

## 8 Continuous R.V's

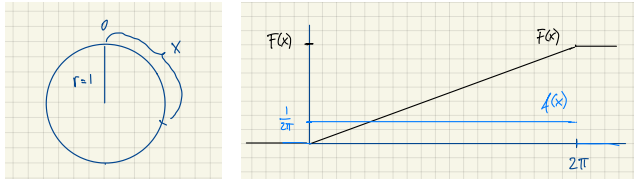
### 8.1 Probability Distributions in $\mathcal{R}$

Slide 1

Probability Distributions in  $\mathcal{R}$

§8.1.1 in the book. We skipped §5, 6 and 7 in the book.

**Example:** consider a roulette wheel of radius<sup>1</sup> 1, and record  $X$  = the location where it stops, as distance from 0.



In this case,  $\Pr(X = x) = 0$  for any particular value. Instead we work with probabilities of intervals, e.g.,  $X \leq x$ .

**(Cumulative) Distribution function (cdf):**  $F(x) = \Pr(X \leq x)$ .

This is meaningful for any r.v.

The figure also indicates  $f(x) = \frac{d}{dx}F(x)$  – more about  $f(x)$  later.

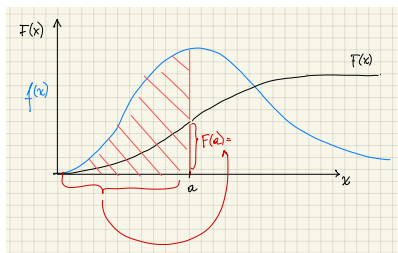
Slide 2

**Continuous r.v.:** We say  $X$  is a *continuous r.v.* if  $F(x)$  is a *continuous function of  $x$* .

In that case  $\Pr(X < x) = \Pr(X \leq x)$ , since  $\Pr(X = x) = 0$ .

**(Prob.) Density function (pdf):** If there is a function  $f(t)$  such

$$\text{that } F(a) = \int_{-\infty}^a f(t) dt$$



then  $f(t)$  (or  $f_X(t)$  if needed for clarity) is called the *p.d.f.* of  $F(x)$ .

We also use notation like  $X \sim f(\cdot)$  or  $X \sim F(\cdot)$ .

**Result:** By the fundamental theorem of calculus,  $f(x) = \frac{d}{dx}F(x)$ . 1. Suppose that  $X$  is a r.v. with p.d.f.

**Probability Mass Function (PMF):** The PMF is a concept associated with discrete random variables.

**Probability Density Function (PDF):** The PDF is a concept associated with continuous random variables.

<sup>1</sup>book uses “circumference” – changed for nicer figure below

### 8.2 Using the Density Function

Slide 3

Using the pdf  $f(x)$

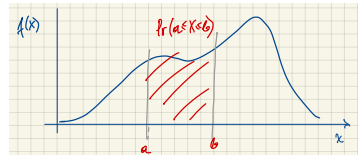
**Using  $f(x)$ :** use  $f(x)$  to evaluate  $\Pr(X \in A)$  for any event  $A$ , e.g.

$A = [a, b]$ :

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

$$\int_a^b f(x) dx$$

we can think of the pdf as the probability of a little rectangle of width 1, roughly. The pdf, if multiplied by the size of a short interval, gives us the probability of the random.



**Interpreting  $f(x)$ :** think of  $\Pr(x \leq x + \Delta) \approx f(x)\Delta$ .

$$\Pr(x \leq X \leq x + \Delta)$$

Slide 4

**Expectations:** recall  $E(X) = \sum_x x p_X(x)$  for discrete r.v.'s.

Similarly, for a continuous r.v.

$$E(X) = \int_{-\infty}^{\infty} x f(x) dx$$

**Functions  $g(X)$ :** can show  $E\{g(X)\} = \int_{-\infty}^{\infty} g(x) f(x) dx$ ,

including, e.g.,  $E(X^k) = \int x^k f(x) dx$ , and ...

