CMPT 210: Probability and Computing

Lecture 10

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Recap

Conditional probability: $\Pr[E|F] = \frac{\Pr[E \cap F]}{\Pr[F]}$.

Multiplication Rule: For events $E_1, E_2, \ldots, E_n$,
$\Pr[E_1 \cap E_2 \ldots \cap E_n] = \Pr[E_1] \Pr[E_2|E_1] \Pr[E_3|E_1 \cap E_2] \ldots \Pr[E_n|E_1 \cap E_2 \cap \ldots E_{n-1}]$.

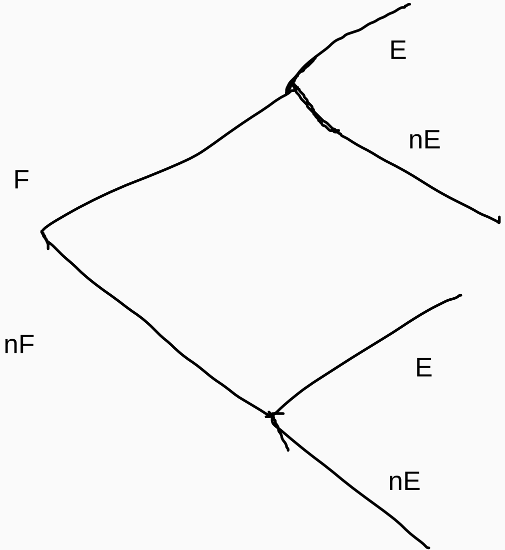
Conditional probability for complement events: For events E, F, $\Pr[E^c|F] = 1 - \Pr[E|F]$.

Bayes Rule: For events E and F if $\Pr[E] \neq 0$ and $\Pr[F] \neq 0$, then, $\Pr[F|E] = \frac{\Pr[E|F]\Pr[F]}{\Pr[E]}$.

Can calculate probability of past event given current information
or calculate probability of current event given past information

Law of Total Probability and Bayes rule

Law of Total Probability: For events E and F, $\Pr[E] = \Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c]$.



Law of Total Probability and Bayes rule

Law of Total Probability: For events E and F, $\Pr[E] = \Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c]$.

Proof:

Disjoint

$$E = (E \cap F) \cup (E \cap F^c)$$

$$\implies \Pr[E] = \Pr[(E \cap F) \cup (E \cap F^c)] = \Pr[E \cap F] + \Pr[E \cap F^c] \quad \text{(By union-rule for disjoint events)}$$

$$\Pr[E] = \Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c] \quad \text{(By definition of conditional probability)}$$

Uses law of conditional probability to get the equivalency for E INTS F

Law of Total Probability and Bayes rule

Law of Total Probability: For events E and F, $\Pr[E] = \Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c]$.
Proof:

$$E = (E \cap F) \cup (E \cap F^c)$$

$$\implies \Pr[E] = \Pr[(E \cap F) \cup (E \cap F^c)] = \Pr[E \cap F] + \Pr[E \cap F^c]$$

(By union-rule for disjoint events)

$$\Pr[E] = \Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c]$$ (By definition of conditional probability)

Combining Bayes rule and Law of total probability

Definition of conditional probability   Bayes rule

$$\Pr[F|E] = \frac{\Pr[F \cap E]}{\Pr[E]} = \frac{\Pr[E|F]\ \Pr[F]}{\Pr[E]}$$ (By definition of conditional probability)

$$\Pr[F|E] = \frac{\Pr[E|F]\ \Pr[F]}{\Pr[E|F]\Pr[F] + \Pr[E|F^c]\Pr[F^c]}$$ (By law of total probability)

You use law of total probability
in order to split apart E

Total Probability - Examples

Guessing implies random selection

Q: In answering a question on a multiple-choice test, a student either knows the answer or she guesses. Let p be the probability that she knows the answer and $1 - p$ the probability that she guesses. Assume that a student who guesses at the answer will be correct with probability $\frac{1}{m}$, where m is the number of multiple-choice alternatives. What is the conditional probability that a student knew the answer to a question given that she answered it correctly?

Let K be the event the student they know the answer.
Let C be the event that the student answered the question correctly.

Pr(K|C) = ?
pr(K | C) = Pr(K INTS C)/Pr(C)

P(K | C) = (P(C | K) * Pr(K))/Pr(C)
P(K | C) = p / (p + (1-p)/m)

Pr(C) = Pr(C|K)Pr(K) + Pr(C|nK)Pr(nK)
= p + (1-p)/m

Total Probability - Examples

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Let C be the event that the student answers the question correctly. Let K be the event that the student knows the answer. We wish to compute $\Pr[K|C]$.

