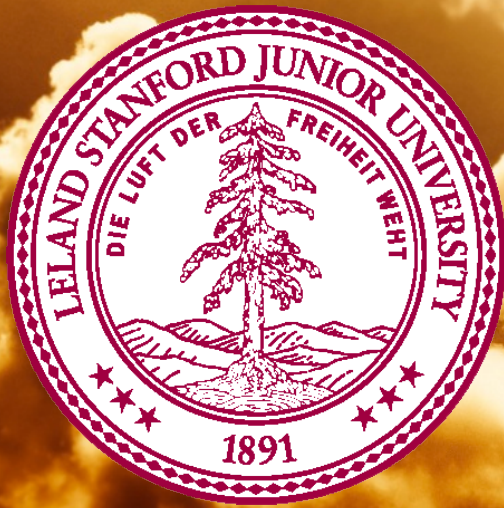




Great Expectations

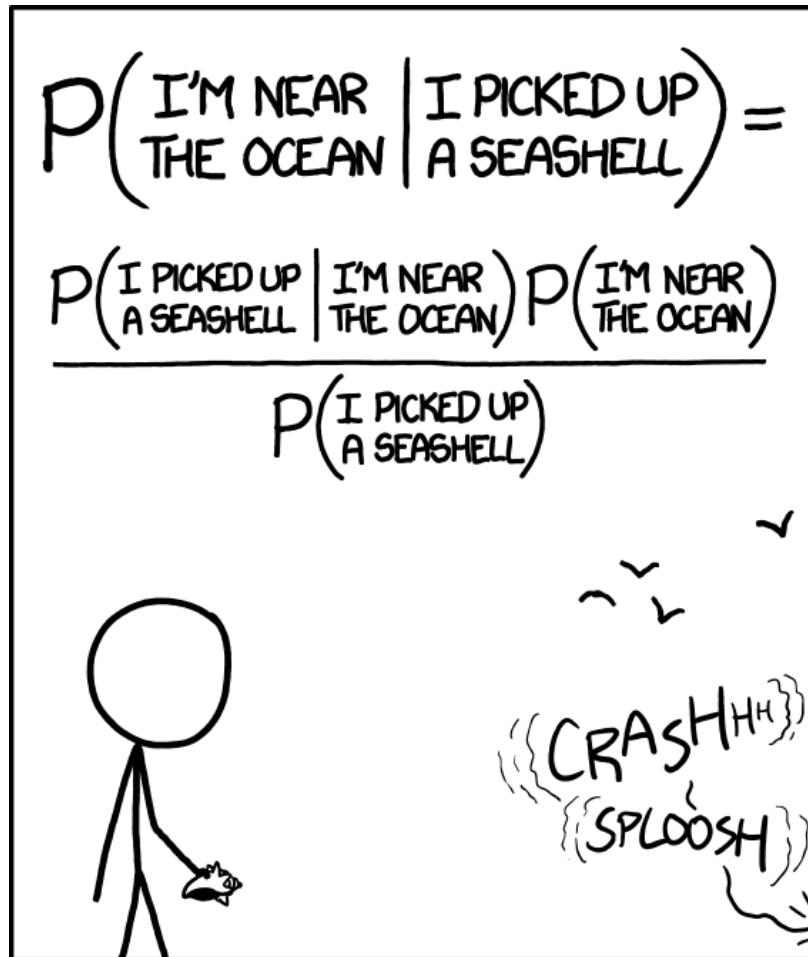
Chris Piech (and Dickens)
CS109, Stanford University

Course Mean

$E[\text{CS109}]$

*This is actual midpoint of course
(Just wanted you to know)*

Sea side



STATISTICALLY SPEAKING, IF YOU PICK UP A SEASHELL AND DON'T HOLD IT TO YOUR EAR, YOU CAN PROBABLY HEAR THE OCEAN.

Review

Expected Values of Sums

$$E[X + Y] = E[X] + E[Y]$$

Generalized:
$$E\left[\sum_{i=1}^n X_i\right] = \sum_{i=1}^n E[X_i]$$

Holds regardless of dependency between X_i 's

End Review



Boole Was Cool

- Let $E_1, E_2, \dots, E_n$ be events with indicator RVs X_i
 - If event E_i occurs, then $X_i = 1$, else $X_i = 0$
 - Recall $E[X_i] = P(E_i)$
 - Why?

$$E[X_i] = 0 \cdot (1 - P(E_i)) + 1 \cdot P(E_i)$$

Bernoulli aka Indicator Random Variables were studied extensively by George Boole

Boole died of being too cool



Expectation of Binomial

- Let $Y \sim \text{Bin}(n, p)$
 - n independent trials
 - Let $X_i = 1$ if i -th trial is “success”, 0 otherwise
 - $X_i \sim \text{Ber}(p)$ $E[X_i] = p$

$$Y = X_1 + X_2 + \cdots + X_n = \sum_{i=1}^n X_i$$

$$E[Y] = E\left[\sum_{i=1}^n X_i\right]$$

$$= \sum_{i=1}^n E[X_i]$$

$$= E[X_1] + E[X_2] + \cdots E[X_n]$$

$$= np$$

Expectation of Negative Binomial

- Let $Y \sim \text{NegBin}(r, p)$
 - Recall Y is number of trials until r “successes”
 - Let $X_i = \#$ of trials to get success after $(i - 1)$ st success
 - $X_i \sim \text{Geo}(p)$ (i.e., Geometric RV) $E[X_i] = \frac{1}{p}$

$$Y = X_1 + X_2 + \cdots + X_r = \sum_{i=1}^r X_i$$

$$E[Y] = E\left[\sum_{i=1}^r X_i\right]$$

$$= \sum_{i=1}^r E[X_i]$$

$$= E[X_1] + E[X_2] + \cdots + E[X_r]$$

$$= \frac{r}{p}$$

Differential Privacy

Aims to provide means to **maximize the accuracy** of probabilistic queries while minimizing the **probability** of identifying its records.



Cynthia Dwork's celebrity lookalike is Cynthia Dwork.

