Scientific Method in Practice

Vincent Lepetit

université de BORDEAUX

Your Advisor and You

you are not a mere executant

you should not be on your own

- be independent and take initiative, but
- know when to ask for advice.

Meet your advisor often.

université de BORDEAUX

Meeting your Advisor

How it should **not** go:

- "it does not work"

université de BORDEAUX

Meeting your Advisor

How it **should** go:

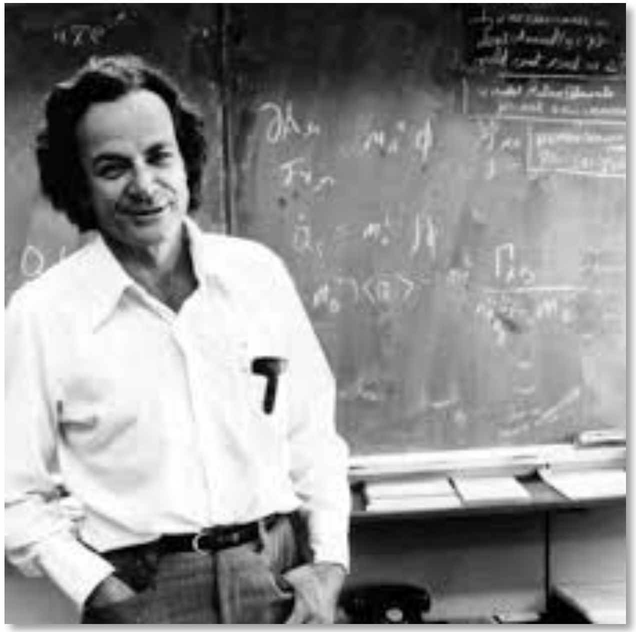
- "Last time we decided to…"
- "Here is what I did…"
- "It does not work."
- "Here is how I interpret the results…" / "what I did to understand the problem",

or *better*:

- "Here is what I propose to solve the problem" / "what I did to solve the problem"

université de BORDEAUX

Work Hard



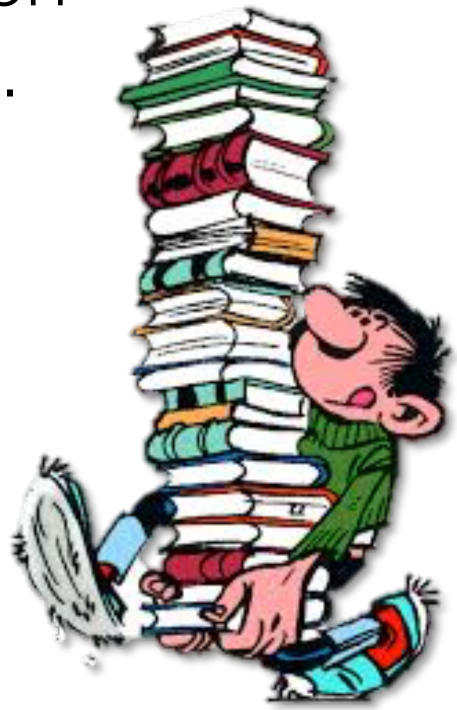
"I was a normal person who studied hard."
Richard Feyman (Nobel laureate in Physics).