We know that $\Pr[K] = p$ and $\Pr[C|K^c] = 1/m$, $\Pr[C|K] = 1$. Hence,
$\Pr[C] = \Pr[C|K]\Pr[K] + \Pr[C|K^c]\Pr[K^c] = (1)(p) + \frac{1}{m}(1-p)$.
$\Pr[K|C] = \frac{\Pr[C|K]\ \Pr[K]}{\Pr[C]} = \frac{mp}{1+(m-1)p}$.

Total Probability - Examples

Q: An insurance company believes that people can be divided into two classes — those that are accident prone and those that are not. Their statistics show that an accident-prone person will have an accident at some time within a fixed 1-year period with probability 0.4, whereas this probability decreases to 0.2 for a non-accident-prone person. If we assume that 30% of the population is accident prone, what is the probability that a new policy holder will have an accident within a year of purchasing a policy?

Let A be the event that a person is accident prone.
Let AC be the event that a policy holder has an accident

Calculate Pr(AC)?

Pr(AC) = Pr(AC | A)Pr(A) +Pr(AC| nA)Pr(nA)
Pr(AC) = 0.4 * 0.3 + 0.2 * 0.7

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Let A = event that a new policy holder will have an accident within a year of purchasing a policy. Let B = event that the new policy holder is accident prone. We know that $\Pr[B] = 0.3$, $\Pr[A|B] = 0.4$, $\Pr[A|B^c] = 0.2$. By the law of total probability,
$\Pr[A] = \Pr[A|B]\Pr[B] + \Pr[A|B^c]\Pr[B^c] = (0.4)(0.3) + (0.2)(0.7) = 0.26.$

Total Probability - Examples

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Q: Suppose that a new policy holder has an accident within a year of purchasing their policy. What is the probability that they are accident prone?

Pr(A | AC) = ?Pr(A | AC) = Pr(A INTS

Total Probability - Examples

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Q: Suppose that a new policy holder has an accident within a year of purchasing their policy. What is the probability that they are accident prone?

Compute $\Pr[B|A] = \frac{\Pr[A|B]\ \Pr[B]}{\Pr[A]} = \frac{0.12}{0.26} = 0.4615$.

Total Probability - Examples

Q: Alice is taking a probability class and at the end of each week she can be either up-to-date or she may have fallen behind. If she is up-to-date in a given week, the probability that she will be up-to-date (or behind) in the next week is 0.8 (or 0.2, respectively). If she is behind in a given week, the probability that she will be up-to-date (or behind) in the next week is 0.6 (or 0.4, respectively). Alice is (by default) up-to-date when she starts the class. What is the probability that she is up-to-date after three weeks?

Pr(U_2lB_1) = 0.6
Pr(B_2lB_1) = 0.4
Pr(U_3}B_2) = 0.6

Let U_i be the event Alice is up to date after i weeks
Let B_i be the event Alice is behind after i weeks
Pr(U_3) = ?

Pr(U_2lU_1) = 0.8
Pr(B_2lU_1) = 0.2

P(U_1) = 0.8 since we started off being up to date
Pr(B_1) = 0.2
Pr(U_2) = Pr(U_2lU_1)Pr(U_1) + Pr(U_2lB_1)Pr(B_1)

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Let U_i and B_i be the events that Alice is up-to-date or behind respectively after i weeks. Since Alice starts the class up-to-date, $\Pr[U_1] = 0.8$ and $\Pr[B_1] = 0.2$. We also know that $\Pr[U_2|U_1] = 0.8$, $\Pr[U_3|U_2] = 0.8$ and $\Pr[B_2|U_1] = 0.2$, $\Pr[B_3|U_2] = 0.2$. Similarly, $\Pr[U_2|B_1] = 0.6$, $\Pr[U_3|B_2] = 0.6$ and $\Pr[B_2|B_1] = 0.4$, $\Pr[B_3|B_2] = 0.4$.

Total Probability - Examples

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We wish to compute $\Pr[U_3]$. By the law of total probability,
$\Pr[U_3] = \Pr[U_3|U_2]\Pr[U_2] + \Pr[U_3|B_2]\Pr[B_2]$ and
$\Pr[U_2] = \Pr[U_2|U_1]\Pr[U_1] + \Pr[U_2|B_1]\Pr[B_1]$.

If you wanted to do this for ten weeks, then you would need to use induction

Hence, $\Pr[U_2] = (0.8)(0.8) + (0.6)(0.2) = 0.76$, and $\Pr[U_3] = (0.8)(0.76) + (0.6)(0.24) = 0.752$.