Differential Privacy

100 independent values $X_1 \dots X_{100}$ where $X_i \sim \text{Bern}(p)$

```
# Maximize accuracy, while preserving privacy.
```

```
def calculateYi(Xi):  
    obfuscate = random()  
    if obfuscate:  
        return indicator(random())  
    else:  
        return Xi
```

random() returns
True or False with
equal likelihood

Differential Privacy

100 independent values $X_1 \dots X_{100}$ where $X_i \sim \text{Bern}(p)$

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# Maximize accuracy, while preserving privacy.
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def calculateYi(Xi):
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    obfuscate = random()
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    if obfuscate:
```

```
        return indicator(random())
```

```
    else:
```

```
        return Xi
```

random() returns
True or False with
equal likelihood

What is $E[Y_i]$?

$$E[Y_i] = P(Y_i = 1) = \frac{p}{2} + \frac{1}{4}$$

Differential Privacy

100 independent values $X_1 \dots X_{100}$ where $X_i \sim \text{Bern}(p)$

```
# Maximize accuracy, while preserving privacy.
```

```
def calculateYi(Xi):
```

```
    obfuscate = random()
```

```
    if obfuscate:
```

```
        return indicator(random())
```

```
    else:
```

```
        return Xi
```

random() returns
True or False with
equal likelihood

Let $Z = \sum_{i=1}^{100} Y_i$

What is the $E[Z]$?

$$E[Z] = E\left[\sum_{i=1}^{100} Y_i\right] = \sum_{i=1}^{100} E[Y_i] = \sum_{i=1}^{100} \left(\frac{p}{2} + \frac{1}{4}\right) = 50p + 25$$

Differential Privacy

100 independent values $X_1 \dots X_{100}$ where $X_i \sim \text{Bern}(p)$