**Variance:** if  $\text{Var}(X)$  exists, then

$$\begin{aligned} \text{Var}(X) &= E\{(X - EX)^2\} \\ &= \int_{-\infty}^{\infty} (X - EX)^2 f(x) dx = E(X^2) - \{E(X)\}^2 \end{aligned}$$

**Lemma 8.1:** If  $X \geq 0$ , then

$$E(X) = \int_0^{\infty} \Pr(X \geq x) dx = \int_0^{\infty} (1 - F(x)) dx$$

The proof is analogous to the discrete case ( $\rightarrow$  Lemma 2.9)

### 8.3 Examples

Slide 5

Examples

$$f(x) = \begin{cases} C(4x - 2x^2) & 0 < x < 2, \\ 0 & \text{otherwise} \end{cases}$$

Find (a)  $C$ , (b)  $\Pr(X > 1)$  and, (c)  $E(X)$ .

$p_{X,Y}(a, b) = \Pr((X = a) \cap (Y = b))$   
 For short, we often write just  $\Pr(X = a, Y = b)$ .

**Definition 8.1:** The *joint (cumulative) distribution function* (cdf) is

$$F(x, y) = \Pr(X \leq x, Y \leq y).$$

We call  $f(x, y)$  the *joint (probability) density function* if

$$F(a) = \int f(t) dt \quad F(x, y) = \int_{-\infty}^y \int_{-\infty}^x f(u, v) du dv$$

Similar to the univariate case

$$f(x, y) = \frac{\partial^2}{\partial x \partial y} F(x, y)$$

Finally, if needed for clarity we write  $F_{X,Y}(x, y)$  and  $f_{X,Y}(x, y)$ .

**Solution:**

(a) Use  $\int_0^2 C(4x - 2x^2) dx = 1$

$$1/C = \int_0^2 \frac{2x^2 + 2/3x^3}{4x - 2x^2} dx = (8 - \frac{2}{3}) = 8/3 \implies C = 3/8.$$

(b)  $\Pr(X > 1) = \int_1^2 C(4x - 2x^2) dx = C(2x^2 - \frac{2}{3}x^3)|_1^2 = \frac{1}{2}.$

(c) Finally,  $E(X) = \int_{-\infty}^{\infty} x f_X(x) dx =$

$$= C \int_0^2 x(4x - 2x^2) dx = C(\frac{4}{3}x^3 - \frac{1}{2}x^4)|_0^2 = \frac{3}{8}(\frac{32}{3} - \frac{16}{2}).$$

Slide 6 Random Variable  $X$ , which represents the outcome of rolling a fair six-sided die.  $\Pr(X = 1) = 1/6$ ,  $\Pr(X = 2) = 1/6$ .

2. For the r.v.  $X$  from before, let  $Y = X/2$ . Find  $f_Y(y)$ .

**Solution:** Easiest to start with  $F_Y(\cdot)$  and then differentiate.

First, note that  $0 < Y < 1$ , and

$$F_Y(y) = \Pr(Y \leq y) = \Pr(X/2 \leq y) = \Pr(X \leq 2y) = F_X(2y).$$

$$\begin{aligned} \implies f_Y(y) &= \frac{d}{dy} F_Y(y) = \frac{d}{dy} F_X(2y) \\ &= f_X(2y) \cdot 2 \\ &= C(8y - 8y^2) \cdot 2 = 6(y - y^2), \end{aligned}$$

$$0 < y < 1.$$

**General rule:** same works for any monotone

$$Y = g(X) \text{ or } X = g^{-1}(Y).$$

$$\text{Second last line: } f_Y(y) = f_X[g^{-1}(y)] \cdot \left| \frac{d}{dy} g^{-1}(y) \right|.$$

Slide 7

*Functions of a R.V.*

The same solution works for any r.v.  $Y = g(X)$ , with an (increasing or decreasing) monotone differentiable function  $g(\cdot)$ .

**Theorem:** If  $Y = g(X)$ , with  $g(\cdot)$  strictly monotone and differentiable, then

$$f_Y(y) = f_X[g^{-1}(y)] \left| \frac{d}{dy} g^{-1}(y) \right|.$$

and  $f_Y(y) = 0$  if  $y \neq g(x)$  for all  $x$ .

## 8.4 Joint Distributions

Slide 8

*Joint distributions*

When we record multiple numerical summaries of a chance experiment we get multiple jointly distributed r.v.'s.

We can define *joint* cdf and pdf, similar to before:

Slide 9

**Marginal cdf and pdf:** To distinguish the univariate cdf (for  $X$  only) from the joint cdf (for  $X, Y$ ), we include a  $x$  index in

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

and refer to it as *marginal distribution*. Same for the *marginal density*,  $f_X(x)$ .

