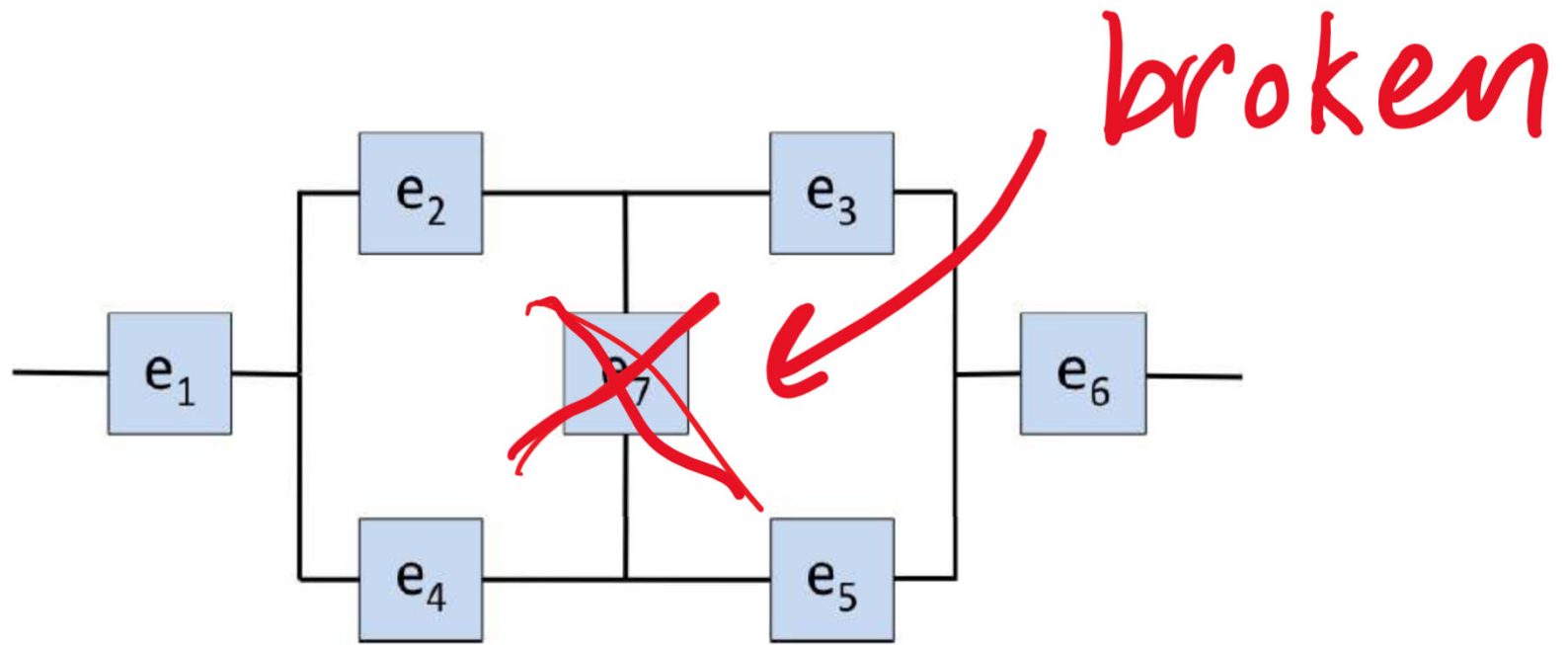


Component	$e_1$	$e_2$	$e_3$	$e_4$	$e_5$	$e_6$	$e_7$
Probability of component working	0.3	0.8	0.2	0.2	0.5	0.6	0.4