Simpson's Paradox

In 1973, there was a lawsuit against a university with the claim that a male candidate is more likely to be admitted to the university than a female.

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Let us consider a simplified case – there are two departments, EE and CS, and men and women apply to the program of their choice. Let us define the following events: A is the event that the candidate is admitted to the program of their choice, F_E is the event that the candidate is a woman applying to EE, F_C is the event that the candidate is a woman applying to CS. Similarly, we can define M_E and M_C. Assumption: Candidates are either men or women, and that no candidate is allowed to be part of both EE and CS.

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Lawsuit claim: Male candidate is more likely to be admitted to the university than a female i.e. $\Pr[A|M_E \cup M_C] > \Pr[A|F_E \cup F_C]$.

University response: In any given department, a male applicant is less likely to be admitted than a female i.e. $\Pr[A|F_E] > \Pr[A|M_E]$ and $\Pr[A|F_C] > \Pr[A|M_C]$.

Simpson's Paradox

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Paradoxical since we expect Pr(A I ME U MC) = Pr(A I ME) + Pr(AIMC)

When you only look on the right hand side, the union bound rule does not apply

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Lawsuit claim: Male candidate is more likely to be admitted to the university than a female i.e. $\Pr[A|M_E \cup M_C] > \Pr[A|F_E \cup F_C]$.

Pr(A U B I F) = Pr(AIF) + Pr(BIF)

University response: In any given department, a male applicant is less likely to be admitted than a female i.e. $\Pr[A|F_E] > \Pr[A|M_E]$ and $\Pr[A|F_C] > \Pr[A|M_C]$.

Simpson's Paradox: Both the above statements can be simultaneously true.

Simpson's Paradox

CS	2 men admitted out of 5 candidates	40%
	50 women admitted out of 100 candidates	50%
EE	70 men admitted out of 100 candidates	70%
	4 women admitted out of 5 candidates	80%
Overall	72 men admitted, 105 candidates	$\approx$ 69%
	54 women admitted, 105 candidates	$\approx$ 51%

Pr(AIMC) = 0.4
Pr(A IFC) = 0.5
Pr(A I ME) = 0.7
Pr(A IFE) = 0.8

In the above example, $\Pr[A|F_E] = 0.8 > 0.7 = \Pr[A|M_E]$ and $\Pr[A|F_C] = 0.5 > 0.4 = \Pr[A|M_C]$. $\Pr[A|F_E \cup F_C] \approx 0.51$. Similarly, $\Pr[A|M_E \cup M_C] \approx 0.69$.

CS acceptance: 52/105
EE: 74/105

The trend reverses since CS is harder to get into.
Since CS is competitive

Simpson's Paradox

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In general, Simpson's Paradox occurs when multiple small groups of data all exhibit a similar trend, but that trend reverses when those groups are aggregated.

Questions?

Back to throwing dice - Independent Events

Q: Suppose we throw two standard dice one after the other. What is the probability that we get two 6's in a row?

Old method: S = {(a, b), a, b in {1, 2, 3, 4 ,5, 6}}

E is the event we get a six in the first throw

F is the event we get a 6 in the second throw

Pr(E INTS F) = Pr(F lE)Pr(E)

Pr(F l E) = 1/6 = Pr(E)

1/36

Back to throwing dice - Independent Events

Q: Suppose we throw two standard dice one after the other. What is the probability that we get two 6's in a row?

E = We get a 6 in the second throw. F = We get a 6 in the first throw. $E \cap F$ = we get two 6's in a row. We are computing $\Pr[E \cap F]$. $\Pr[E] = \Pr[F] = \frac{1}{6}$.

$\Pr[E|F] = \frac{\Pr[E \cap F]}{\Pr[F]} \implies \Pr[E \cap F] = \Pr[E|F] \Pr[F]$.

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$\Pr[E|F] = \frac{\Pr[E \cap F]}{\Pr[F]} \implies \Pr[E \cap F] = \Pr[E|F] \Pr[F]$.

Since the two dice are *independent*, knowing that we got a 6 in the first throw does not change the probability that we will get a 6 in the second throw. Hence, $\Pr[E|F] = \Pr[E]$ (conditioning does not change the probability of the event).

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$\Pr[E|F] = \frac{\Pr[E \cap F]}{\Pr[F]} \implies \Pr[E \cap F] = \Pr[E|F]\,\Pr[F]$.

Since the two dice are *independent*, knowing that we got a 6 in the first throw does not change the probability that we will get a 6 in the second throw. Hence, $\Pr[E|F] = \Pr[E]$ (conditioning does not change the probability of the event).