**Marginalization:** note The marginal distribution function is a special case of the joint distribution function

$$\begin{aligned} F_X(a) &= \Pr(X \leq a) \\ &= \Pr(X \leq a, Y \leq \infty) = F_{X,Y}(a, \infty) \end{aligned}$$

Since  $F_{X,Y}(a, \infty) = \int_{-\infty}^{\infty} \int_{-\infty}^a f_{X,Y}(x, y) dy dx$  we have

$$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x, y) dy$$

## 8.5 Independence

Slide 10

*Independence*

**Definition 8.2:** Similar to discrete r.v.'s we define  $X \perp Y$  to be independent if

$$\begin{aligned} F_{X,Y}(x, y) &= \Pr(X \leq x, Y \leq y) \\ &= \Pr(X \leq x) \cdot \Pr(Y \leq y) = F_X(x) \cdot F_Y(y) \end{aligned}$$

for all  $x$  and  $y$ .

Taking derivatives we get an equivalent condition

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

## 8.6 Examples

### Slide 11

#### Examples

1. Let  $X$  and  $Y$  be two jointly distributed r.v.'s with

$$F(x, y) = 1 - e^{-ax} - e^{-by} + e^{-(ax+by)}, \quad x > 0, y > 0$$

Find

(a)  $F_X(x)$ , (b)  $F_Y(y)$ , (c)  $f(x, y)$ , and (d) determine if  $X \perp Y$ .

**Solution:** (a)  $F_X(x) = F(x, \infty) = 1 - e^{-ax}$ ,  $F_X(a) = \Pr(X \leq a)$   
 $= \Pr(X \leq a, Y < \infty)$   
 $= F_X, Y(a, \infty)$

(b)  $F_Y(y) = F(\infty, y) = 1 - e^{-by}$ .

(c)  $f(x, y) = ab e^{-(ax+by)}$

(d) To show independence note

$$\begin{aligned} F_X(x)F_Y(y) &= (1 - e^{-ax})(1 - e^{-by}) \\ &= 1 - e^{-ax} - e^{-by} + e^{-(ax+by)} \\ &= F(x, y) \end{aligned}$$

$$\Rightarrow X \perp Y.$$

- A r.v. with  $f_W(w) \propto w^{a-1} e^{-bw}$ ,  $w > 0$  is known as a *gamma* r.v.,  $W \sim \text{Ga}(a, b)$ . See more later.  
In the example,  $W = X + Y \sim \text{Ga}(2, 1)$ .

- We have shown: The sum of two independent exponential r.v.'s is a gamma r.v.

### Slide 14

#### Sums of Random Variables

Eq (1) on the previous slide is a general formula for  $f_{X+Y}$ , modifying the integration limits in general as implied by the support of  $f_Y$ .

**Result:** Consider two independent r.v.'s  $X$  and  $Y$ , with p.d.f.  $f_X(x)$  and  $f_Y(y)$ , respectively, and let  $S = X + Y$ . Then

$$f_S(s) = \int_{-\infty}^{\infty} f_X(x) f_Y(s-x) dx.$$

Using the result, keep in mind that  $f_X(x) = 0$  outside the support of  $f_X$  and similarly for  $f_Y$  (which typically restricts the integration limits).

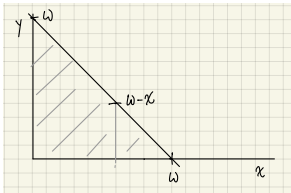
**Proof:** Same as the first few lines of the previous example.

### Slide 12

#8.2: Let  $X \perp Y$  be independent r.v.'s,  $f_X(t) = f_Y(t) = e^{-t}$ ,  $t > 0$ . Find  $f_W(w)$  for  $W = X + Y$ .

