



Conditional Probability

Statistical Inference

Brian Caffo, Jeff Leek, Roger Peng
Johns Hopkins Bloomberg School of Public Health

Conditional probability, motivation

- The probability of getting a one when rolling a (standard) die is usually assumed to be one sixth
- Suppose you were given the extra information that the die roll was an odd number (hence 1, 3 or 5)
- conditional on this new information, the probability of a one is now one third

Conditional probability, definition

- Let B be an event so that $P(B) > 0$
- Then the conditional probability of an event A given that B has occurred is

$$P(A | B) = \frac{P(A \cap B)}{P(B)}$$

- Notice that if A and B are independent, then

$$P(A | B) = \frac{P(A)P(B)}{P(B)} = P(A)$$

Example

- Consider our die roll example
- $B = \{1, 3, 5\}$
- $A = \{1\}$

$$\begin{aligned} P(\text{one given that roll is odd}) &= P(A \mid B) \\ &= \frac{P(A \cap B)}{P(B)} \\ &= \frac{P(A)}{P(B)} \\ &= \frac{1/6}{3/6} = \frac{1}{3} \end{aligned}$$

Bayes' rule

$$P(B | A) = \frac{P(A | B)P(B)}{P(A | B)P(B) + P(A | B^c)P(B^c)} .$$

because: $p(B|A) = p(B) \cap p(A) / p(A)$ (by definition, see page 3)

and $p(B) \cap p(A) = p(A|B) * p(B)$

and $p(A) = p(A \cap B) + p(A \cap !B)$ (where !B means B compliment)

which is $= p(A|B)*p(B) + p(A|!B)*p(!B)$ (again by definition, see page 3)

Diagnostic tests

- Let $+$ and $-$ be the events that the result of a diagnostic test is positive or negative respectively
- Let D and D^c be the event that the subject of the test has or does not have the disease respectively
- The **sensitivity** is the probability that the test is positive given that the subject actually has the disease, $P(+ \mid D)$
- The **specificity** is the probability that the test is negative given that the subject does not have the disease, $P(- \mid D^c)$

More definitions

- The **positive predictive value** is the probability that the subject has the disease given that the test is positive, $P(D \mid +)$
- The **negative predictive value** is the probability that the subject does not have the disease given that the test is negative, $P(D^c \mid -)$
- The **prevalence** of the disease is the marginal probability of disease, $P(D)$

More definitions

- The diagnostic likelihood ratio of a positive test, labeled DLR_+ , is $P(+ | D)/P(+ | D^c)$, which is the

$$sensitivity / (1 - specificity)$$

- The diagnostic likelihood ratio of a negative test, labeled DLR_- , is $P(- | D)/P(- | D^c)$, which is the

$$(1 - sensitivity) / specificity$$

Example

- A study comparing the efficacy of HIV tests, reports on an experiment which concluded that HIV antibody tests have a sensitivity of 99.7% and a specificity of 98.5%
- Suppose that a subject, from a population with a .1% prevalence of HIV, receives a positive test result. What is the probability that this subject has HIV?
- Mathematically, we want $P(D | +)$ given the sensitivity, $P(+ | D) = .997$, the specificity, $P(- | D^c) = .985$, and the prevalence $P(D) = .001$

Using Bayes' formula

$$\begin{aligned}P(D \mid +) &= \frac{P(+ \mid D)P(D)}{P(+ \mid D)P(D) + P(+ \mid D^c)P(D^c)} \\&= \frac{P(+ \mid D)P(D)}{P(+ \mid D)P(D) + \{1 - P(- \mid D^c)\}\{1 - P(D)\}} \\&= \frac{.997 \times .001}{.997 \times .001 + .015 \times .999} \\&= .062\end{aligned}$$

- In this population a positive test result only suggests a 6% probability that the subject has the disease
- (The positive predictive value is 6% for this test)

More on this example

- The low positive predictive value is due to low prevalence of disease and the somewhat modest specificity
- Suppose it was known that the subject was an intravenous drug user and routinely had intercourse with an HIV infected partner
- Notice that the evidence implied by a positive test result does not change because of the prevalence of disease in the subject's population, only our interpretation of that evidence changes

Likelihood ratios

- Using Bayes rule, we have

$$P(D \mid +) = \frac{P(+ \mid D)P(D)}{P(+ \mid D)P(D) + P(+ \mid D^c)P(D^c)}$$

and

$$P(D^c \mid +) = \frac{P(+ \mid D^c)P(D^c)}{P(+ \mid D)P(D) + P(+ \mid D^c)P(D^c)}.$$

$$p(!D|+) = 1 - p(D|+)$$

$$p(D|+) / p(!D|+) = \text{ODDS of disease given a positive test}$$

Likelihood ratios

- Therefore

$$\frac{P(D \mid +)}{P(D^c \mid +)} = \frac{P(+ \mid D)}{P(+ \mid D^c)} \times \frac{P(D)}{P(D^c)}$$

ie

$$\text{post-test odds of } D = DLR_+ \times \text{pre-test odds of } D$$

- Similarly, DLR_- relates the decrease in the odds of the disease after a negative test result to the odds of disease prior to the test.

HIV example revisited

- Suppose a subject has a positive HIV test
- $DLR_+ = .997 / (1 - .985) \approx 66$
- The result of the positive test is that the odds of disease is now 66 times the pretest odds
- Or, equivalently, the hypothesis of disease is 66 times more supported by the data than the hypothesis of no disease

HIV example revisited

- Suppose that a subject has a negative test result
- $DLR_- = (1 - .997)/.985 \approx .003$
- Therefore, the post-test odds of disease is now .3% of the pretest odds given the negative test.
- Or, the hypothesis of disease is supported .003 times that of the hypothesis of absence of disease given the negative test result