université de BORDEAUX

Look for Related Work…

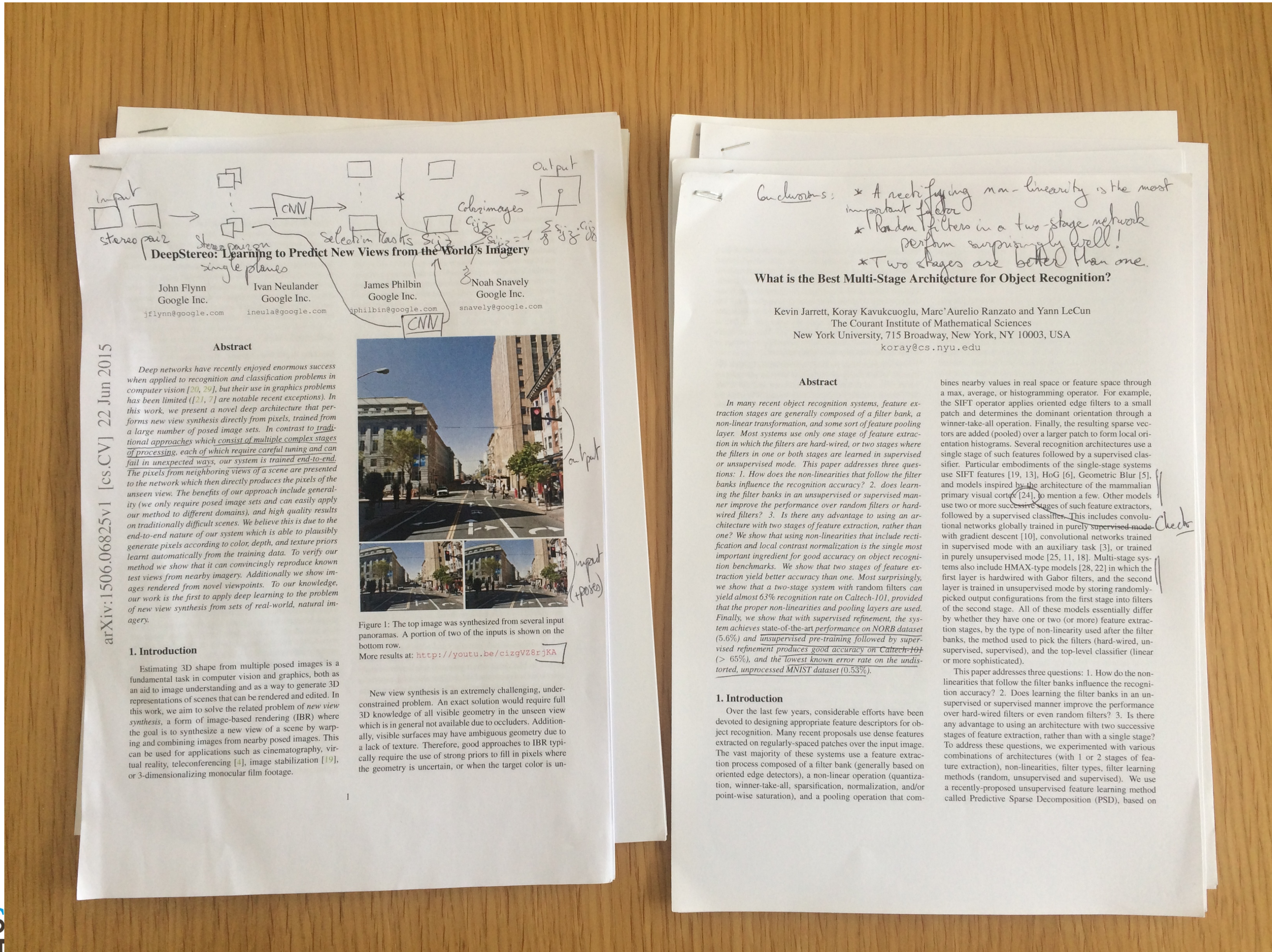
Smart people have probably worked on related problems, or a similar solution.