**Solution:** Find  $\Pr(W \leq w)$ .

To determine the following integration limits keep in mind that  $f_X(t) = f_Y(t) = 0$  for  $t < 0$ .



$$\begin{aligned} F_W(w) &= \Pr(X + Y \leq w) \\ &= \int_0^w \int_{y \leq w-x} f_Y(y) dy f_X(x) dx \\ &= \int_0^w F_Y(w-x) f_X(x) dx. \end{aligned}$$

By differentiation we get

$$\begin{aligned} f_W(w) &= \int_0^w f_Y(w-x) f_X(x) dx \\ &= \int_0^w e^{-(w-x)-x} dx = w e^{-w} \end{aligned}$$

### Slide 15

## 8.7 Conditional Distributions

#### Conditional Distributions

Recall for two discrete r.v.'s  $V, W$  we defined

$$p_{V|W}(v | W = w) = \frac{\Pr(V = v, W = w)}{\Pr(W = w)}$$

(for  $\Pr(W = w) > 0$ ).

The definition does not generalize to continuous r.v.'s since  $\Pr(X = x) = 0$  for a continuous r.v.

But it can also be written as

$$\dots = \frac{p_{V,W}(v, w)}{p_W(w)}.$$

(1) We use this as a definition!

**Conditional density function:** for two continuous r.v.'s  $X, Y$ ,

$$f_{X|Y}(x | y) = \frac{f_{X,Y}(x, y)}{f_Y(y)}.$$

### Slide 13

#### Sum of Exponential Variables

Some comments about this example

- A r.v. with  $f_X(x) = \lambda e^{-\lambda x}$ ,  $x > 0$  is known as *exponential* r.v.  
We write  $X \sim \text{Exp}(\lambda)$ .  
In the example we had  $X \sim \text{Exp}(1)$ ,  $Y \sim \text{Exp}(1)$ .

### Slide 16

**Example:** Recall the earlier example with  $f(x, y) = abe^{-(ax+by)}$ . We could find

$$f_{X|Y}(x | Y = 4) = \frac{abe^{-(ax+4b)}}{be^{-4b}}$$

and, for example

$$\Pr(X \leq 3 \mid Y = 4) = \int_{x=0}^3 \frac{abe^{-(ax+4b)}}{be^{-4b}} = 1 - e^{-3a}.$$

We could have done it faster remembering the independence,

$X \perp Y$

$$\Rightarrow \Pr(X \leq 3 \mid Y = 4) = \Pr(X \leq 3) = F_X(3) = 1 - e^{-3a},$$

using  $F_X(\cdot)$  from earlier.

**Conditional expectation:** use  $f_{X|Y}$  to define an expectation

$$E(X \mid Y = y) = \int_{x=-\infty}^{\infty} x f_{X|Y}(x \mid y) dx$$

## 8.8 Example

Slide 17

*Example*

Suppose  $f(x, y) = \frac{e^{-x/y} e^{-y}}{y}$ ,  $x > 0, y > 0$  for two r.v.'s  $X$  and  $Y$ .

(a) Find  $f_{X|Y}(x \mid y)$ ; and (b)  $\Pr(X > 1 \mid Y = y)$ .

**Solution:** (a)

$$f_{X|Y}(x \mid y) = \frac{f(x, y)}{f_Y(y)} = \frac{e^{-x/y-y}/y}{e^{-y} \underbrace{\int_0^{\infty} (1/y) e^{-x/y} dx}_{=1}} = \frac{1}{y} e^{-x/y}$$

(for the integral, see also later, about the exponential distribution).

(b) therefore

$$\Pr(X > 1 \mid Y = y) = \int_1^{\infty} \frac{1}{y} e^{-x/y} dx = e^{-1/y}.$$

(again, see also later about the exponential c.d.f).

## 8.9 The Uniform Distribution

Slide 18

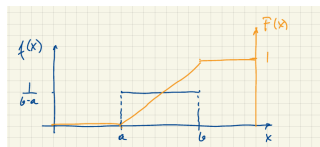
*The Uniform Distribution*

Assume that  $X$  assumes values in an interval  $[a, b]$ , such that all subintervals of equal length have equal probability.

