1\{x \in [0, 1]\}$. Then

$$F(b) - F(a) = \int_a^b f(x) dx.$$

Thus, the probability of an event is the integral of $f(x)$ over the event:

$$Pr[X \in A] = \int_A f(x) dx.$$

Uniformly at Random in $[0, 1]$.



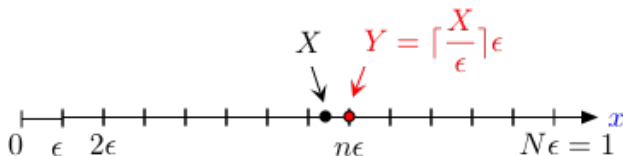
Think of $f(x)$ as describing how
one unit of probability is spread over $[0, 1]$: uniformly!

Then $Pr[X \in A]$ is the probability mass over A .

Observe:

- This makes the probability automatically additive.
- We need $f(x) \geq 0$ and $\int_{-\infty}^{\infty} f(x) dx = 1$.

Uniformly at Random in $[0, 1]$.



Discrete Approximation: Fix $N \gg 1$ and let $\epsilon = 1/N$.

Define $Y = n\epsilon$ if $(n-1)\epsilon < X \leq n\epsilon$ for $n = 1, \dots, N$.

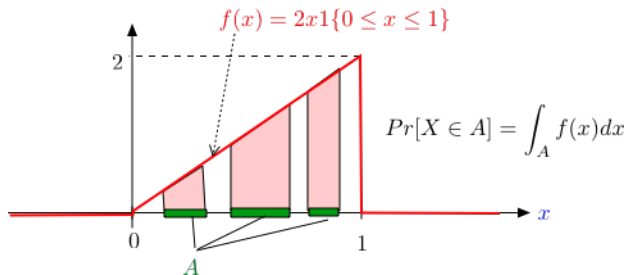
Then $|X - Y| \leq \epsilon$ and Y is discrete: $Y \in \{\epsilon, 2\epsilon, \dots, N\epsilon\}$.

Also, $\Pr[Y = n\epsilon] = \frac{1}{N}$ for $n = 1, \dots, N$.

Thus, X is ‘almost discrete.’

Calculus view: $\Pr[Y = n\epsilon]$ is area of rectangle in Riemann sum.

Nonuniformly at Random in $[0, 1]$.



This figure shows a different choice of $f(x) \geq 0$ with $\int_{-\infty}^{\infty} f(x) dx = 1$.

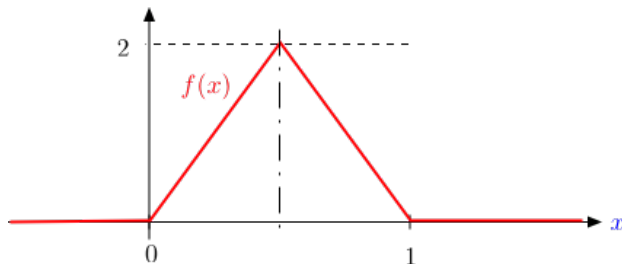
It defines another way of choosing X at random in $[0, 1]$.

Note that X is more likely to be closer to 1 than to 0.

One has $Pr[X \leq x] = \int_{-\infty}^x f(u) du = x^2$ for $x \in [0, 1]$.

Also, $Pr[X \in (x, x + \varepsilon)] = \int_x^{x+\varepsilon} f(u) du \approx f(x)\varepsilon$.

Another Nonuniform Choice at Random in $[0, 1]$.



This figure shows yet a different choice of $f(x) \geq 0$ with $\int_{-\infty}^{\infty} f(x) dx = 1$.

It defines another way of choosing X at random in $[0, 1]$.

Note that X is more likely to be closer to $1/2$ than to 0 or 1.

For instance, $Pr[X \in [0, 1/3]] = \int_0^{1/3} 4x dx = 2[x^2]_0^{1/3} = \frac{2}{9}$.

Thus, $Pr[X \in [0, 1/3]] = Pr[X \in [2/3, 1]] = \frac{2}{9}$ and $Pr[X \in [1/3, 2/3]] = \frac{5}{9}$.

General Random Choice in \mathfrak{R}

Let $F(x)$ be a nondecreasing function with $F(-\infty) = 0$ and $F(+\infty) = 1$.