Hence, $\Pr[E \cap F] = \Pr[E|F]\,\Pr[F] = \Pr[E]\,\Pr[F] = \frac{1}{6}\,\frac{1}{6} = \frac{1}{36}$.

Independent Events

Independent Events: Events E and F are said to be independent, if knowledge that F has occurred does not change the probability that E occurs. Formally,

$$\Pr[E|F] = \Pr[E] \quad ; \quad \Pr[E \cap F] = \Pr[E] \Pr[F]$$

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Q: I toss two independent, fair coins. What is the probability that I get the HT sequence?

Helps you decompose the probability of events occurring so
you can take the product of multiple probabilities

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Define E to be the event that I get a heads in the first toss, and F be the event that I get a tails in the second toss. Since the two coins are independent, events E and F are also independent. $\Pr[E \cap F] = \Pr[E] \Pr[F] = \frac{1}{2} \frac{1}{2} = \frac{1}{4}$.

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Knowing that something is prime changes your knowledge of the numbers available.

Q: I randomly choose a number from $\{1, 2, \ldots, 10\}$. E is the event that the number I picked is a prime. F is the event that the number I picked is odd. Are E and F independent?

Pr(E) = 2/5, Pr(F) = 1/2, Pr(E INTS F) = 3/4

Pr(E)Pr(F) != Pr(E INTS F)

Pr(E|F) = 3/5

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Q: I randomly choose a number from $\{1, 2, \ldots, 10\}$. E is the event that the number I picked is a prime. F is the event that the number I picked is odd. Are E and F independent?

$\Pr[E] = \frac{2}{5}$, $\Pr[F] = \frac{1}{2}$, $\Pr[E \cap F] = \frac{3}{10}$. $\Pr[E \cap F] \neq \Pr[E]\,\Pr[F]$. Another way: $\Pr[E|F] = \frac{3}{5}$ and $\Pr[E] = \frac{2}{5}$, and hence $\Pr[E|F] \neq \Pr[E]$. Conditioning on F tell us that prime number cannot be 2, so it changes the probability of E.

Independent Events - Example

Q: We have a machine that has 2 independent components. The machine breaks if *each* of its 2 components break. Suppose each component can break with probability p, what is the probability that the machine does not break?

Union: check if events are mutually exclusive
Intersection: check if events are independent

Independent Events - Example

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Let E_1 = Event that the first component breaks, E_2 = Event that the second component breaks. M = Event that the machine breaks = $E_1 \cap E_2$.

Independent Events - Example

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Parallel connection: works even if one fails

Let E_1 = Event that the first component breaks, E_2 = Event that the second component breaks. M = Event that the machine breaks = $E_1 \cap E_2$.

$\Pr[M] = \Pr[E_1 \cap E_2]$. Since the two components are independent, E_1 and E_2 are independent, meaning that $Pr[E_1 \cap E_2] = Pr[E_1] \Pr[E_2] = p^2$.

Probability that the machine does not break = $\Pr[M^c] = 1 - \Pr[M] = 1 - p^2$.

Independent Events - Examples

Q: We have a new machine that has 2 independent components. The machine breaks if *either* of its 2 components break. Suppose each component can break with probability p, what is the probability that the machine breaks?

For this machine, let M' be the event that it breaks. In this case, $\Pr[M'] = \Pr[E_1 \cup E_2]$.

E1 and E2 being independent does not imply that they are mutually exclusive

Independent Events - Examples

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Incorrect: By the union rule for mutually exclusive events, $\Pr[E_1 \cup E_2] = \Pr[E_1] + \Pr[E_2] = 2p$.

Independent Events - Examples

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Series connection: connection breaks if either component breaks.

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Incorrect: By the union rule for mutually exclusive events, $\Pr[E_1 \cup E_2] = \Pr[E_1] + \Pr[E_2] = 2p$.

Mistake: *Independence does not imply mutual exclusivity* and we can not use the union rule. Independence implies that for any two events E and F, $\Pr[E \cap F] = \Pr[E]\Pr[F]$, while mutual exclusivity requires that $\Pr[E \cap F] = 0$.

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For this machine, let M' be the event that it breaks. In this case, $\Pr[M'] = \Pr[E_1 \cup E_2]$.

Incorrect: By the union rule for mutually exclusive events, $\Pr[E_1 \cup E_2] = \Pr[E_1] + \Pr[E_2] = 2p$.

Mistake: *Independence does not imply mutual exclusivity* and we can not use the union rule. Independence implies that for any two events E and F, $\Pr[E \cap F] = \Pr[E]\Pr[F]$, while mutual exclusivity requires that $\Pr[E \cap F] = 0$.