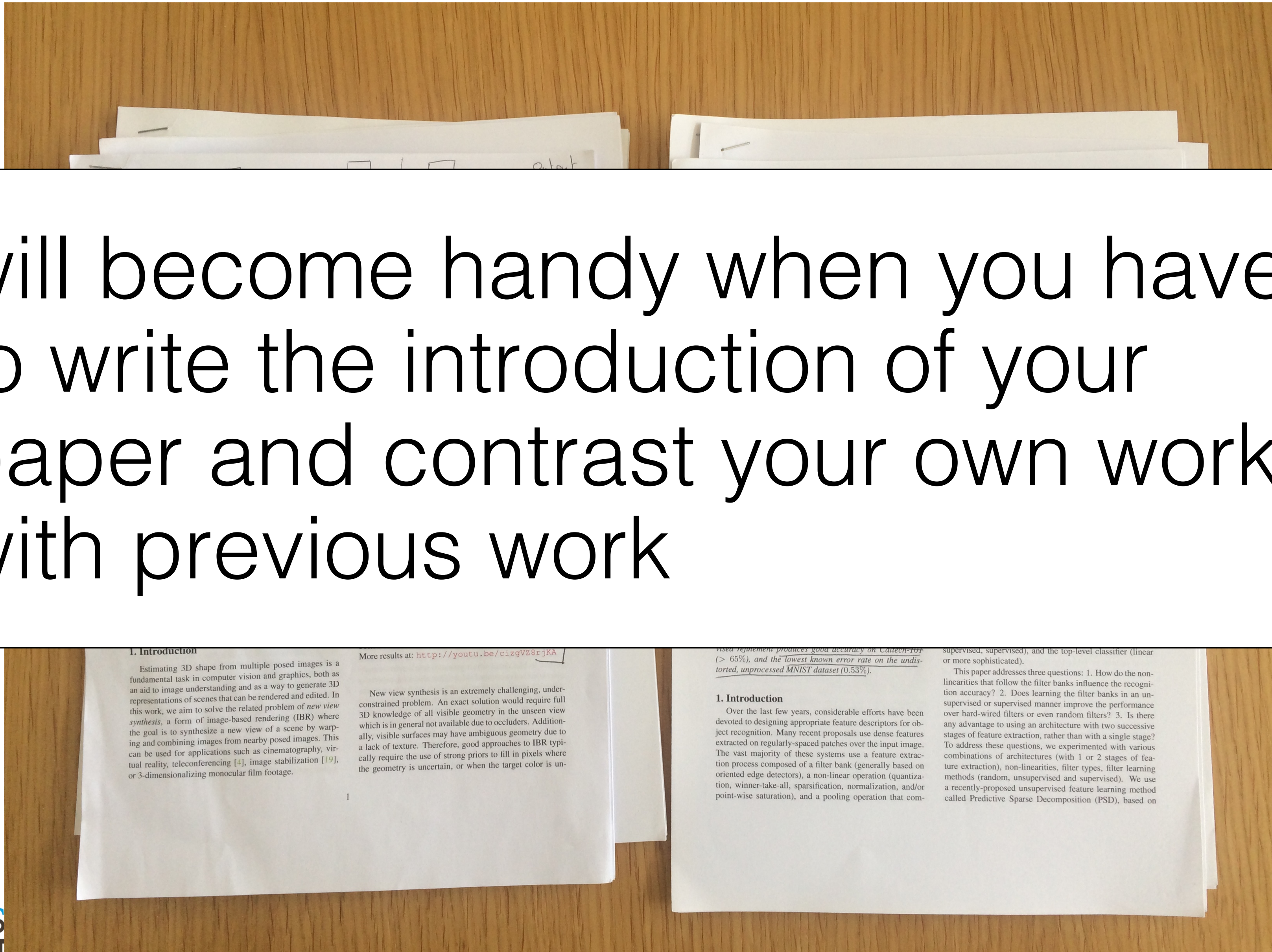
Focus on the main conferences and journals of the field.



université de BORDEAUX

…and Keep Track of It





will become handy when you have to write the introduction of your paper and contrast your own work with previous work

The Main Goal of your PhD

1. To develop good research;
2. *Communicate* about it so that other people can profit from it

Quality is more important than quantity

identify a problem
about current research

propose a solution

more difficult,
stronger impact

important in practice
(if the method is
actually useful)