Define X by $Pr[X \in (a, b]] = F(b) - F(a)$ for $a < b$. Also, for $a_1 < b_1 < a_2 < b_2 < \dots < b_n$,

$$\begin{aligned} Pr[X \in (a_1, b_1] \cup (a_2, b_2] \cup (a_n, b_n]] \\ &= Pr[X \in (a_1, b_1]] + \dots + Pr[X \in (a_n, b_n]] \\ &= F(b_1) - F(a_1) + \dots + F(b_n) - F(a_n). \end{aligned}$$

Let $f(x) = \frac{d}{dx} F(x)$. Then,

$$Pr[X \in (x, x + \varepsilon]] = F(x + \varepsilon) - F(x) \approx f(x)\varepsilon.$$

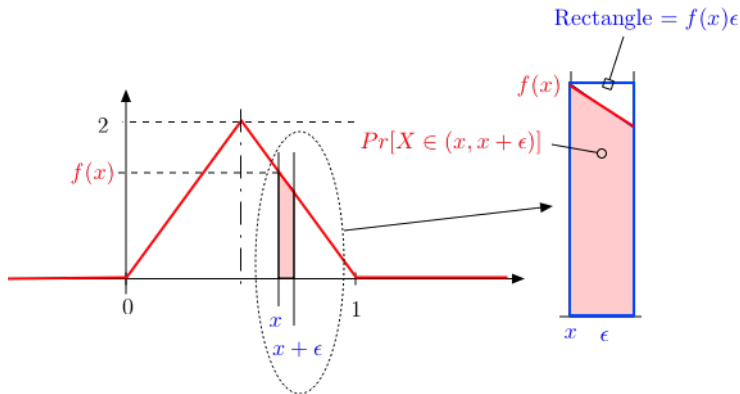
$F(x)$ is **cumulative distribution function (cdf)** of X

$f(x)$ is the **probability density function (pdf)** of X .

When F and f correspond RV X : $F_X(x)$ and $f_X(x)$.

$$Pr[X \in (x, x + \epsilon)]$$

An illustration of $Pr[X \in (x, x + \epsilon)] \approx f_X(x)\epsilon$:



Thus, the pdf is the ‘local probability by unit length.’

It is the ‘probability density.’

Discrete Approximation

Fix $\varepsilon \ll 1$ and let $Y = n\varepsilon$ if $X \in (n\varepsilon, (n+1)\varepsilon]$.

Thus, $Pr[Y = n\varepsilon] = F_X((n+1)\varepsilon) - F_X(n\varepsilon)$.

Note that $|X - Y| \leq \varepsilon$ and Y is a discrete random variable.

Also, if $f_X(x) = \frac{d}{dx} F_X(x)$, then $F_X(x + \varepsilon) - F_X(x) \approx f_X(x)\varepsilon$.

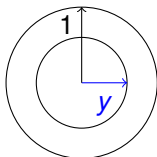
Hence, $Pr[Y = n\varepsilon] \approx f_X(n\varepsilon)\varepsilon$.

Thus, we can think of X of being almost discrete with

$Pr[X = n\varepsilon] \approx f_X(n\varepsilon)\varepsilon$.

Example: CDF, pre-poll

Example: hitting random location on gas tank.
Random location on circle.

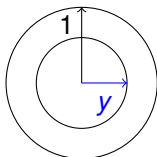


What is probability of being within y of the center, for non-negative $y \leq 1$?

- (A) 1.
- (B) 0.
- (C) $\int_0^y (2\pi y) dy$
- (D) y^2 .
- (D) Next slide.

Example: CDF

Example: hitting random location on gas tank.
Random location on circle.



Random Variable: Y distance from center.
Probability within y of center:

$$\begin{aligned}Pr[Y \leq y] &= \frac{\text{area of small circle}}{\text{area of dartboard}} \\&= \frac{\pi y^2}{\pi} = y^2.\end{aligned}$$

Hence,

$$F_Y(y) = Pr[Y \leq y] = \begin{cases} 0 & \text{for } y < 0 \\ y^2 & \text{for } 0 \leq y \leq 1 \\ 1 & \text{for } y > 1 \end{cases}$$

Calculation of event with dartboard..

Probability between .5 and .6 of center?

Recall CDF.

$$F_Y(y) = Pr[Y \leq y] = \begin{cases} 0 & \text{for } y < 0 \\ y^2 & \text{for } 0 \leq y \leq 1 \\ 1 & \text{for } y > 1 \end{cases}$$

$$\begin{aligned} Pr[0.5 < Y \leq 0.6] &= Pr[Y \leq 0.6] - Pr[Y \leq 0.5] \\ &= F_Y(0.6) - F_Y(0.5) \\ &= .36 - .25 \\ &= .11 \end{aligned}$$

Example: “Dart” board.