```
# Maximize accuracy, while preserving privacy.
```

```
def calculateYi(Xi):
```

```
    obfuscate = random()
```

```
    if obfuscate:
```

```
        return indicator(random())
```

```
    else:
```

```
        return Xi
```

random() returns
True or False with
equal likelihood

Let $Z = \sum_{i=1}^{100} Y_i$ $E[Z] = 50p + 25$ How do you estimate p ?

$$p \approx \frac{Z - 25}{50}$$

Challenge: What is the probability that our estimate is good?

More Practice!

Computer Cluster Utilization

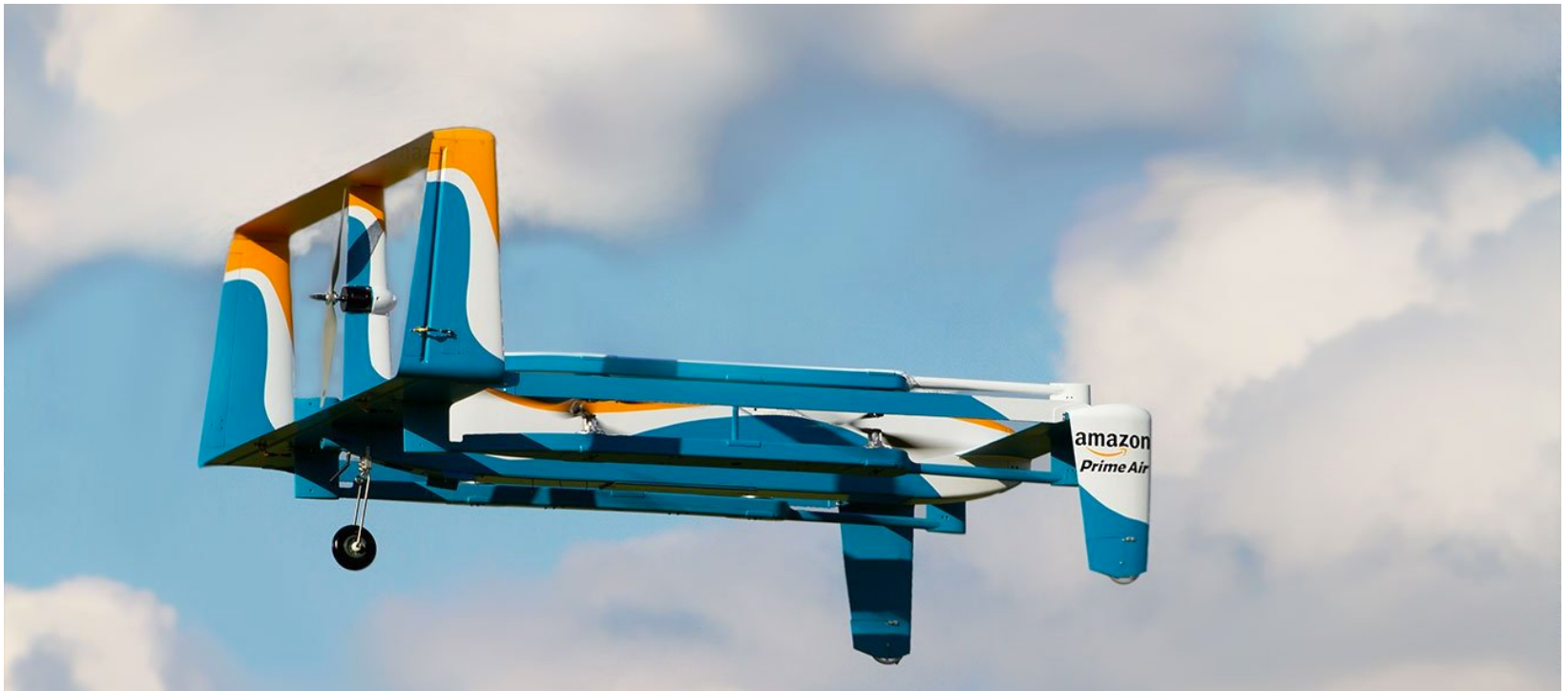
- Computer cluster with k servers
 - Requests independently go to server i with probability p_i
 - Let event A_i = server i receives no requests
 - Let Bernoulli B_i be an indicator for A_i
 - $X = \#$ of events $A_1, A_2, \dots, A_k$ that occur
 - $Y = \#$ servers that receive ≥ 1 request = $k - X$
 - $E[Y]$ after first n requests?
 - Since requests independent: $P(A_i) = (1 - p_i)^n$

$$X = \sum_{i=1}^k B_i$$

$$E[X] = E\left[\sum_{i=1}^k B_i\right] = \sum_{i=1}^k E[B_i] = \sum_{i=1}^k P(A_i) = \sum_{i=1}^k (1 - p_i)^n$$

$$E[Y] = k - E[X] = k - \sum_{i=1}^k (1 - p_i)^n$$

amazon





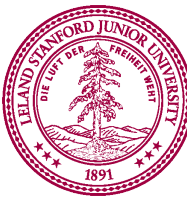
amazon web services™

* 52% of Amazons Profits

**More profitable than Amazon's North America commerce operations



When stuck, brainstorm
about random variables





Hash Tables (aka Toy Collecting)

- Consider a hash table with n buckets
 - Each string equally likely to get hashed into any bucket
 - Let X = # strings to hash until each bucket ≥ 1 string
 - What is $E[X]$?
 - Let X_i = # of trials to get success after i -th success
 - where “success” is hashing string to previously empty bucket