improved method

existing method

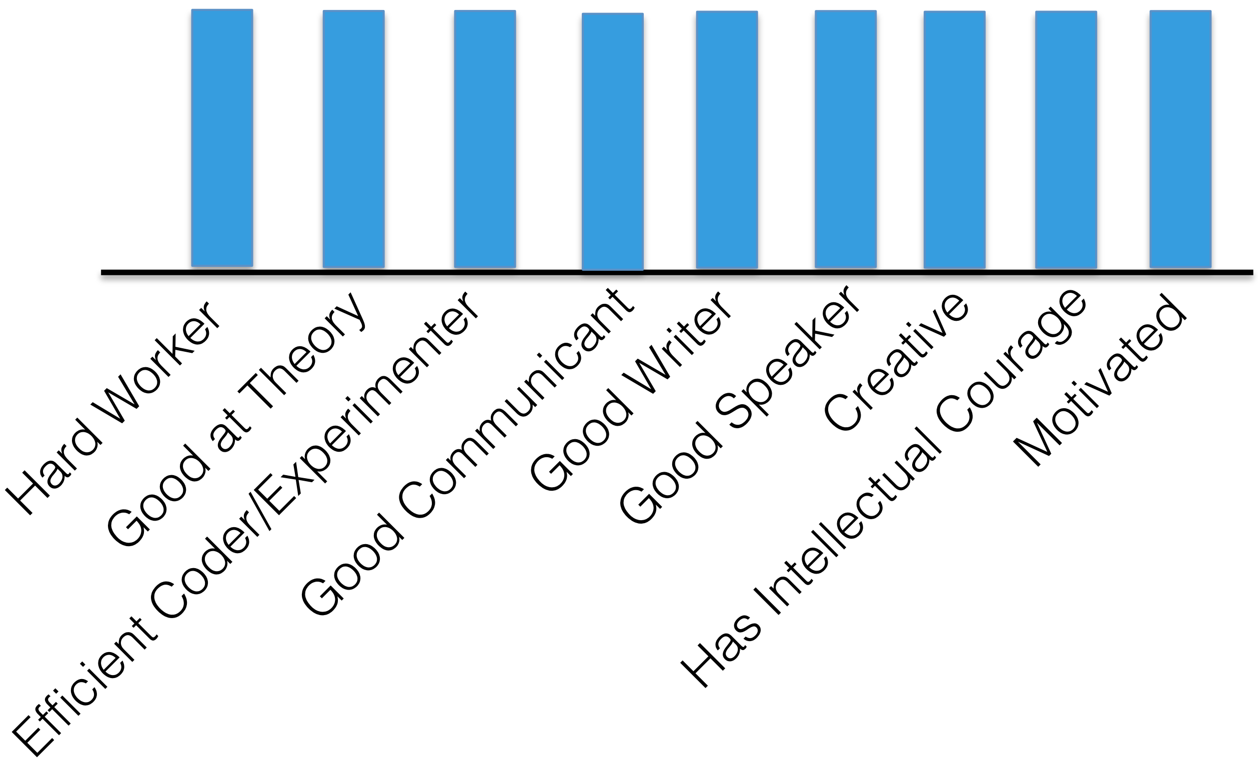
université
de BORDEAUX

Take Some Time to Read about Science

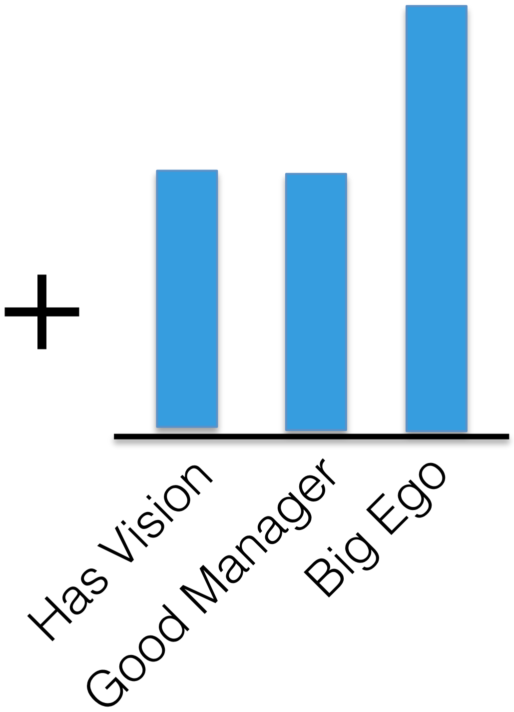
For example:

- *Richard Feynman*;
- The Evolution of *Physics by Albert Einstein and Leopold Infeld*;
- The Selfish Gene *by Richard Dawkins.*

In Summary



+



for a future academic position

"What is the Scientific Method? [..]