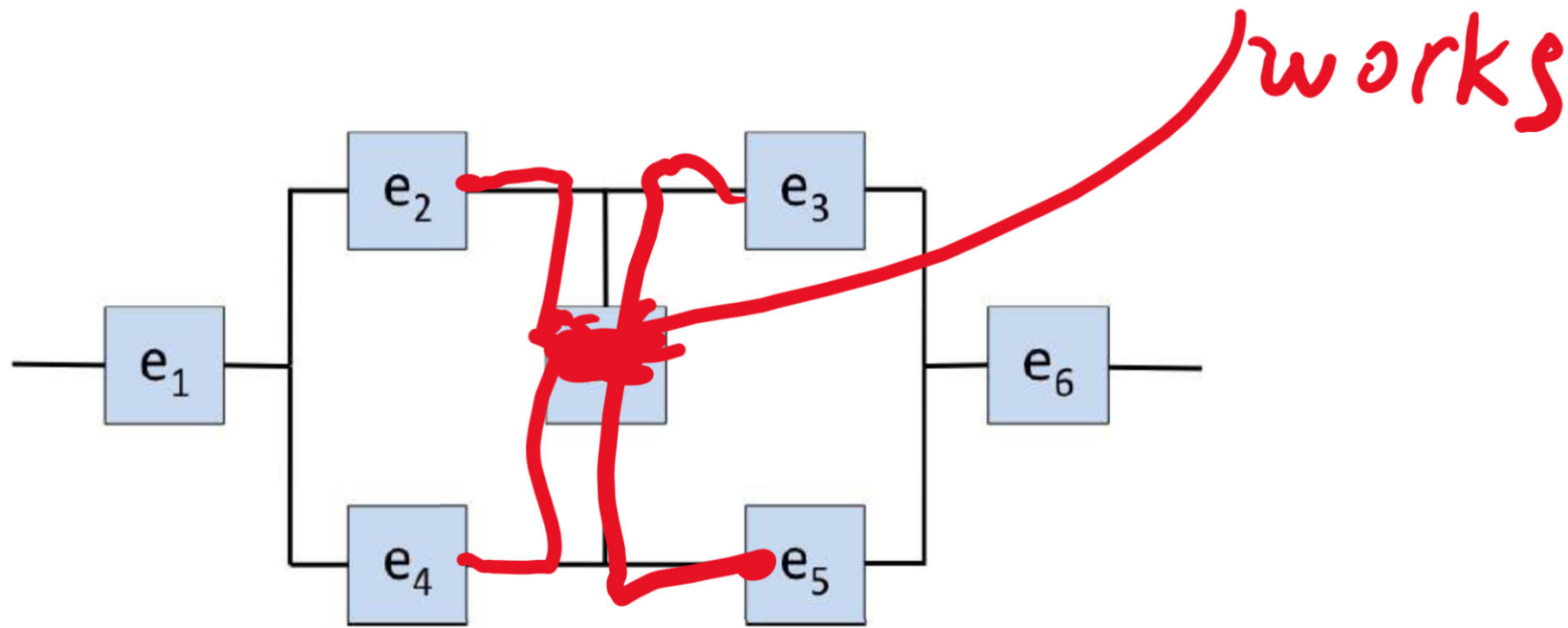


Component	$e_1$	$e_2$	$e_3$	$e_4$	$e_5$	$e_6$	$e_7$
Probability of component working	0.3	0.8	0.2	0.2	0.5	0.6	0.4

$$P(\text{circuit works} \mid e_7 \text{ is broken}) = P(e_1 \text{ works}) * [1 - (1 - P(e_2 \text{ works}) * P(e_3 \text{ works})) * (1 - P(e_4 \text{ works}) * P(e_5 \text{ works}))] * P(e_6 \text{ works}) = 0.3 * (1 - (1 - 0.8 * 0.2) * (1 - 0.2 * 0.5)) * 0.6 = 0.0439$$

The contribution to total probability:

$$P(\text{circuit works} \mid e_7 \text{ is broken}) * P(e_7 \text{ is broken}) = 0.6 * 0.0439 = 0.0264$$



Component	$e_1$	$e_2$	$e_3$	$e_4$	$e_5$	$e_6$	$e_7$
Probability of component working	0.3	0.8	0.2	0.2	0.5	0.6	0.4

$$P(\text{circuit works} \mid e_7 \text{ works}) = P(e_1 \text{ works}) \cdot$$

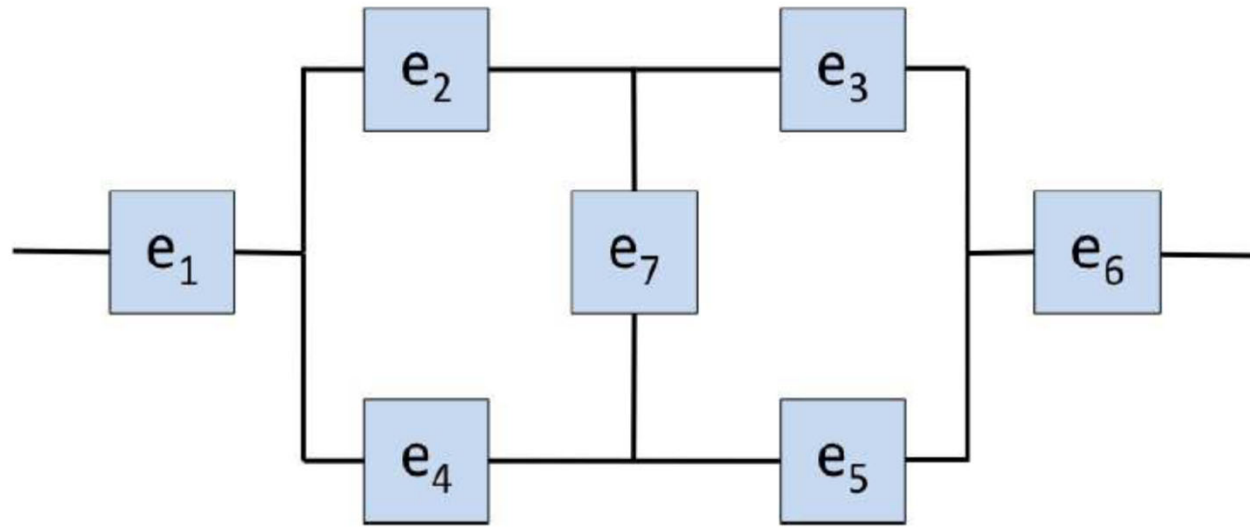
$$[1 - (1 - P(e_2 \text{ works})) \cdot (1 - P(e_3 \text{ works}))]$$

$$\cdot [1 - (1 - P(e_4 \text{ works})) \cdot (1 - P(e_5 \text{ works}))]$$

$$P(e_6 \text{ works}) = 0.3 \cdot (1 - (1 - 0.8) \cdot (1 - 0.2)) \cdot (1 - (1 - 0.2) \cdot (1 - 0.5)) \cdot 0.6 = 0.0907$$

The contribution to total probability:

$$P(\text{circuit works} \mid e_7 \text{ works}) \cdot P(e_7 \text{ works}) = 0.4 \cdot 0.0907 = 0.0363$$



Component	$e_1$	$e_2$	$e_3$	$e_4$	$e_5$	$e_6$	$e_7$
Probability of component working	0.3	0.8	0.2	0.2	0.5	0.6	0.4