 - After i buckets have ≥ 1 string, probability of hashing a string to an empty bucket is $p = (n - i) / n$
 - $P(X_i = k) = \frac{n-i}{n} \left(\frac{i}{n} \right)^{k-1}$ equivalently: $X_i \sim \text{Geo}((n - i) / n)$
 - $E[X_i] = 1 / p = n / (n - i)$
 - $X = X_0 + X_1 + \dots + X_{n-1} \Rightarrow E[X] = E[X_0] + E[X_1] + \dots + E[X_{n-1}]$
$$E[X] = \frac{n}{n} + \frac{n}{n-1} + \frac{n}{n-2} + \dots + \frac{n}{1} = n \left[\frac{1}{n} + \frac{1}{n-1} + \dots + 1 \right] = O(n \log n)$$

This is your final answer

Break



Conditional Expectation

Conditional Expectation

- X and Y are jointly discrete random variables
 - Recall conditional PMF of X given Y = y:

$$p_{X|Y}(x | y) = P(X = x | Y = y) = \frac{p_{X,Y}(x, y)}{p_Y(y)}$$

- Define conditional expectation of X given Y = y:

$$E[X | Y = y] = \sum_x x P(X = x | Y = y) = \sum_x x p_{X|Y}(x | y)$$

- Analogously, jointly continuous random variables:

$$f_{X|Y}(x | y) = \frac{f_{X,Y}(x, y)}{f_Y(y)} \qquad E[X | Y = y] = \int_{-\infty}^{\infty} x f_{X|Y}(x | y) dx$$

Rolling Dice

- Roll two 6-sided dice D_1 and D_2
 - $X = \text{value of } D_1 + D_2$ $Y = \text{value of } D_2$
 - What is $E[X \mid Y = 6]$?

$$\begin{aligned} E[X \mid Y = 6] &= \sum_x xP(X = x \mid Y = 6) \\ &= \left(\frac{1}{6}\right)(7 + 8 + 9 + 10 + 11 + 12) = \frac{57}{6} = 9.5 \end{aligned}$$

- Intuitively makes sense: $6 + E[\text{value of } D_1] = 6 + 3.5$

Properties of Conditional Expectation

- X and Y are jointly distributed random variables

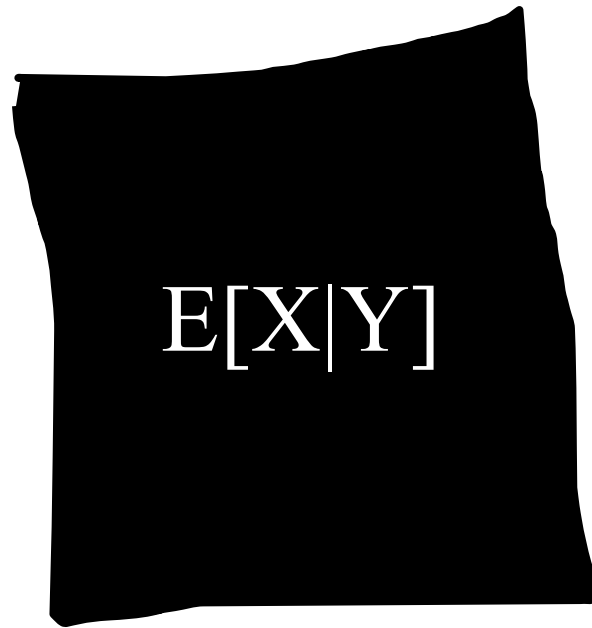
$$E[g(X) | Y = y] = \sum_x g(x) p_{X|Y}(x | y) \quad \text{or} \quad \int_{-\infty}^{\infty} g(x) f_{X|Y}(x | y) dx$$