I very much doubt whether a methodology based on the intellectual practices of physicists and biologists would be of great use to sociologists" (Peter Medawar, Nobel laureate in medicine)

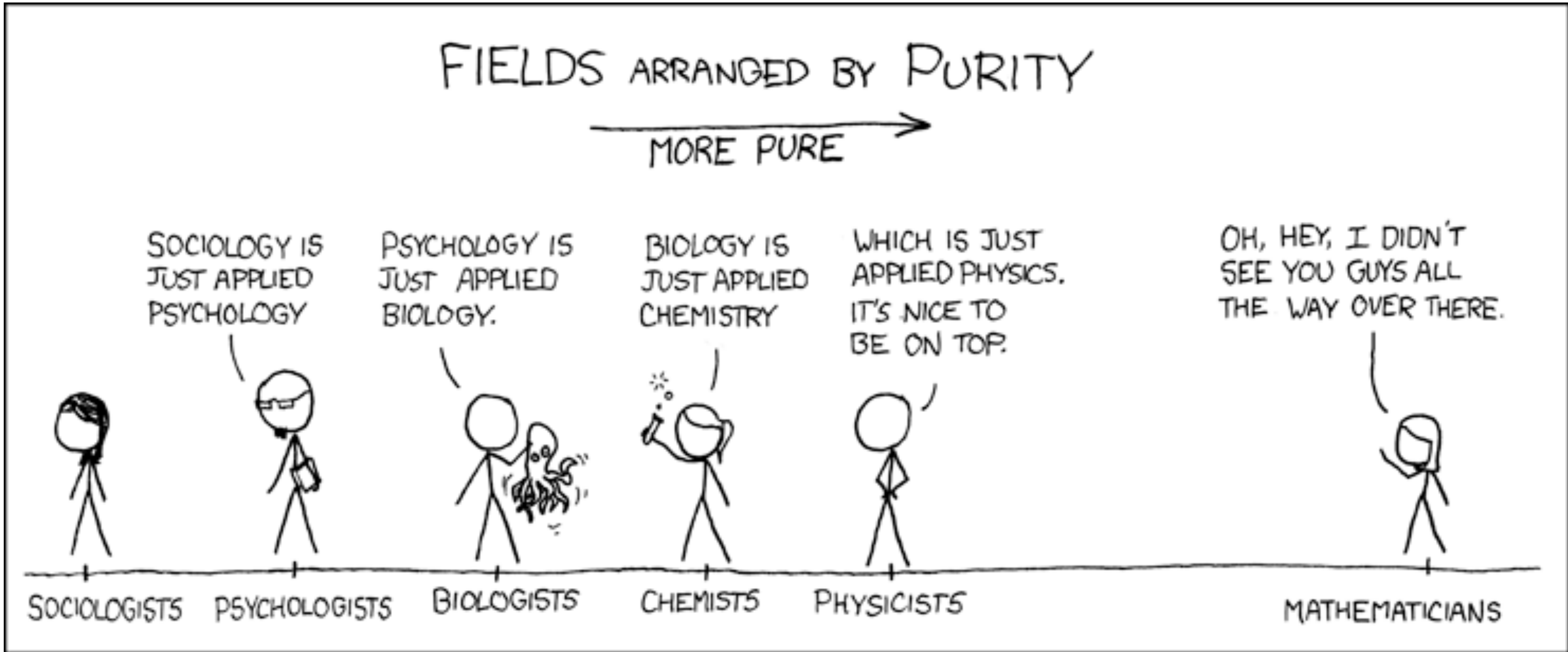
- General principles for the scientific method;
- Specialized techniques.