$P(\text{circuit works}) =$

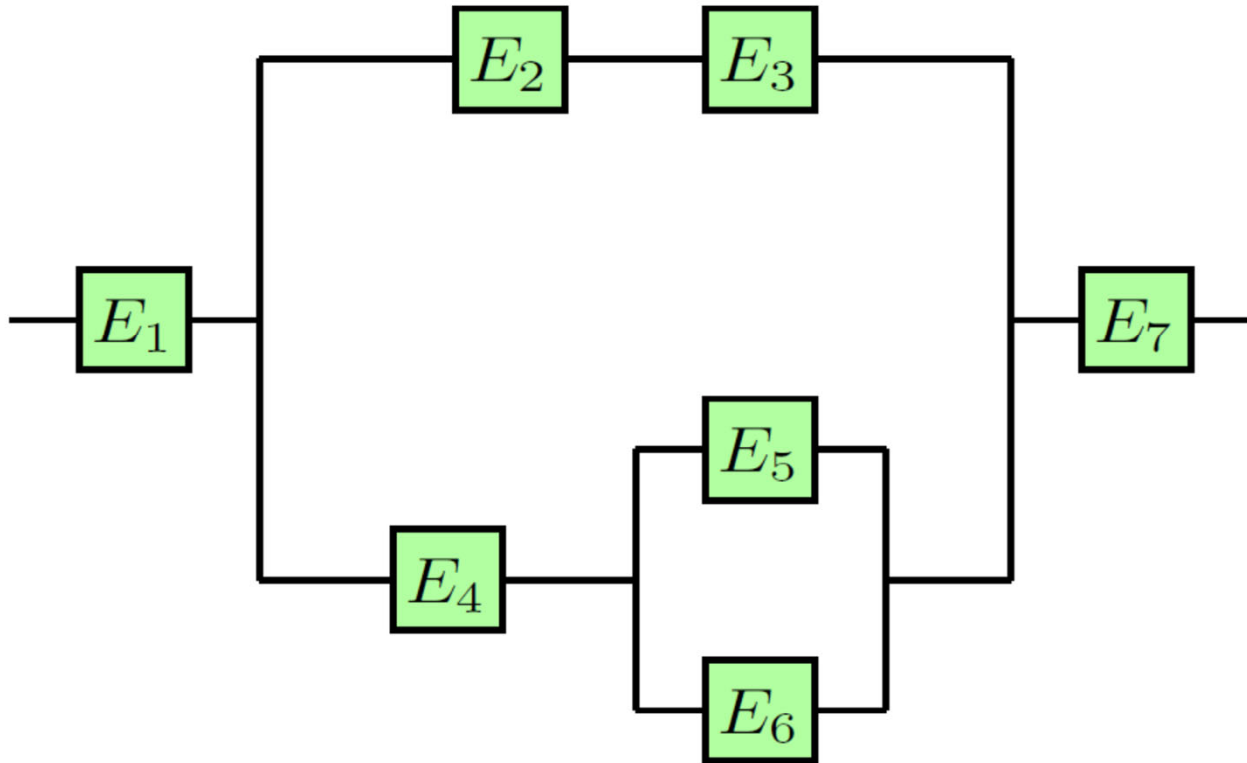
$P(\text{circuit works} \mid e_7 \text{ works}) * P(e_7 \text{ works}) +$

$P(\text{circuit works} \mid e_7 \text{ is broken}) * P(e_7 \text{ is broken}) =$

$= 0.0264 + 0.0363 = 0.0627$

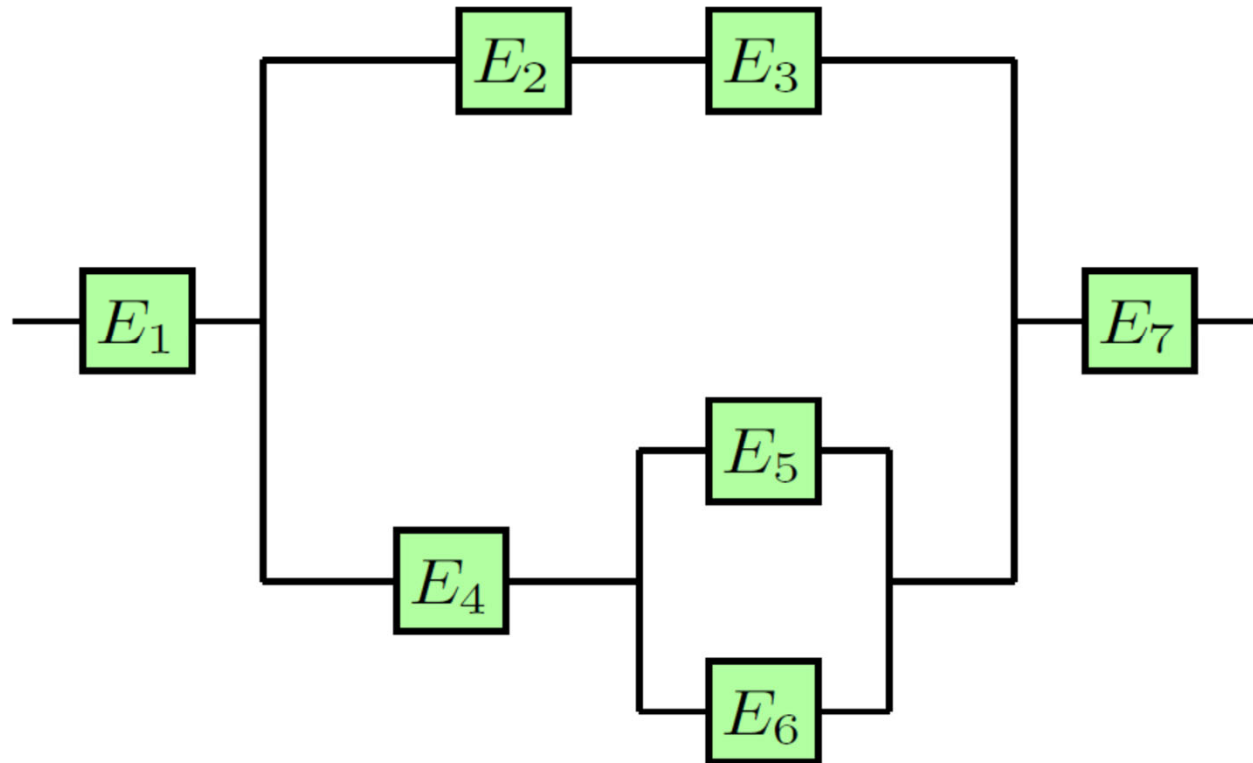
**Answer: 6.27%**

# Circuit $\rightarrow$ Set equation



Component	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
Probability of functioning well	0.9	0.5	0.3	0.1	0.4	0.5	0.8