Recall that

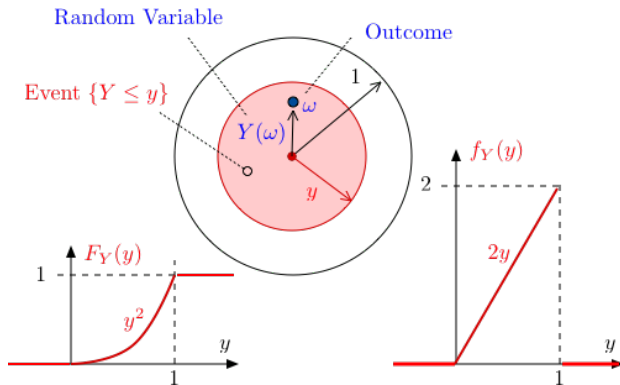
$$F_Y(y) = \Pr[Y \leq y] = \begin{cases} 0 & \text{for } y < 0 \\ y^2 & \text{for } 0 \leq y \leq 1 \\ 1 & \text{for } y > 1 \end{cases}$$

$$f_Y(y) = F'_Y(y) = \begin{cases} 0 & \text{for } y < 0 \\ 2y & \text{for } 0 \leq y \leq 1 \\ 0 & \text{for } y > 1 \end{cases}$$

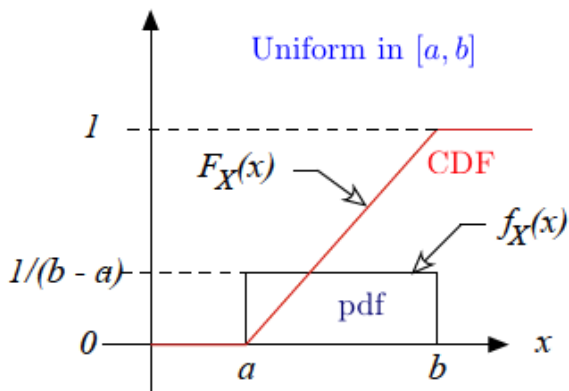
The cumulative distribution function (cdf) and probability distribution function (pdf) give full information.

Use whichever is convenient.

Target



$U[a, b]$



Exponential derivation: Poll.

$$\Pr[X = i] = (1 - p)^{i-1} p.$$

Let $p = \lambda/n$. and $Y = X/n$.

What is true?

(A) $X \sim G(p)$

(B) $\Pr[X > i] = (1 - p)^i$. (C) $\Pr[Y > i/n] = (1 - \lambda/n)^i$.

(D) $\Pr[Y > y] = (1 - \lambda/n)^{ny}$.

(E) $\lim_{n \rightarrow \infty} (1 - \lambda/n)^{ny} = e^{-\lambda y}$.

(A) True by definition.

(B) $\Pr[X > i] = (1 - p)^i$ at least i coin flips fail.

(C) True, definition of Y

(D) True, $y = i/n$ means $i = ny$.

(E) $(1 - \lambda/n)^{ny} = ((1 - \lambda/n)^{n/\lambda})^{\lambda y}$
and $\lim_{n \rightarrow \infty} (1 - \frac{\lambda}{n})^{n/\lambda} = e$.

The limit as $n \rightarrow \infty$ of Y has $\Pr[Y > y] = e^{-\lambda y}$.

$\Pr[Y > y]$ is defined as “Survival function.”

Expo(λ)

“Limit of geometric.”

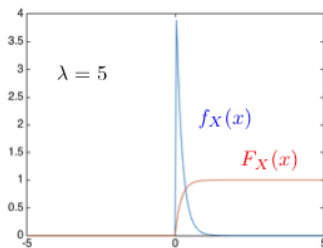
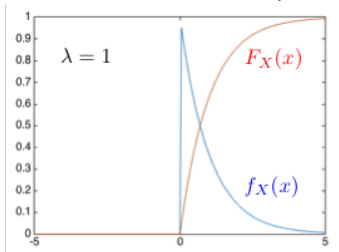
From last slide: $S(t) = \Pr[X > t] = e^{-\lambda t}$ for $t > 0$.

Note: $f_X(x) = F'(x) = 1 - S(t) = -S'(t)$.