- Expectation of conditional sum:

$$E\left[\sum_{i=1}^n X_i | Y = y\right] = \sum_{i=1}^n E[X_i | Y = y]$$

Conditional Expectation Functions

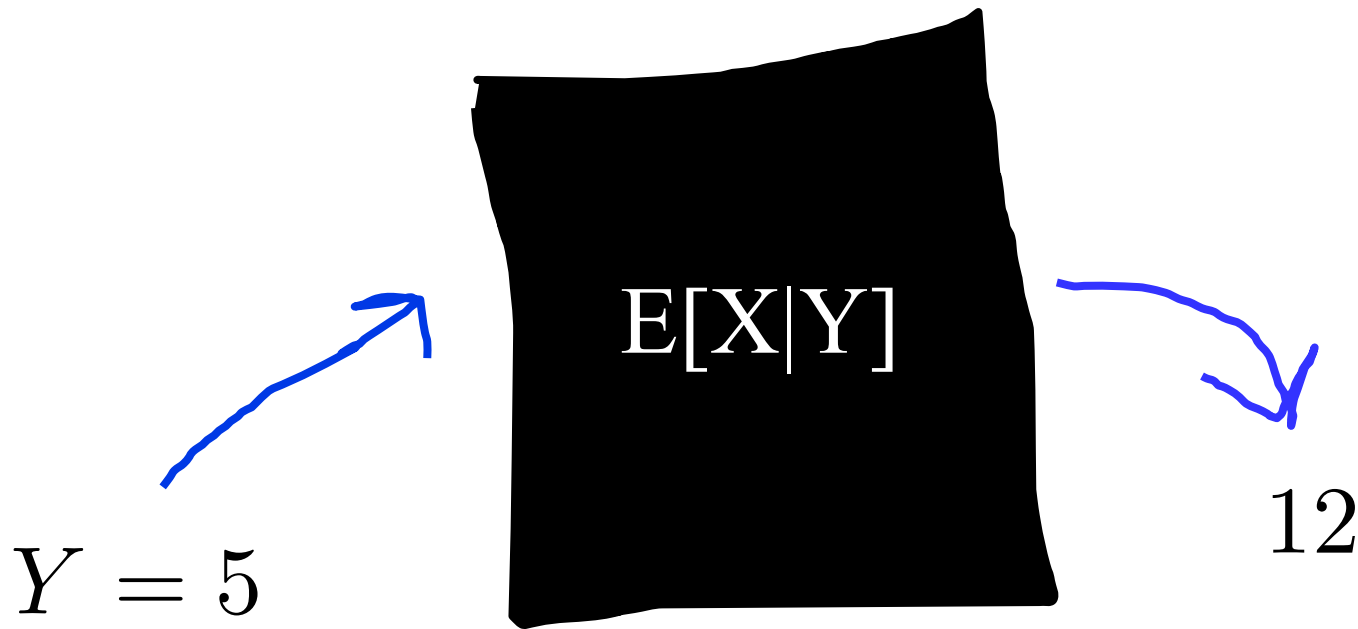
- Define $g(Y) = E[X | Y]$
 - For any $Y = y$, $g(Y) = E[X | Y = y]$
 - This is just function of Y



This is a function with Y as input

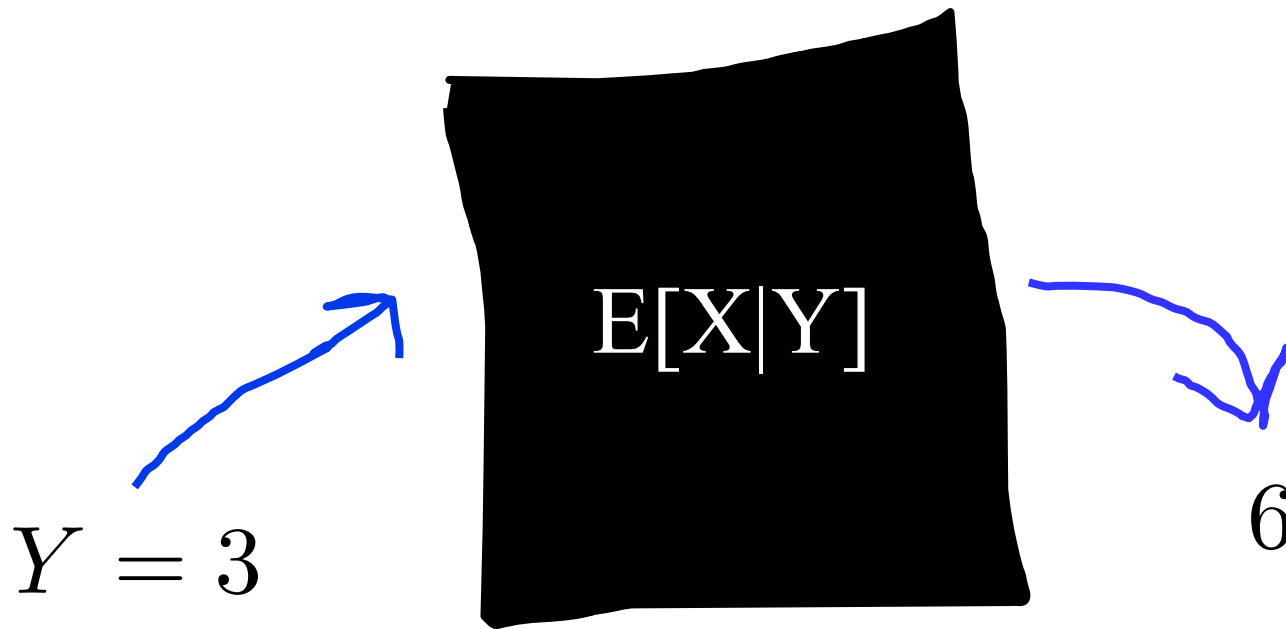
Conditional Expectation Functions

- Define $g(Y) = E[X | Y]$
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Conditional Expectation Functions

- Define $g(Y) = E[X | Y]$
 - For any $Y = y$, $g(Y) = E[X | Y = y]$
 - This is just function of Y

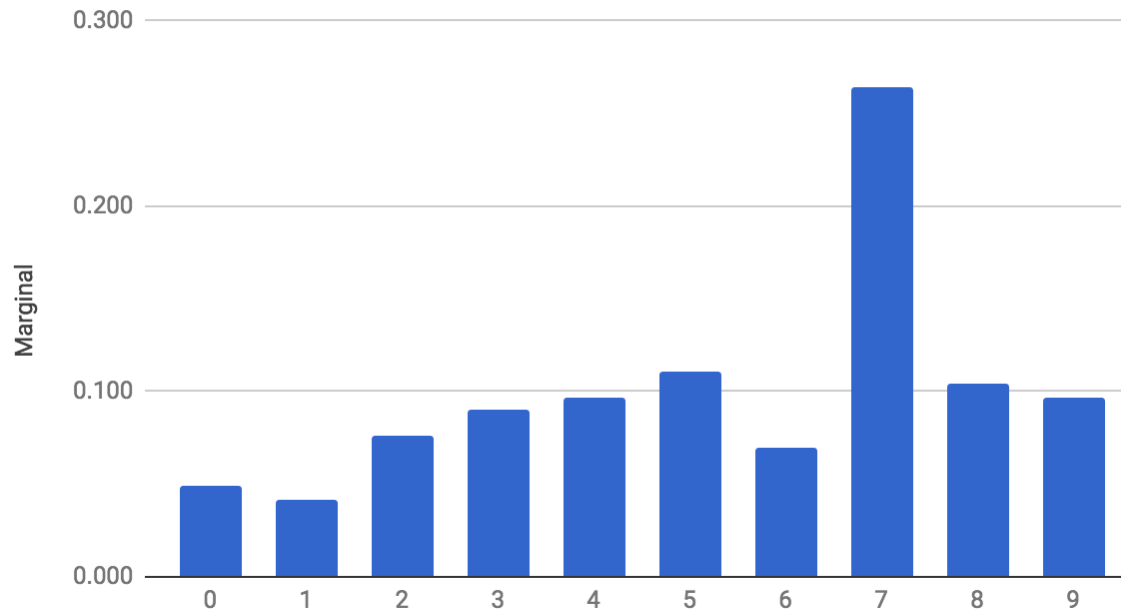


Conditional Expectation Functions

X = favorite number

Y = year in school

Favorite Digit



$$E[X] = 0 * 0.05 + \dots + 9 * 0.10 = 5.38$$

Conditional Expectation Functions

X = favorite number

Y = year in school

$$E[X | Y] ?$$

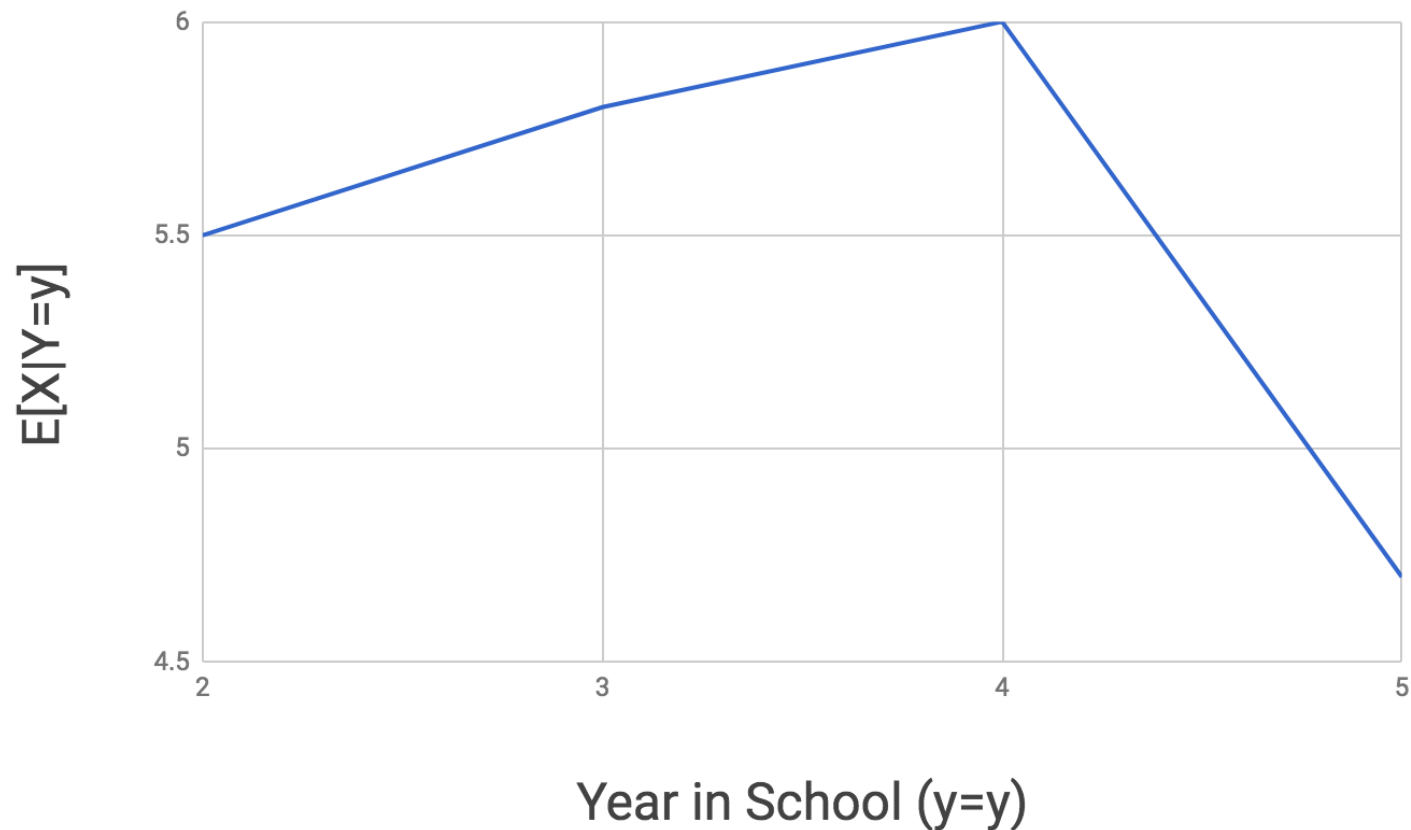
Year in school, $Y = y$	$E[X Y = y]$
2	5.5
3	5.8
4	6.0
5	4.7

Conditional Expectation Functions

X = favorite number

Y = year in school

$E[X | Y] ?$



Law of Total Expectation

$$E[E[X|Y]] = E[X]$$

$$E[E[X|Y]] = \sum_y E[X|Y = y]P(Y = y) \quad g(Y) = E[X|Y]$$

$$= \sum_y \sum_x xP(X = x|Y = y)P(Y = y) \quad \text{Def of } E[X|Y]$$

$$= \sum_y \sum_x xP(X = x, Y = y) \quad \text{Chain rule!}$$

$$= \sum_x \sum_y xP(X = x, Y = y) \quad \text{I switch the order of the sums}$$

$$= \sum_x x \sum_y P(X = x, Y = y) \quad \text{Move that } x \text{ outside the } y \text{ sum}$$

$$= \sum_x xP(X = x) \quad \text{Marginalization}$$

$$= E[X] \quad \text{Def of } E[X]$$

Analyzing Recursive Code