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

**Uniform pdf:** constant over  $a \leq x \leq b$ ,

$$f(x) = \begin{cases} 0 & \text{if } x < a \\ 1/(b-a) & \text{if } a \leq x \leq b \\ 0 & \text{if } x > b, \end{cases}$$



**Distribution function:** integrating a constant  $\rightarrow$  straight line:

$$F(x) = \begin{cases} 0 & \text{if } x < a \\ \frac{x-a}{b-a} & \text{if } a \leq x \leq b \\ 1 & \text{if } x > b \end{cases}$$

Slide 19

**Moments:** we find

$$E(X) = \frac{b+a}{2},$$

$$E(X^2) = \int_a^b x \frac{x}{b-a} dx = \frac{b^2 + ab + a^2}{3}$$

$$\Rightarrow \text{Var}(X) = E(X^2) - (EX)^2 = \dots = \frac{(b-a)^2}{12}.$$

## 8.10 Uniform - Conditional and Order Statistics

Slide 20

*Conditional distribution*

**Lemma 8.2:** Assume  $X \sim \text{Unif}(a, b)$ , then for  $x \leq d$ :

$$\Pr(X \leq x \mid X \leq d) = \frac{x-a}{d-a}$$

In words, conditional on  $X \leq d$ ,  $X$  is simply  $\text{Unif}(a, d)$ .

And similarly,  $X \mid X \geq d \sim \text{Unif}(d, b)$ .

Slide 21

*Order Statistics*

**Lemma 8.3:** Let  $X_i \sim \text{Unif}(0, 1)$ ,  $i = 1, \dots, n$ , i.i.d. (independent and identically distributed).

Let  $Y_1, \dots, Y_n$  be the sorted values of  $X_1, \dots, X_n$  (in increasing order) ("order statistic").

Then  $E(Y_k) = k/(n+1)$ .

**Proof:** First, consider  $Y_1 = \min\{X_1, \dots, X_n\}$ . Then

$$\Pr(Y_1 \geq y) = \Pr(X_1 \geq y, X_2 \geq y, \dots, X_n \geq y) = (1-y)^n.$$

The last equality is true because of independence of the  $X_i$ , and  $\Pr(X_i \geq y) = (1-y)$ .

By Lemma 8.1. we have  $E(Y_1) = \int_0^1 (1-y)^n dy = \frac{1}{n+1}$ .  
Extension to  $E(Y_k) \rightarrow$  Exercise

## 8.11 Example

Slide 22

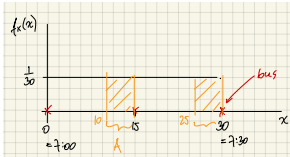
### Example

Buses arrive at a specified stop at 15-minute intervals starting at 7am. That is, they arrive at 7, 7:15, 7:30, 7:45, and so on. If a passenger arrives at the stop at a time that is uniformly distributed between 7 and 7:30, find the probability of

(a)  $A = \{< 5\text{min wait}\}$ ; (b)  $B = \{> 10\text{min wait}\}$ .

In the solution, let  $X$  = the number of minutes past 7am that the passenger arrives. Then  $X \sim \text{Unif}(0, 30)$ .

**Solution:** Note that  $f_X(x) = 1/30, 0 < x < 30$ .



$$\Pr(A) = \Pr(\{10 < X < 15\} \cup \{25 < X < 30\})$$

$$= 10/30 = 1/3.$$

Similarly,

$$\Pr(B) = \Pr(\{0 < X < 5\} \cup \{15 < X < 20\})$$

$$= 10/30 = 1/3.$$

**Memoryless property:** a remarkable property:

$$\Pr(X > s + t | X > t) = \Pr(X > s)$$

**Proof:** Will use  $\Pr(X > t) = 1 - \Pr(X \leq t) = 1 - F(t) = e^{-\theta t}$ .

Note:  $1 - F(t)$  is known as *survival function*.

$$\begin{aligned} \Pr(X > s + t | X > t) &= \frac{\Pr(X > s + t)}{\Pr(X > t)} \\ &= \frac{e^{-\theta(s+t)}}{e^{-\theta t}} = e^{-\theta s} = \Pr(X > s) \end{aligned}$$

If  $X$  is a waiting time (for some event) in min's – after waiting for  $t$  minutes, the prob of waiting another  $s$  minutes is the same as initially.

Slide 25

**Sums of exponential r.v.'s:** Recall #8.2. We showed:

If  $X \sim \text{Exp}(1)$  and  $Y \sim \text{Exp}(1)$  are independent r.v.'s then  $W = X + Y$  is a **gamma r.v.**,  $W \sim \text{Ga}(2, 1)$ .

In general, if  $X_i \sim \text{Exp}(\lambda)$ ,  $i = 1, \dots, n$ , independently, then

$$W = \sum_{i=1}^n X_i \sim \text{Ga}(n, \lambda).$$

Proof is as in #8.2, using induction for  $n > 2$ .