The exponential distribution with parameter $\lambda > 0$ is defined by

$$f_X(x) = \lambda e^{-\lambda x} 1_{\{x \geq 0\}}$$

$$F_X(x) = \begin{cases} 0, & \text{if } x < 0 \\ 1 - e^{-\lambda x}, & \text{if } x \geq 0. \end{cases}$$



Continuous Random Variables

Continuous random variable X , specified by

1. $F_X(x) = \Pr[X \leq x]$ for all x .

Cumulative Distribution Function (cdf).

$$\Pr[a < X \leq b] = F_X(b) - F_X(a)$$

1.1 $0 \leq F_X(x) \leq 1$ for all $x \in \Re$.

1.2 $F_X(x) \leq F_X(y)$ if $x \leq y$.

2. Or $f_X(x)$, where $F_X(x) = \int_{-\infty}^x f_X(u) du$ or $f_X(x) = \frac{d(F_X(x))}{dx}$.

Probability Density Function (pdf).

$$\Pr[a < X \leq b] = \int_a^b f_X(x) dx = F_X(b) - F_X(a)$$

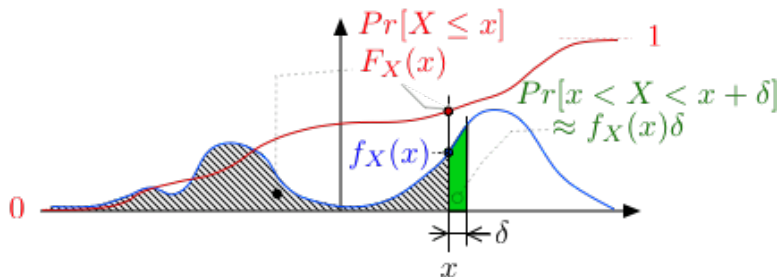
2.1 $f_X(x) \geq 0$ for all $x \in \Re$.

2.2 $\int_{-\infty}^{\infty} f_X(x) dx = 1$.

Recall that $\Pr[X \in (x, x + \delta)] \approx f_X(x)\delta$.

X “takes” value $n\delta$, for $n \in \mathbb{Z}$, with $\Pr[X = n\delta] = f_X(n\delta)\delta$

A Picture



The pdf $f_X(x)$ is a nonnegative function that integrates to 1.

The cdf $F_X(x)$ is the integral of f_X .

$$Pr[x < X < x + \delta] \approx f_X(x)\delta$$

$$Pr[X \leq x] = F_X(x) = \int_{-\infty}^x f_X(u) du$$

Multiple Continuous Random Variables

One defines a pair (X, Y) of continuous RVs by specifying $f_{X,Y}(x, y)$ for $x, y \in \Re$ where

$$f_{X,Y}(x, y) dx dy = Pr[X \in (x, x + dx), Y \in (y, y + dy)].$$

The function $f_{X,Y}(x, y)$ is called the **joint pdf** of X and Y .

Example: Choose a point (X, Y) uniformly in the set $A \subset \Re^2$. Then

$$f_{X,Y}(x, y) = \frac{1}{|A|} \mathbf{1}\{(x, y) \in A\}$$

where $|A|$ is the area of A .

Interpretation. Think of (X, Y) as being discrete on a grid with mesh size ε and $Pr[X = m\varepsilon, Y = n\varepsilon] = f_{X,Y}(m\varepsilon, n\varepsilon)\varepsilon^2$.

Recall Marginal Distribution:

$$Pr[X = x] = \sum_y Pr[X = x, Y = y].$$

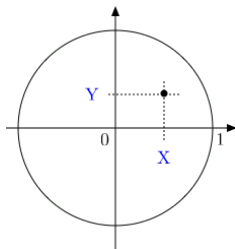
Similarly:

$$f_X(x) = \int f_{X,Y}(x, y) dy.$$

Sum “goes to” integral.

Example of Continuous (X, Y)

Pick a point (X, Y) uniformly in the unit circle.



Thus, $f_{X,Y}(x,y) = \frac{1}{\pi} 1\{x^2 + y^2 \leq 1\}$.