```
int Recurse() {  
    int x = randomInt(1, 3); // Equally likely values  
    if (x == 1) return 3;  
    else if (x == 2) return (5 + Recurse());  
    else return (7 + Recurse());  
}
```

- Let Y = value returned by `Recurse()`. What is $E[Y]$?

$$E[Y] = E[Y | X = 1]P(X = 1) + E[Y | X = 2]P(X = 2) + E[Y | X = 3]P(X = 3)$$

$$E[Y | X = 1] = 3$$

$$E[Y | X = 2] = E[5 + Y] = 5 + E[Y]$$

$$E[Y | X = 3] = E[7 + Y] = 7 + E[Y]$$

$$E[Y] = 3(1/3) + (5 + E[Y])(1/3) + (7 + E[Y])(1/3) = (1/3)(15 + 2E[Y])$$

$$E[Y] = 15$$

Protip: do this in CS161

If we have time...

Hiring and Engineer

```
DEFINE JOBSITEINTERVIEWQUICKSORT(LIST):  
  OK SO YOU CHOOSE A PIVOT  
  THEN DIVIDE THE LIST IN HALF  
  FOR EACH HALF:  
    CHECK TO SEE IF IT'S SORTED  
    NO, WAIT, IT DOESN'T MATTER  
    COMPARE EACH ELEMENT TO THE PIVOT  
    THE BIGGER ONES GO IN A NEW LIST  
    THE EQUAL ONES GO INTO, UH  
    THE SECOND LIST FROM BEFORE  
  HANG ON, LET ME NAME THE LISTS  
  THIS IS LIST A  
  THE NEW ONE IS LIST B  
  PUT THE BIG ONES INTO LIST B  
  NOW TAKE THE SECOND LIST  
  CALL IT LIST, UH, A2  
  WHICH ONE WAS THE PIVOT IN?  
  SCRATCH ALL THAT  
  IT JUST RECURSIVELY CALLS ITSELF  
  UNTIL BOTH LISTS ARE EMPTY  
  RIGHT?  
  NOT EMPTY, BUT YOU KNOW WHAT I MEAN  
  AM I ALLOWED TO USE THE STANDARD LIBRARIES?
```

Your company has one job opening for a software engineer.

You have n candidates. But you have to say yes/no **immediately** after each interview!

Proposed algorithm: reject the first k and accept the next one who is better than all of them.

What's the best value of k ?

Hiring and Engineer

n candidates, must say yes/no **immediately** after each interview.
Reject the first k , accept the next who is better than all of them.
What's the best value of k ?

B: event that you hire the best engineer

X: position of the best engineer on the interview schedule

What is the $P(B \mid X = i)$

Hiring and Engineer

n candidates, must say yes/no **immediately** after each interview.
Reject the first k , accept the next who is better than all of them.
What's the best value of k ?

B: event that you hire the best engineer

X: position of the best engineer on the interview schedule

$$P_k(B) = \frac{1}{n} \sum_{i=1}^n P_k(B|X = i)$$

$$= \frac{1}{n} \sum_{i=k+1}^n \frac{k}{i-1}$$

$$\approx \frac{1}{n} \int_{i=k+1}^n \frac{k}{i-1} di$$

$$= \frac{k}{n} \ln(i-1) \Big|_{k+1}^n = \frac{k}{n} \ln \frac{n-1}{k} \approx \frac{k}{n} \ln \frac{n}{k}$$

since we know $P_k(\text{Best}|X = i)$

By Riemann Sum approximation

Let's Do Some Sorting!

5	3	7	4	8	6	2	1
---	---	---	---	---	---	---	---

QuickSort

5	3	7	4	8	6	2	1
---	---	---	---	---	---	---	---



select
“pivot”

Recursive Insight

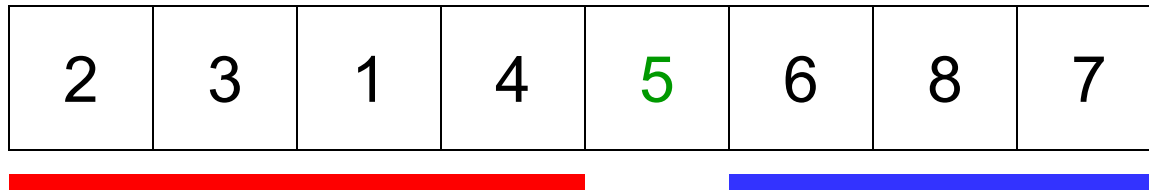
5	3	7	4	8	6	2	1
---	---	---	---	---	---	---	---

Partition array so:

- everything smaller than pivot is on left
- everything greater than or equal to pivot is on right
- pivot is in-between

Recursive Insight

2	3	1	4	5	6	8	7
---	---	---	---	---	---	---	---

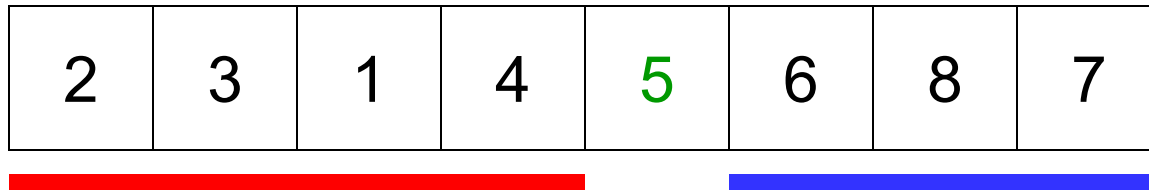


Partition array so:

- everything smaller than pivot is on left
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- pivot is in-between

Recursive Insight

2	3	1	4	5	6	8	7
---	---	---	---	---	---	---	---

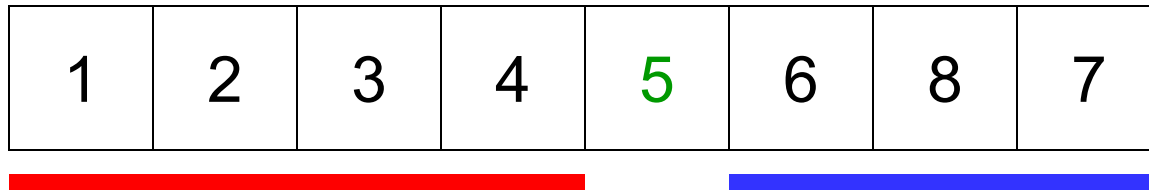


The diagram illustrates an array of eight numbers: 2, 3, 1, 4, 5, 6, 8, and 7. The array is represented as a row of eight boxes. Below the first four boxes (2, 3, 1, 4) is a thick red horizontal line. Below the last four boxes (5, 6, 8, 7) is a thick blue horizontal line. The number 5 in the fifth box is highlighted in green.

Now recursive sort “red” sub-array

Recursive Insight

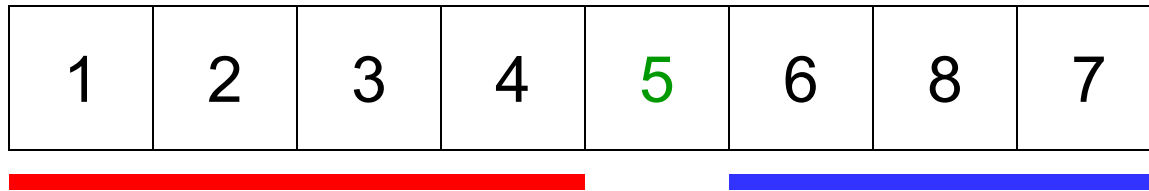
1	2	3	4	5	6	8	7
---	---	---	---	---	---	---	---



Now recursive sort “red” sub-array

Recursive Insight

1	2	3	4	5	6	8	7
---	---	---	---	---	---	---	---

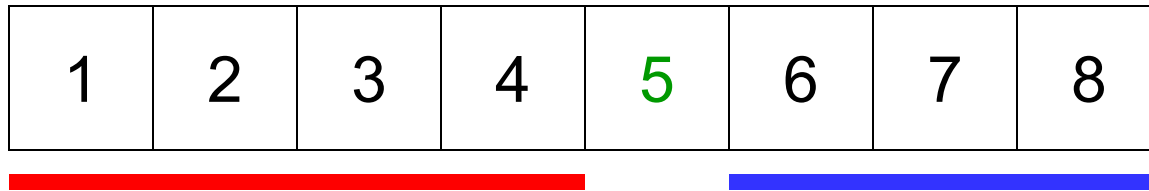


Now recursive sort “red” sub-array

Then, recursive sort “blue” sub-array

Recursive Insight

1	2	3	4	5	6	7	8
---	---	---	---	---	---	---	---



Now recursive sort “red” sub-array

Then, recursive sort “blue” sub-array

Recursive Insight

1	2	3	4	5	6	7	8
---	---	---	---	---	---	---	---

Everything is sorted!