# Circuit → Set equation

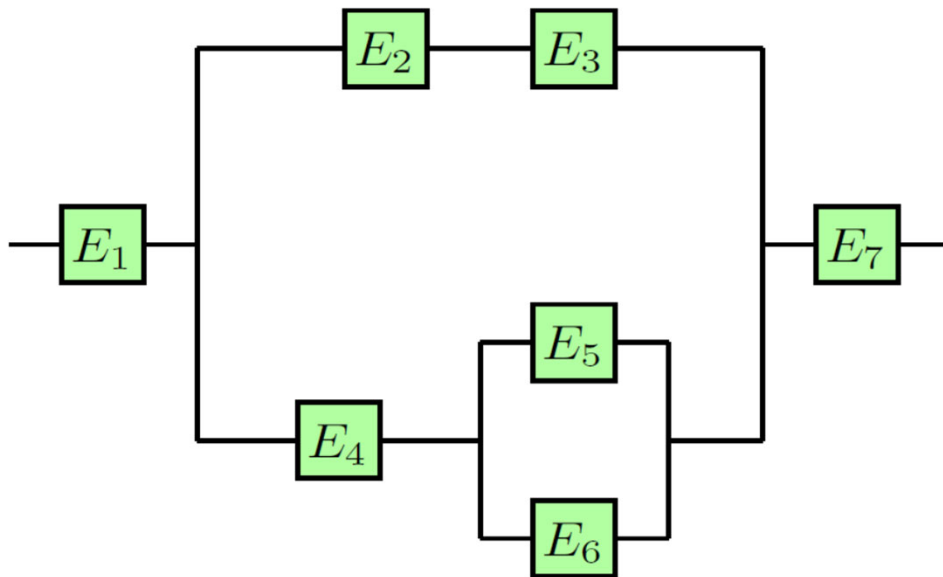


Component	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
Probability of functioning well	0.9	0.5	0.3	0.1	0.4	0.5	0.8

$$P(\text{Works}) = 0.9 \cdot (1 - (1 - 0.5 \cdot 0.3)) \cdot (1 - 0.1 \cdot (1 - 0.6 \cdot 0.5)) \cdot 0.8 = 0.15084$$

# Matlab group exercise

- Test our result for this circuit.
- Download `circuit_template.m` from the website



Component	$E_1$	$E_2$	$E_3$	$E_4$	$E_5$	$E_6$	$E_7$
Probability of functioning well	0.9	0.5	0.3	0.1	0.4	0.5	0.8

$$P(\text{Works}) = 0.9 \cdot (1 - (1 - 0.5 \cdot 0.3)) \cdot (1 - 0.1 \cdot (1 - 0.6 \cdot 0.5)) \cdot 0.8 = 0.15084$$

# Here is how I did it

- Stats=1e6;
- count= 0;
- for i = 1: Stats
- e1 = rand < 0.9; e2 = rand < 0.5; e3 = rand < 0.3;
- e4 = rand < 0.1; e5 = rand < 0.4; e6 = rand < 0.5;
- e7 = rand < 0.8;
- s1 = min(e2,e3); % or s1 = e2\*e3;
- s2 = max(e5,e6); % or s2= e5+e6>0;
- s3 = min(e4,s2); % or s3 = e4\*s2;
- s4 = max(s1,s3); % or s4 = s1+s3 > 0;
- s5= min([e1;s4;e7]); % or s5=e1\*s4\*e7;
- count = count + s5;
- End;
- P\_circuit\_works = count/Stats
- **% our calculation: P(circuit\_works)= 0.9.\*(1-(1-0.5.\*0.3)).\*(1-0.1.\*(1-0.6.\*0.5))).\*0.8==0.15084**



Credit: XKCD  
comics

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WHY ARE THERE DOORS ON THE FREEWAY  
WHY ARE THERE SO MANY SVCHOST.EXE RUNNING  
WHY AREN'T THERE ANY COUNTRIES IN ANTARCTICA  
WHY ARE THERE SCARY SOUNDS IN MINECRAFT  
WHY IS THERE KICKING IN MY STOMACH  
WHY ARE THERE TWO SLASHES AFTER HTTP  
WHY ARE THERE CELEBRITIES  
WHY DO SNAKES EXIST  
WHY DO OYSTERS HAVE PEARLS  
WHY ARE DUCKS CALLED DUCKS  
WHY DO THEY CALL IT THE CLAP  
WHY ARE KYLE AND CARTMAN FRIENDS  
WHY IS THERE AN ARROW ON AANG'S HEAD  
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WHY DO IGUANAS DIE  
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WHY AREN'T ECONOMISTS RICH  
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# WHY ARE THERE ANTS IN MY LAPTOP

WHY ARE THERE BRIDESMAIDS  
WHY DO DYING PEOPLE REACH UP  
WHY AREN'T THERE VARICOSE ARTERIES  
WHY ARE OLD KUNGONS DIFFERENT



WHY ARE THERE TINY SPIDERS IN MY HOUSE  
WHY DO SPIDERS COME INSIDE  
WHY ARE THERE HUGE SPIDERS IN MY HOUSE  
WHY ARE THERE LOTS OF SPIDERS IN MY HOUSE  
WHY ARE THERE SPIDERS IN MY ROOM  
WHY ARE THERE SO MANY SPIDERS IN MY ROOM  
WHY DO SPIDER BITES ITCH  
WHY IS DYING SO SCARY



WHY IS THERE AN OWL IN MY BACKYARD  
WHY IS THERE AN OWL OUTSIDE MY WINDOW  
WHY IS THERE AN OWL ON THE DOLLAR BILL  
WHY DO OWLS ATTACK PEOPLE  
WHY ARE AK 47s SO EXPENSIVE  
WHY ARE THERE HELICOPTERS CIRCLING MY HOUSE  
WHY ARE THERE GODS  
WHY ARE THERE TWO SPOCKS