## 8.12 The Exponential Distribution

Slide 23

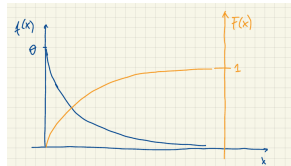
### Exponential Distribution

**Distribution function:** a r.v.  $X \geq 0$  follows the exponential distribution if

$$F(x) = \begin{cases} 1 - e^{-\theta x} & \text{for } x \geq 0, \\ 0 & x < 0 \end{cases}$$

**Density:**

$$f(x) = \frac{d}{dx} F(x) = \theta e^{-\theta x}$$



**Moments:**

$$\begin{aligned} E(X) &= \int_0^\infty t \theta e^{-\theta t} dt = \frac{1}{\theta} \\ E(X^2) &= \int_0^\infty t^2 \theta e^{-\theta t} dt = \frac{2}{\theta^2} \\ \Rightarrow \text{Var}(X) &= E(X^2) - (EX)^2 = \frac{1}{\theta^2} \end{aligned}$$

## 8.14 Exponential Race

Slide 26

### Exponential Race

In words, the minimum of  $n$  exponential r.v.'s is exponential with the sum of the rates.

**Lemma 8.5:** Let  $X_i \sim \text{Exp}(\theta_i)$ ,  $i = 1, \dots, n$ , independently. Then

$$U = \min\{X_1, \dots, X_n\} \sim \text{Exp}\left(\sum \theta_i\right)$$

$$\text{and } \Pr(U = X_i) = \frac{\theta_i}{\sum_{\ell=1}^n \theta_\ell}.$$

**Proof:** for  $n = 2$ , we get

- for  $U$ , using independence of  $X_1, X_2$ :

$$\begin{aligned} \Pr(U > x) &= \Pr(X_1 > x, X_2 > x) \\ &= \Pr(X_1 > x) \cdot \Pr(X_2 > x) \\ &= e^{-\theta_1 x} e^{-\theta_2 x} = e^{-(\theta_1 + \theta_2)x} \end{aligned}$$

which is  $\Pr(U > x)$  for  $U \sim \text{Exp}(\theta_1 + \theta_2)$ .

Use induction to show the same for  $n > 2$ .

## 8.13 Memoryless Property of the Exponential

Slide 24

### Memoryless Property

Slide 27

- We still have to show the second claim. Note that the joint pdf for  $(X_1, X_2)$  is  $f_{X_1, X_2}(x_1, x_2) = f_{X_1}(x_1)f_{X_2}(x_2)$ , and therefore<sup>2</sup>

$$\begin{aligned}\Pr(X_1 < X_2) &= \int_{x_2=0}^{\infty} \int_{x_1=0}^{x_2} \theta_1 e^{-\theta_1 x_1} dx_1 \theta_2 e^{-\theta_2 x_2} dx_2 \\ &= \dots = \frac{\theta_1}{\theta_1 + \theta_2}\end{aligned}$$

Use induction to show the same for  $n > 2$ .

## 8.15 Example

Slide 28

### Example

Consider a post office that is staffed by two clerks. Suppose that:

- Both clerks are helping a customer and nobody is waiting.
- The two customers, A and B, are served with independent service times,  $X_i \sim \text{Exp}(\lambda)$ ,  $i = 1, 2$ .
- A third customer, C, enters the post office, and will be served by the first available clerk, again with exponential service time,  $X_3 \sim \text{Exp}(\lambda)$ .

Find the probability that, of the three customers, C is the last one to leave the post office?

Solution:

- The *remaining* service times  $Y_i$ ,  $i = 1, 2$ , for A and B are also  $\text{Exp}(\lambda)$  (memoryless property of the Exp).

Slide 29

- When the first customer finishes, two customers are left in the post office. Assume for a moment that A finishes first, leaving then B and C to be served, with (remaining) service times  $\text{Exp}(\lambda)$ .
- In that case, the probability that C leaves last is therefore  $\lambda/(\lambda + \lambda) = 1/2$  (or just argue by symmetry).

And the same argument if B finishes first

$$\implies \Pr(\text{"C leaves last"}) = 0.5.$$

<sup>2</sup>In the lecture the blue & black factors of the integrand were interchanged – not wrong, but possibly misleading