```
void Quicksort(int arr[], int n)
{
    if (n < 2) return;

    int boundary = Partition(arr, n);

    // Sort subarray up to pivot
    Quicksort(arr, boundary);

    // Sort subarray after pivot to end
    Quicksort(arr + boundary + 1, n - boundary - 1);
}
```

“boundary” is the index of the pivot

Partition

Pivot

Before

5	3	7	4	8	6	2	1
---	---	---	---	---	---	---	---

After

2	3	1	4	5	6	8	7
---	---	---	---	---	---	---	---



Does one comparison between for every element in the array and the pivot.

Complexity of quicksort is determined by number of comparisons made to pivot

Complexity QuickSort

- QuickSort is $O(n \log n)$, where $n = \#$ elems to sort
 - But in “worst case” it can be $O(n^2)$
 - Worst case occurs when every time pivot is selected, it is maximal or minimal remaining element

Expected Running Time of QuickSort

- Let $X = \#$ comparisons made when sorting n elems
 - $E[X]$ gives us expected running time of algorithm
 - Given $V_1, V_2, \dots, V_n$ in random order to sort
 - Let $Y_1, Y_2, \dots, Y_n$ be $V_1, V_2, \dots, V_n$ in sorted order

When are Y_a and Y_b are compared?

Lets Imagine Our Array in Sorted Order

		Y_a		Y_b	
1	3	5	7	9	11
Y_1	Y_2	Y_3	Y_4	Y_5	Y_6

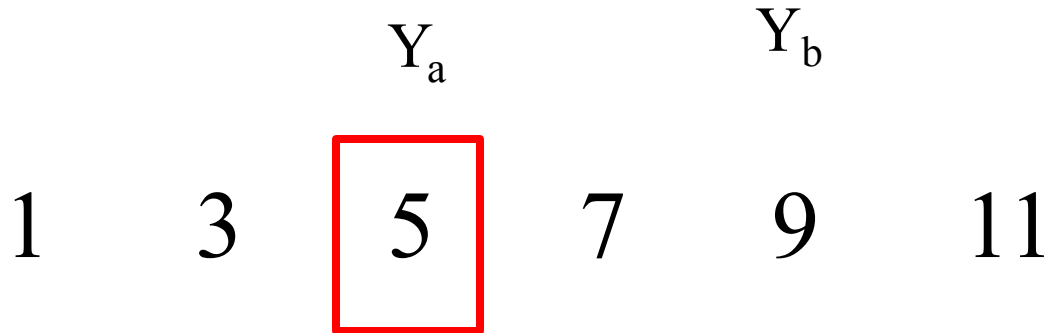
Whether or not they are compared
depends on pivot choice

Lets Imagine Our Array in Sorted Order

		Y_a		Y_b	
1	3	5	7	9	11

Whether or not they are compared
depends on pivot choice

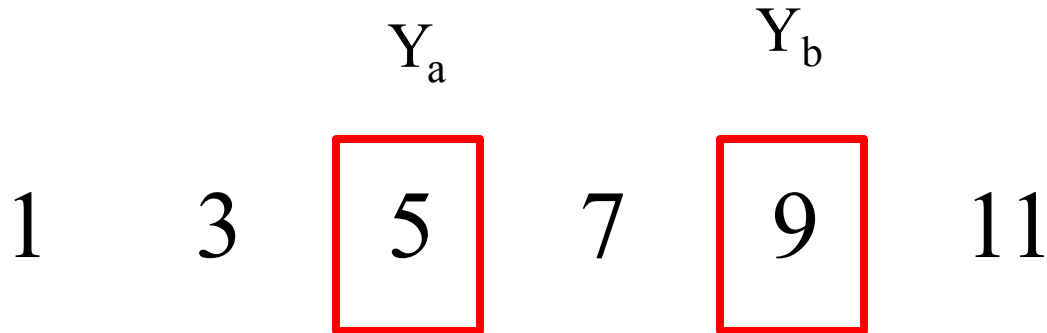
$P(Y_a \text{ and } Y_b \text{ ever compared})$



Consider pivot choice: Y_a

They are compared

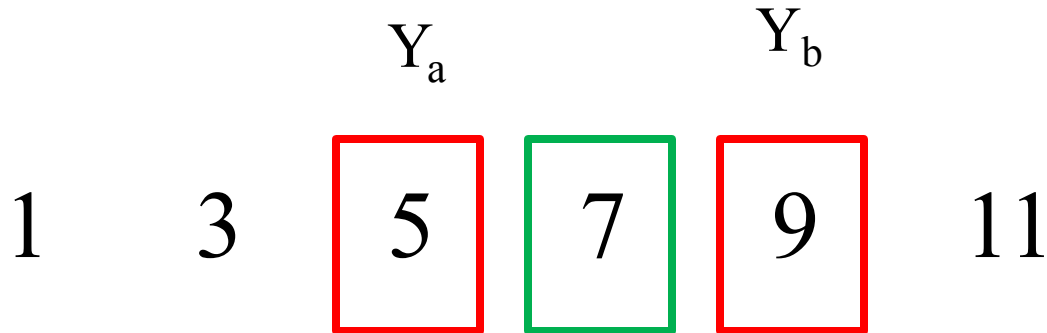
$P(Y_a \text{ and } Y_b \text{ ever compared})$



Consider pivot choice: Y_b

They are compared

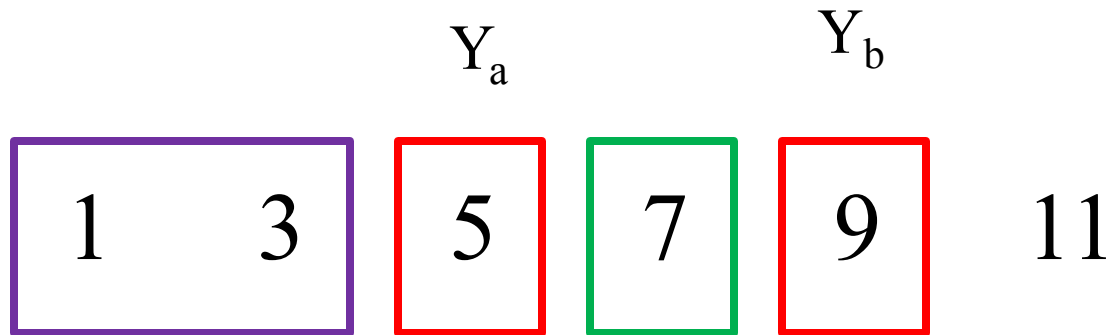
$P(Y_a \text{ and } Y_b \text{ ever compared})$



Consider pivot choice: 7

They are **not** compared

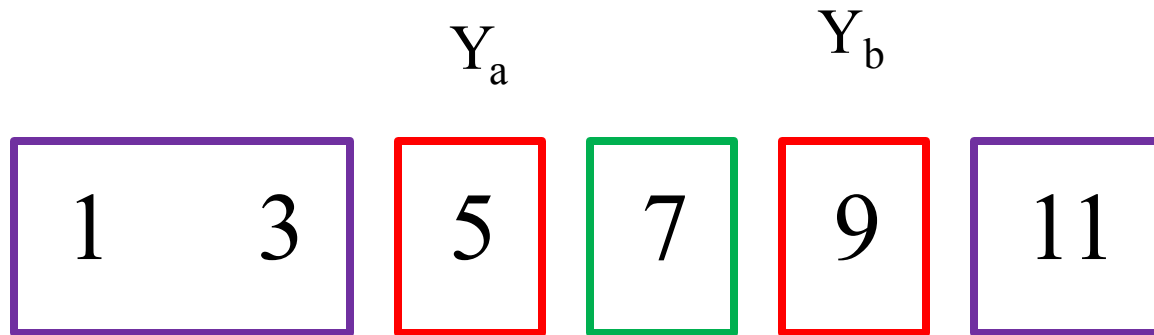
$P(Y_a \text{ and } Y_b \text{ ever compared})$



Consider pivot choice: $< Y_a$

Whether or not they are compared
depends on future pivots

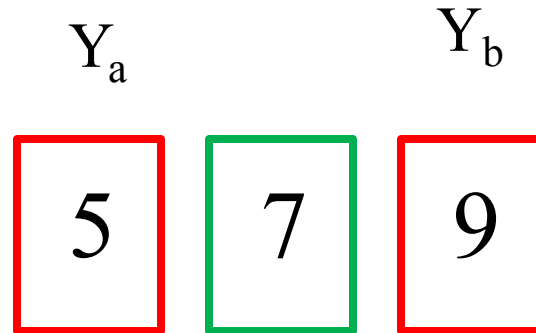
$P(Y_a \text{ and } Y_b \text{ ever compared})$



Consider pivot choice: $> Y_b$

Whether or not they are compared
depends on future pivots

$P(Y_a \text{ and } Y_b \text{ ever compared})$



Are Y_a and Y_b compared?

Keep repeating pivot choice until you get a pivot
In the range $[Y_a, Y_b]$ inclusive

Expected Running Time of QuickSort