WHY ARE DOGS AFRAID OF FIREWORKS  
WHY IS THERE NO KING IN ENGLAND

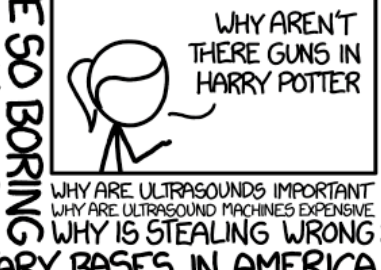
WHY IS PROGRAMMING SO HARD  
WHY IS THERE A 0 OHM RESISTOR  
WHY DO AMERICANS HATE SOCCER  
WHY DO RHYMES SOUND GOOD  
WHY DO TREES DIE  
WHY IS THERE NO SOUND ON CNN  
WHY AREN'T POKEMON REAL  
WHY AREN'T BULLETS SHARP  
WHY DO DREAMS SEEM SO REAL

WHY IS THERE NO GPS IN LAPTOPS  
WHY DO KNEES CLICK  
WHY AREN'T THERE E GRADES  
WHY IS ISOLATION BAD  
WHY DO BOYS LIKE ME  
WHY DON'T BOYS LIKE ME  
WHY IS THERE ALWAYS A JAVA UPDATE  
WHY ARE THERE RED DOTS ON MY THIGHS  
WHY IS LYING GOOD



WHY IS MT VESUVIUS THERE  
WHY DO THEY SAY T MINUS  
WHY ARE THERE OBELISKS  
WHY ARE WRESTLERS ALWAYS WET  
WHY ARE OCEANS BECOMING MORE ACIDIC  
WHY IS ARWEN DYING  
WHY AREN'T MY QUAIL LAYING EGGS  
WHY AREN'T MY QUAIL EGGS HATCHING  
WHY AREN'T THERE ANY FOREIGN MILITARY BASES IN AMERICA

WHY ARE CIGARETTES LEGAL  
WHY ARE THERE DUCKS IN MY POOL  
WHY IS JESUS WHITE  
WHY IS THERE LIQUID IN MY EAR  
WHY DO Q TIPS FEEL GOOD  
WHY DO GOOD PEOPLE DIE



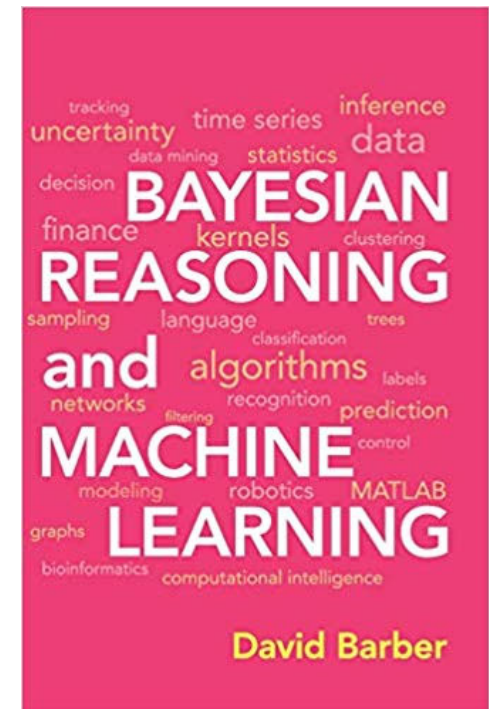
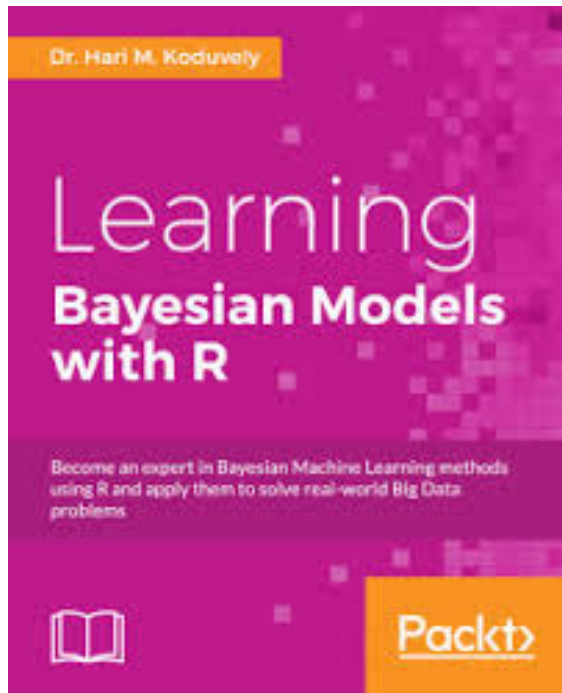
WHY IS LIFE SO BORING  
WHY ARE ULTRASOUNDS IMPORTANT  
WHY ARE ULTRASOUND MACHINES EXPENSIVE  
WHY IS STEALING WRONG

Reminder:  
Conditional probability

# Bayes Theorem



# Bayes' theorem



Thomas Bayes (1701-1761)

English statistician, philosopher, and Presbyterian minister

Bayes' theorem was presented in "An Essay towards solving a Problem in the Doctrine of Chances" which was read to the Royal Society in 1763 already after Bayes' death.

# Bayes' theorem (simple)

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

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

- In Science **we often want to know**:  
“**How much faith** should I put into **hypothesis, given the data?**”  
or  $P(H|D)$  (see also the inductive definition of probability)
- What **we usually can calculate** if the hypothesis/model is OK:  
“Assuming that this **hypothesis is true**, what is the **probability of the observed data?**” or  $P(D|H)$
- Bayes' theorem can help:  $P(H|D) = P(D|H) \cdot P(H) / P(D)$
- The problem is  $P(H)$  (so-called **prior**) is often **not known**