- Not a fixed sequence of steps;
- still a highly variable and creative process.

université de BORDEAUX

Science tries to understand nature

"Science is a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe."



XKCD – based on Auguste Comte

Applied Science

Civil engineering

Electrical engineering

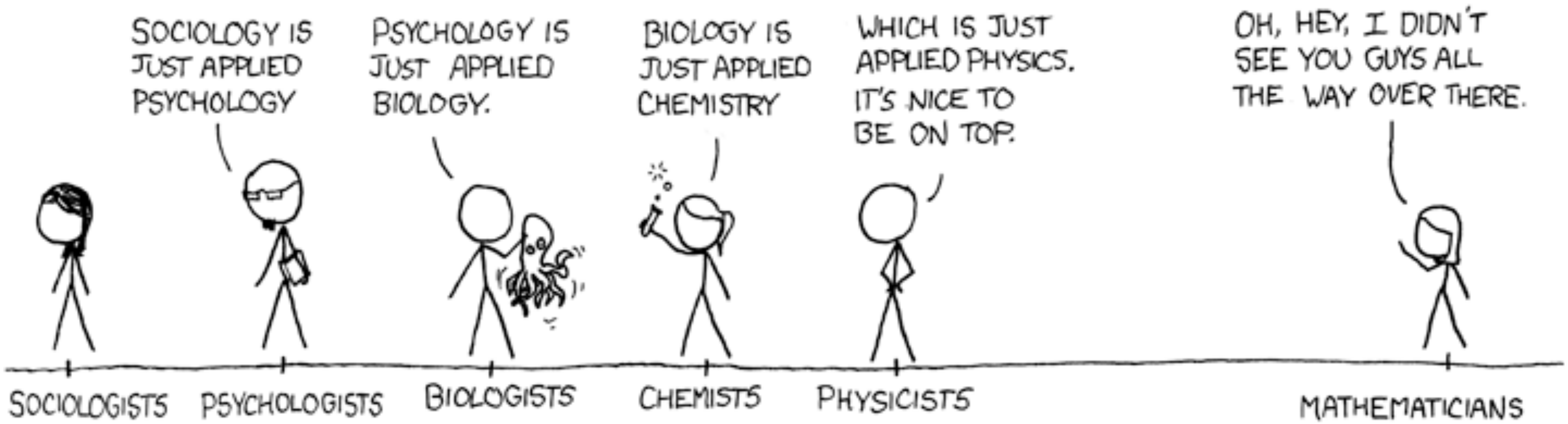
Mechanical engineering

…

Life science engineering

Chemical engineering

Computer Science



Applied Science

Civil engineering

Electrical engineering

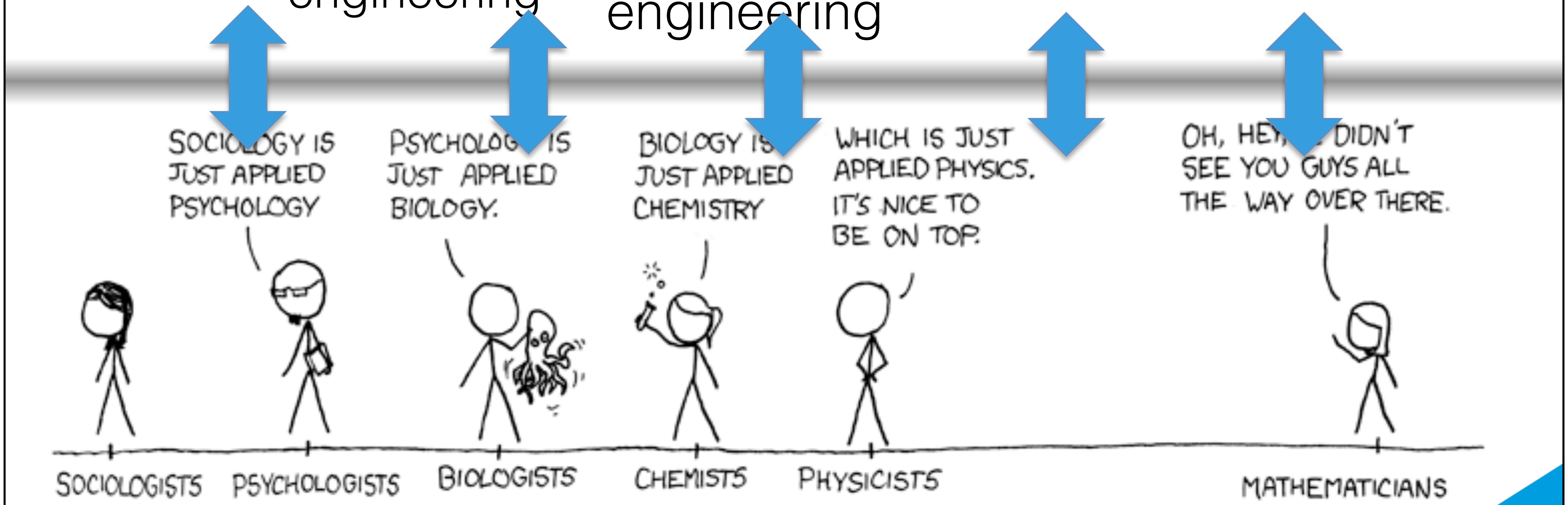
Mechanical engineering

. . .

Life science engineering

Chemical engineering

Computer Science



université de BORDEAUX

Scientific Method

1. Observation and Formulation of a question:

- evaluating evidence from previous experiments,
- personal scientific observations or assertions, and
- the work of other scientists

→ literature review: do not reinvent the wheel

→ *determining a good question can be very difficult and affects the final outcome of the investigation*

université de BORDEAUX

DNA Example

1. Question: What is the structure of DNA?

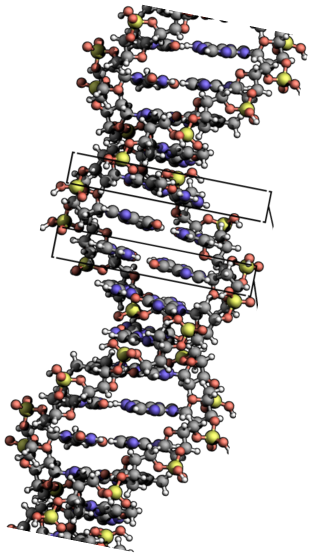
"Hard Science" Research Method