Correct way:

$$\begin{aligned}
\Pr[E_1 \cup E_2] &= \Pr[E_1] + \Pr[E_2] - \Pr[E_1 \cap E_2] && \text{(By the inclusion-exclusion rule)} \\
&= \Pr[E_1] + \Pr[E_2] - \Pr[E_1]\Pr[E_2] = 2p - p^2 && \text{(Since } E_1 \text{ and } E_2 \text{ are independent.)}
\end{aligned}$$

Questions?

Matrix Multiplication

Given two $n \times n$ matrices – A and B, if $C = AB$, then,

$$C_{i,j} = \sum_{k=1}^{n} A_{i,k} B_{k,j}$$

Hence, in the worst case, computing $C_{i,j}$ is an $O(n)$ operation. There are n^2 entries to fill in C and hence, in the absence of additional structure, matrix multiplication takes $O(n^3)$ time.

Multiplying a row by a column is O(N)

With every entry in C, it takes O(n) time to compute an entry.

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There are non-trivial algorithms for doing matrix multiplication more efficiently:

- (Strassen, 1969) Requires $O(n^{2.81})$ operations.
- (Coppersmith-Winograd, 1987) Requires $O(n^{2.376})$ operations.
- (Alman-Williams, 2020) Requires $O(n^{2.373})$ operations.
- Belief is that it can be done in time $O(n^{2+\epsilon})$ for $\epsilon > 0$.

Verifying Matrix Multiplication

As an example, let us focus on A, B being binary 2×2 matrices.

Example: $A = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ then $C = AB = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$

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Frievald's Algorithm: Randomized algorithm to verify matrix multiplication with high probability in $O(n^2)$ time.

Improvement over n^3

with high probability: not always guaranteed to verify it correctly, but it will do it the majority of the time.

(Basic) Frievald's Algorithm

Q: For $n \times n$ matrices A, B and D, is $D = AB$?

Algorithm:

1. Generate a random n-bit vector x, by making each bit x_i either 0 or 1 *independently* with probability $\frac{1}{2}$. E.g, for $n = 2$, toss a fair coin independently twice with the scheme – H is 0 and T is 1). If we get HT, then set $x = [0\,;\,1]$.

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Computational complexity: Step 1 can be done in $O(n)$ time. Step 2 requires 3 matrix vector multiplications and can be done in $O(n^2)$ time. Step 3 requires comparing two n-dimensional vectors and can be done in $O(n)$ time. Hence, the total computational complexity is $O(n^2)$.

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Let us run the algorithm on an example. Suppose we have generated $x = [1\,;\,0]$

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In this case, $y = z$ and the algorithm will incorrectly output "yes" even though $D \neq AB$.

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Q: Suppose we have generated $x = [0\,;\,1]$. What is y and z?

In this case again, $y = z$ and the algorithm will correctly output "yes".

(Basic) Frievald's Algorithm

Let us analyze the algorithm for general matrix multiplication.

Case (i): If $D = AB$, does the algorithm always output "yes"?

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Claim: For any input matrices A, B, D if $D \neq AB$, then the (Basic) Frievald's algorithm will output "no" with probability $\geq \frac{1}{2}$.

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Claim: For any input matrices A, B, D if $D \neq AB$, then the (Basic) Frievald's algorithm will output "no" with probability $\geq \frac{1}{2}$.

	Yes	No
$D = AB$	1	0
$D \neq AB$	$< \frac{1}{2}$	$\geq \frac{1}{2}$

Table 1: Probabilities for Basic Frievalds Algorithm

(Basic) Frievald's Algorithm

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&= \Pr[(r_1 = 0) \cap (r_2 = 0) \cap \ldots \cap (r_i = 0) \cap \ldots]
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To complete the proof, on the next slide, we will prove that $\Pr[r_i = 0] \leq \frac{1}{2}$.

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$$r_i = \sum_{k=1}^{n} E_{i,k} x_k = E_{i,j} x_j + \sum_{k \neq j} E_{i,k} x_k = E_{i,j} x_j + \omega \qquad (\omega := \textstyle\sum_{k \neq j} E_{i,k} x_k)$$

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$(\Pr[E^c] = 1 - \Pr[E])$

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Hence, if $D \neq AB$, the Algorithm outputs "yes" with probability $\leq \frac{1}{2} \implies$ the Algorithm outputs "no" with probability $\geq \frac{1}{2}$.

In the worst case, the algorithm can be incorrect half the time! We promised the algorithm would return the correct answer with "high" probability close to 1.

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A common trick in randomized algorithms is to have m independent trials of an algorithm and aggregate the answer in some way, reducing the probability of error, thus *amplifying the probability of success*.

Questions?