# Bayes' theorem (continued)

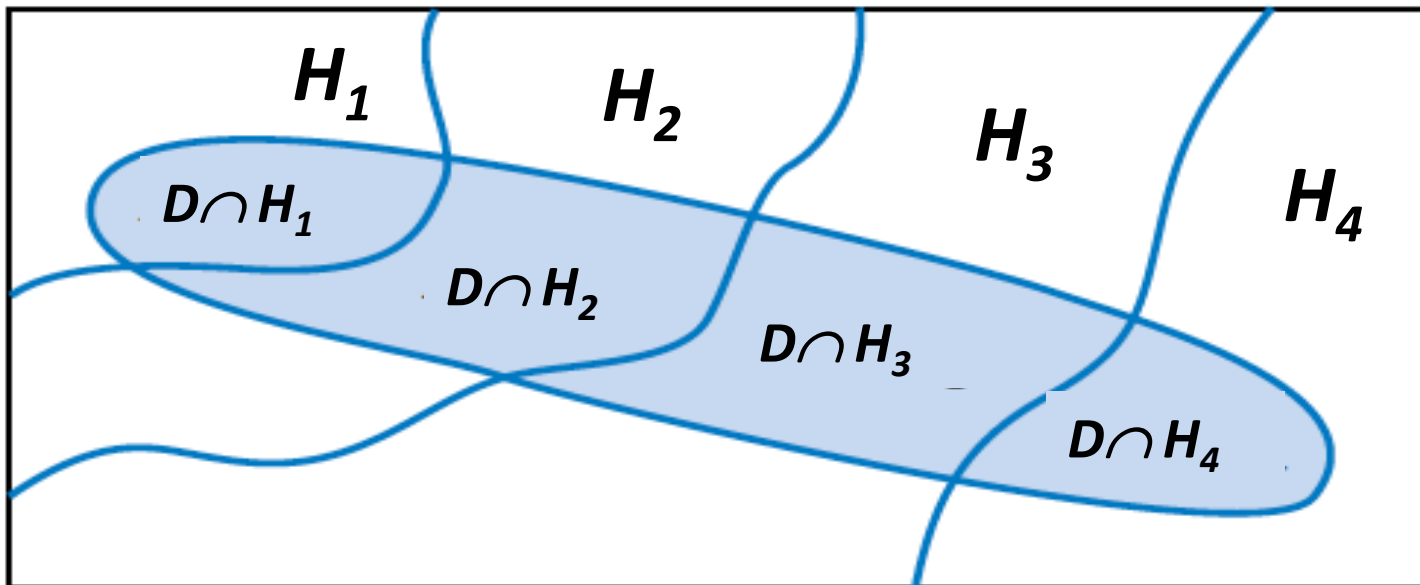
Works best with **exhaustive** and **mutually-exclusive** hypotheses:

$H_1, H_2, \dots, H_n$  such that  $H_1 \cup H_2 \cup H_3 \dots \cup H_n = S$  and  $H_i \cap H_j = \emptyset$  for  $i \neq j$

$$P(H_k|D) = P(D|H_k) \cdot P(H_k) / P(D)$$

where:

$$P(D) = P(D|H_1) \cdot P(H_1) + P(D|H_2) \cdot P(H_2) + \dots + P(D|H_n) \cdot P(H_n)$$



An awesome new test has been invented for an early detection of cancer. The probability that it **correctly identifies someone with cancer as positive is 95%**, and the probability that it **correctly identifies someone without cancer as negative is 99%**. The **incidence** of this type of cancer in the general population is  $10^{-4}$ . A random person in the population takes the test, and the result is positive.

What is the probability that he/she has cancer?

- A. 99%
- B. 95%
- C. 30%
- D. 1%

Get your i-clickers

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participants  
 $10^6$  ← 100 - cancer — 95 positive tests  
 $10^6 - 100 \approx 10^6$  no cancer

$10^6$  participants with no cancer → 10,000 positive tests

$$P(C|P) = \frac{95}{10,000 + 95} \approx 1\%$$



Events:  $C$  - cancer,  $C'$  - no cancer  
Test events  $P$  - positive,  $N$  - negative

We know:

$$P(C) = 10^{-4}, \quad P(P|C) = 0.95$$
$$P(N|C') = 0.99$$

We need

$$P(C|P)$$

Bayes:

$$P(C|P) = P(P|C) \cdot \frac{P(C)}{P(P)} ?$$



$P(P)$  - probability that a random person will test positive

$$\begin{aligned} P(P) &= P(P \cap C) + P(P \cap C') = \\ &= P(P|C)P(C) + P(P|C')P(C') = \\ &= 0.95 \times 10^{-4} + (1 - 0.99) \times (1 - 10^{-4}) \approx \\ &\approx 10^{-4} + 10^{-2} \approx 10^{-2} = 1\% \end{aligned}$$

$$P(C|P) = P(P|C) \cdot \frac{P(C)}{P(P)} = 0.95 \times \frac{10^{-4}}{10^{-2}} \approx 1\%$$

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What is the probability that he/she has cancer?

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A. 99%

B. 95%

C. 30%

D. 1%

Get your i-clickers





What if a doctor is already 50% sure of cancer based on other tests?

That changes things!

Now  $P(C) = P(C') = 0.5$

$$P(C|P) = \frac{P(P|C) \cdot P(C)}{P(P|C) \cdot P(C) + P(P|C') \cdot P(C')} =$$
$$= \frac{0.95 \times 0.5}{0.95 \times 0.5 + (1 - 0.99) \times 0.5} \approx 0.99$$

# How come?

I thought it was a great test..