- Let $X = \#$ comparisons made when sorting n elems
 - $E[X]$ gives us expected running time of algorithm
 - Given $V_1, V_2, \dots, V_n$ in random order to sort
 - Let $Y_1, Y_2, \dots, Y_n$ be $V_1, V_2, \dots, V_n$ in sorted order
 - Let $I_{a,b} = 1$ if Y_a and Y_b are compared, 0 otherwise
 - Order where $Y_b > Y_a$, so we have:
$$X = \sum_{a=1}^{n-1} \sum_{b=a+1}^n I_{a,b}$$

Expected Running Time of QuickSort

Aside:
$$X = \sum_{a=1}^{n-1} \sum_{b=a+1}^n I_{a,b}$$

When $a = 1$ $I_{1,2} + I_{1,3} + \dots + I_{1,n}$

When $a = 2$ $+ I_{2,3} + \dots + I_{2,n}$

When $a = n-1$ $+ I_{n-1,n}$

Contains a comparison between each i and j
(where i does not equal j)
exactly once

Expected Running Time of QuickSort

- Let $X = \#$ comparisons made when sorting n elems
 - $E[X]$ gives us expected running time of algorithm
 - Given $V_1, V_2, \dots, V_n$ in random order to sort
 - Let $Y_1, Y_2, \dots, Y_n$ be $V_1, V_2, \dots, V_n$ in sorted order
 - Let $I_{a,b} = 1$ if Y_a and Y_b are compared, 0 otherwise
 - Order where $Y_b > Y_a$, so we have: $X = \sum_{a=1}^{n-1} \sum_{b=a+1}^n I_{a,b}$

$$E[X] = E\left[\sum_{a=1}^{n-1} \sum_{b=a+1}^n I_{a,b}\right] = \sum_{a=1}^{n-1} \sum_{b=a+1}^n E[I_{a,b}] = \sum_{a=1}^{n-1} \sum_{b=a+1}^n P(Y_a \text{ and } Y_b \text{ ever compared})$$

P(Y_a and Y_b ever compared)

- Consider when Y_a and Y_b are directly compared
 - We only care about case where pivot chosen from set:
 $\{Y_a, Y_{a+1}, Y_{a+2}, \dots, Y_b\}$
 - From that set either Y_a and Y_b must be selected as pivot (with equal probability) in order to be compared
 - So,

$$P(Y_a \text{ and } Y_b \text{ ever compared}) = \frac{2}{b-a+1}$$

$$E[X] = \sum_{a=1}^{n-1} \sum_{b=a+1}^n P(Y_a \text{ and } Y_b \text{ ever compared}) = \sum_{a=1}^{n-1} \sum_{b=a+1}^n \frac{2}{b-a+1}$$

Bring it on Home (i.e. Solve the Sum)

$$E[X] = \sum_{a=1}^{n-1} \sum_{b=a+1}^n \frac{2}{b-a+1}$$
$$\sum_{b=a+1}^n \frac{2}{b-a+1} \approx \int_{a+1}^n \frac{2}{b-a+1} db$$

Recall: $\int \frac{1}{x} dx = \ln(x)$

Thanks
Riemann

$$= 2 \ln(b-a+1) \Big|_{a+1}^n = 2 \ln(n-a+1) - 2 \ln(2)$$

$$\approx 2 \ln(n-a+1) \text{ for large } n$$

$$E[X] \approx \sum_{a=1}^{n-1} 2 \ln(n-a+1) \approx 2 \int_{a=1}^{n-1} \ln(n-a+1) da$$

Let $y = n-a+1$

$$= -2 \int_{y=n}^2 \ln(y) dy$$

$$= -2(y \ln(y) - y) \Big|_n^2$$

Recall:

$$\int \ln(x) dx = x \ln(x) - x$$

$$= -2[(2 \ln(2) - 2) - (n \ln(n) - n)] \approx 2n \ln(n) - 2n = O(n \log n)$$

Ahhh 😊