Consequently,

$$Pr[X > 0, Y > 0] = \frac{1}{4}$$

$$Pr[X < 0, Y > 0] = \frac{1}{4}$$

$$Pr[X^2 + Y^2 \leq r^2] = \frac{\pi r^2}{\pi} = r^2$$

$$Pr[X > Y] = \frac{1}{2}.$$

Independent Continuous Random Variables

Definition: Continuous RVs X and Y independent if and only if

$$Pr[X \in A, Y \in B] = Pr[X \in A]Pr[Y \in B], \forall A, B.$$

Theorem: Continuous RVs X and Y independent if and only if

$$f_{X,Y}(x,y) = f_X(x)f_Y(y).$$

Note: $f_X(x)$ ($f_Y(y)$) is (marginal) distribution of X (Y).

Proof: Intervals: $A = [x, x + dx]$, $B = [y, y + dy]$.

$$\begin{aligned} Pr[X \in A, Y \in B] &= Pr[X \in A] \times Pr[Y \in B] \\ &\approx f_X(x) dx \times f_Y(y) dy \\ &= f_X(x)f_Y(y) dx dy. \end{aligned}$$

Thus, $f_{X,Y}(x,y) = f_X(x)f_Y(y)$.



Mutual Independence.

Definition: Continuous RVs X_1, \dots, X_n are mutually independent if

$$Pr[X_1 \in A_1, \dots, X_n \in A_n] = Pr[X_1 \in A_1] \cdots Pr[X_n \in A_n], \forall A_1, \dots, A_n.$$

Theorem: Continuous RVs X_1, \dots, X_n are mutually independent if and only if

$$f_{\mathbf{X}}(x_1, \dots, x_n) = f_{X_1}(x_1) \cdots f_{X_n}(x_n).$$

Proof: As in the discrete case.

Conditional density.

Conditional Density: $f_{X|Y}(x, y)$.

Conditional Probability: $Pr[X \in A | Y \in B] = \frac{Pr[X \in A, Y \in B]}{Pr[Y \in B]}$

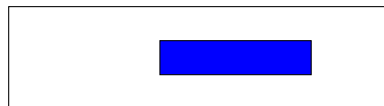
$$Pr[X \in [x, x + dx] | Y \in [y, y + dy]] = \frac{f_{X,Y}(x,y) dx dy}{f_Y dy}$$

$$f_{X|Y}(x, y) = \frac{f_{X,Y}(x,y)}{f_Y(y)} = \frac{f_{X,Y}(x,y)}{\int_{-\infty}^{+\infty} f_{X,Y}(x,y) dy}$$


Corollary: For independent random variables, $f_{X|Y}(x, y) = f_X(x)$.


Independent Random Variables?

Uniform on a rectangle? Independent?



$$\propto \Pr[Y \in B]$$

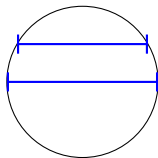

$$\propto \Pr[X \in A]$$


$$f_{X|Y}(x, y) = f_X(x) \text{ for all } y$$

Also: $\Pr[X \in A, Y \in B] \propto \text{Area of rectangle} \propto \Pr[X \in A] \times \Pr[Y \in B]$.

Independent!

Uniform on a circle? Independent?



$$f_{X|Y}(x, .5)$$

$$f_{X|Y}(x, 0)$$

Not independent!

Summary

Continuous Probability 1

1. **pdf:** $Pr[X \in (x, x + \delta)] = f_X(x)\delta$.
2. **CDF:** $Pr[X \leq x] = F_X(x) = \int_{-\infty}^x f_X(y)dy$.
3. **$U[a, b]$:** $f_X(x) = \frac{1}{b-a}1\{a \leq x \leq b\}$; $F_X(x) = \frac{x-a}{b-a}$ for $a \leq x \leq b$.
4. **$Expo(\lambda)$:**
 $f_X(x) = \lambda \exp\{-\lambda x\}1\{x \geq 0\}$; $F_X(x) = 1 - \exp\{-\lambda x\}$ for $x \geq 0$.
5. **Target:** $f_X(x) = 2x1\{0 \leq x \leq 1\}$; $F_X(x) = x^2$ for $0 \leq x \leq 1$.
6. **Joint pdf:** $Pr[X \in (x, x + \delta), Y \in (y, y + \delta)] = f_{X,Y}(x, y)\delta^2$.
 - 6.1 Conditional Distribution: $f_{X|Y}(x, y) = \frac{f_{X,Y}(x, y)}{f_Y(y)}$.
 - 6.2 Independence: $f_{X|Y}(x, y) = f_X(x)$

Summary

Continuous Probability

- ▶ Continuous RVs are similar to discrete RVs (break into intervals.)
- ▶ Think that $X \approx x$ with probability $f_X(x)\varepsilon$
- ▶ Sums become integrals,