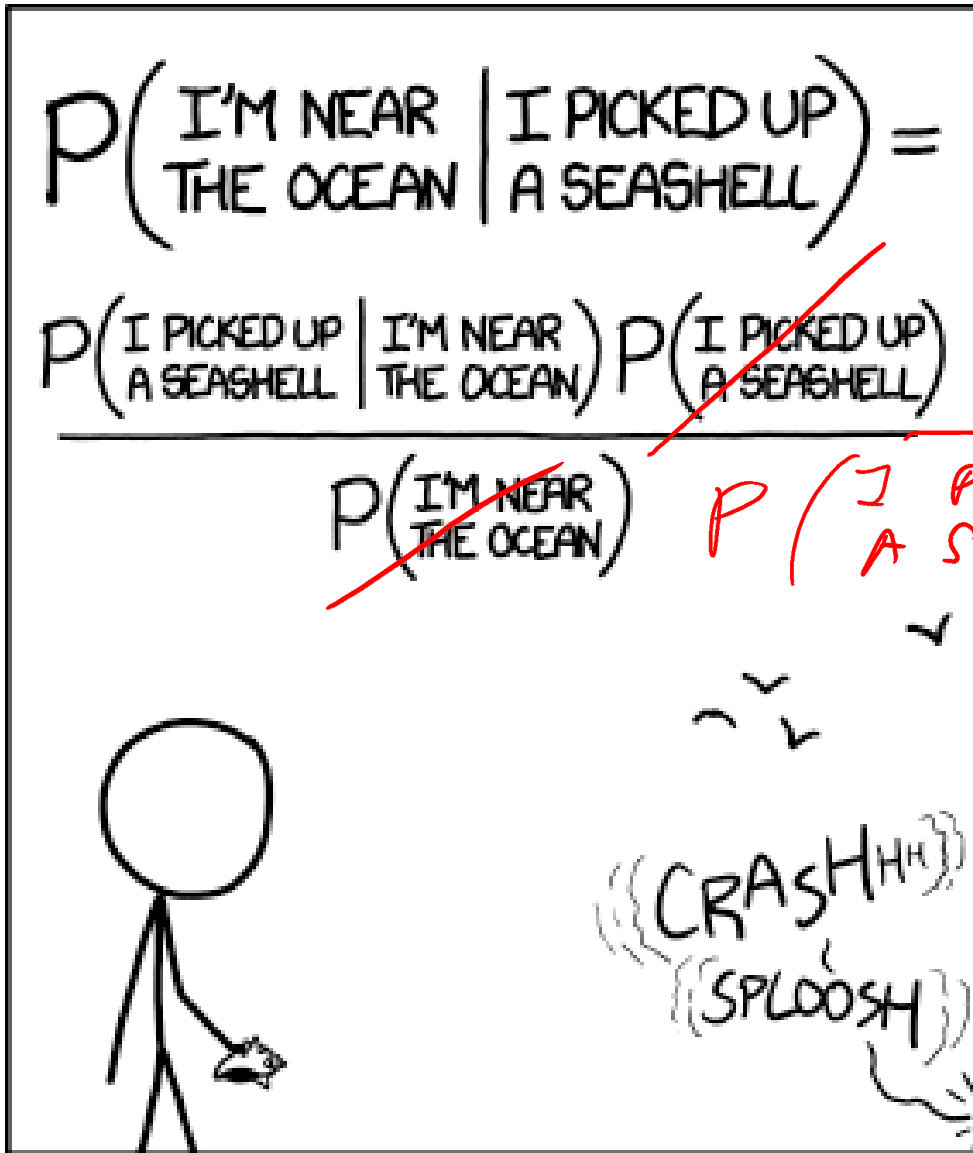
- Let  $C$  – be the event that the patient has cancer;  
 $C'$  – patient is cancer free
- $P/N$  – events that test is Positive/Negative  
( $N=Y'$ )
- We know:  $P(C)=10^{-4}$ ,  $P(P|C)=0.95$ ,  $P(N|C')=0.99$
- We need to find  $P(C|P)$
- Bayes to the rescue:  $P(C|P)=P(P|C)*P(C)/P(P)$
- What on earth is  $P(P)$  ???

# What on Earth is $P(P)$ ???

- Likelihood that a random patient would test Y:  
$$P(P) = P(P \cap C) + P(P \cap C') = P(P|C)P(C) + P(P|C')P(C') = 0.95 * 10^{-4} + (1 - 0.99) * (1 - 10^{-4}) \approx 0.01$$
- Hence  $P(C|P) = P(P|C) * P(C) / P(P) \approx 10^{-4} / 0.01 = 0.01 = 1\%$
- But we would like it to be 100%, please!!!
- Until the false positive discovery rate  $1 - P(N|C')$  does not fall below the general population prevalence the result will never be close 100%

# What if I am already 50% sure (based on other tests) that a patient has cancer?

- That changes everything!
- Now  $P(C)=P(C')=0.5$
- $P(C|P)=P(P|C)*P(C)/[P(P|C)*P(C)+P(P|C')*P(C')]=0.95*0.5/[0.95*0.5+(1-0.99)*0.5]=0.99$
- Now the doctor can be almost 100% sure.
- The importance of prior:
  - If prior belief that one has cancer is  $10^{-4}$  – test is useless
  - If prior belief is at least 1% - the test is useful



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

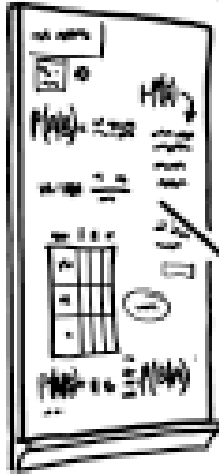
What is wrong in this comics?

$P(I'M NEAR THE OCEAN)$   
 $P(I PICKED UP A SEASHELL)$

If you are not yet reading XKCD comics <https://xkcd.com/> you should start

GIVEN THESE PREVALENCES,  
IS IT LIKELY THAT THE TEST  
RESULT IS A FALSE POSITIVE?

WELL, THIS CHAPTER IS ON  
BAYES' THEOREM, SO YES.



SOMETIMES, IF YOU UNDERSTAND  
BAYES' THEOREM WELL ENOUGH,  
YOU DON'T NEED IT.

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# Sensitivity/specificity of the standard test for prostate cancer: PSA level > 4.0ng/mL

- Sensitivity of the test is 71.9%
  - fraction of cancer patients who will test positive
  - False negative rate is 28.1%
- Specificity of the test is 90%
  - fraction of healthy patients who will test negative
  - False positive rate is 10%

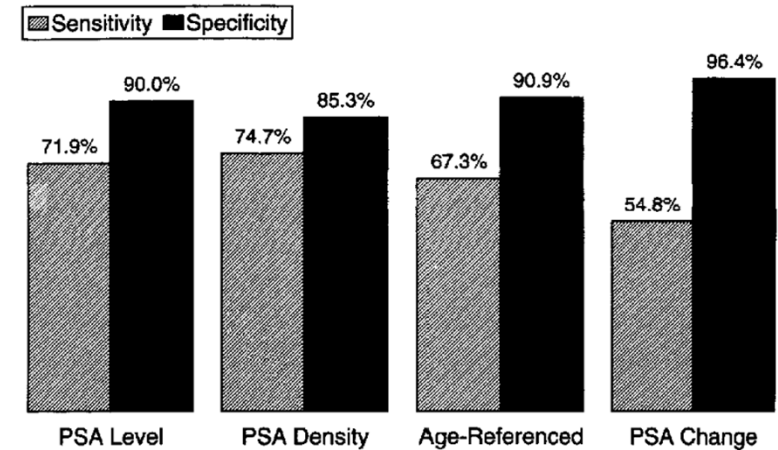


Figure 1. The relative sensitivity and specificity of different indexes of prostate specific antigen (PSA). Except for PSA change, sensitivity is the proportion of 171 known cancers cases for whom the index was positive and specificity is the proportion of 2011 men with normal transrectal ultrasound and digital rectal examinations not known to have prostate cancer who were negative on the index. The sensitivity and specificity of PSA change was evaluated in 84 men with prostate cancer and 1473 men without prostate cancer for on whom multiple PSA measures were available. A PSA level of 4.0 ng/ml or less was considered normal. A PSA density of 0.1 ng/ml per cubic centimeter of ultrasound-measured gland volume was considered normal. Age-referenced PSA was considered normal if it was 3.5 ng/ml or less in men aged 50–59, 4.5 ng/ml in men aged 60–69, and 6.5 ng/ml in men aged 70–79. PSA change was considered normal if the annual rate of PSA change was 0.75 ng/ml or less per year.



Prostate cancer is the most common type of cancer found in males. It is checked by PSA test that is notoriously unreliable. The probability that a noncancerous man will have an elevated PSA level  $>4.0$  ng/mL is approximately 0.1, with this probability increasing to approximately 0.719 if the man does have prostate cancer. If, based on other factors, a physician is 50 percent certain that a male has prostate cancer, what is the conditional probability that he has the cancer given that the test indicates an elevated PSA level?

A. 99.9%

B. 95%

C. 88%

D. 55%

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All this trouble for a lousy  
38% gain in confidence?  
I don't believe you!

- Let  $C$  – be the event that the patient has cancer;  
 $C'$  – patient is cancer free,  $E$  – events that the  
PSA test was elevated
- We know doctor's prior belief:  $P(C)=0.5$
- We know test stats:  $P(E | C)=0.719$ ,  $P(E | C')=0.1$
- We need to find  $P(C | E)=P(E | C)*P(C)/P(E)$
- $P(E)=P(E | C)*P(C)+P(E | C')*P(C')=$   
 $=0.719*0.5+0.1*0.5=0.41$
- $P(C | E)=0.5*0.719/0.41=0.88$  or 88%

Credit: XKCD  
comics

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WHY ARE THERE BRIDESMAIDS  
WHY DO DYING PEOPLE REACH UP  
WHY AREN'T THERE VARICOSE ARTERIES  
WHY ARE OLD KUNGONS DIFFERENT

WHY IS EARTH TILTED  
WHY IS SPACE BLACK  
WHY IS OUTER SPACE SO COLD  
WHY ARE THERE PYRAMIDS ON THE MOON  
WHY IS NASA SHUTTING DOWN



WHY IS THERE AN OWL IN MY BACKYARD  
WHY IS THERE AN OWL OUTSIDE MY WINDOW  
WHY IS THERE AN OWL ON THE DOLLAR BILL  
WHY DO OWLS ATTACK PEOPLE  
WHY ARE AK 47s SO EXPENSIVE  
WHY ARE THERE HELICOPTERS CIRCLING MY HOUSE  
WHY ARE THERE GODS  
WHY ARE THERE TWO SPOCKS

WHY ARE DOGS AFRAID OF FIREWORKS  
WHY IS THERE NO KING IN ENGLAND



WHY ARE THERE TINY SPIDERS IN MY HOUSE  
WHY DO SPIDERS COME INSIDE  
WHY ARE THERE HUGE SPIDERS IN MY HOUSE  
WHY ARE THERE LOTS OF SPIDERS IN MY HOUSE  
WHY ARE THERE SPIDERS IN MY ROOM  
WHY ARE THERE SO MANY SPIDERS IN MY ROOM  
WHY DO SPIDER BITES ITCH  
WHY IS DYING SO SCARY

WHY IS MT VESUVIUS THERE  
WHY DO THEY SAY T MINUS  
WHY ARE THERE OBELISKS  
WHY ARE WRESTLERS ALWAYS WET  
WHY ARE OCEANS BECOMING MORE ACIDIC  
WHY IS ARWEN DYING  
WHY AREN'T MY QUAIL LAYING EGGS  
WHY AREN'T MY QUAIL EGGS HATCHING  
WHY AREN'T THERE ANY FOREIGN MILITARY BASES IN AMERICA

WHY ARE CIGARETTES LEGAL  
WHY ARE THERE DUCKS IN MY POOL  
WHY IS JESUS WHITE  
WHY IS THERE LIQUID IN MY EAR  
WHY DO Q TIPS FEEL GOOD  
WHY DO GOOD PEOPLE DIE



WHY IS PROGRAMMING SO HARD  
WHY IS THERE A 0 OHM RESISTOR  
WHY DO AMERICANS HATE SOCCER  
WHY DO RHYMES SOUND GOOD  
WHY DO TREES DIE  
WHY IS THERE NO SOUND ON CNN  
WHY AREN'T POKEMON REAL  
WHY AREN'T BULLETS SHARP  
WHY DO DREAMS SEEM SO REAL

WHY IS THERE NO GPS IN LAPTOPS  
WHY DO KNEES CLICK  
WHY AREN'T THERE E GRADES  
WHY IS ISOLATION BAD  
WHY DO BOYS LIKE ME  
WHY DON'T BOYS LIKE ME  
WHY IS THERE ALWAYS A JAVA UPDATE  
WHY ARE THERE RED DOTS ON MY THIGHS  
WHY IS LYING GOOD



WHY IS GPS FREE