1. Observation and Formulation of a question

2. Hypothesis: conjecture that may explain the observed behavior

université de BORDEAUX

DNA Example



1. Question: What is the structure of DNA?

2. Hypothesis: Francis Crick and James D. Watson hypothesized that DNA had a helical structure.

"Hard Science" Research Method

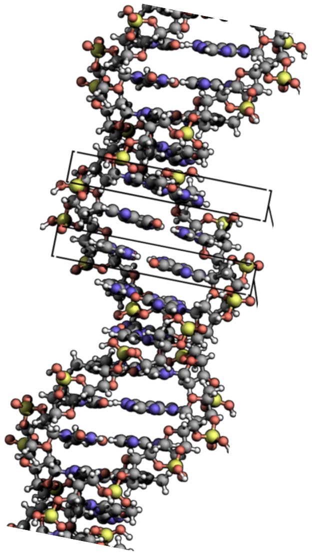
1. Observation and Formulation of a question

2. Hypothesis: conjecture that may explain the observed behavior

3. Prediction: to predict the outcomes of the hypothesis

- even more convincing if the answer to the prediction is not already known (avoid "hindsight bias")
- Ideally, the prediction should distinguish the hypothesis from likely alternatives: if two hypotheses make the same prediction, observing the prediction to be correct is not evidence for either one over the other (Bayes' Theorem)

DNA Example



1. Question: What is the structure of DNA?

2. Hypothesis: Francis Crick and James D. Watson hypothesized that DNA had a helical structure.

3. Prediction: If DNA had a helical structure, its X-ray diffraction pattern would be X-shaped (derived from the mathematics of the helix transform).

"Hard Science" Research Method

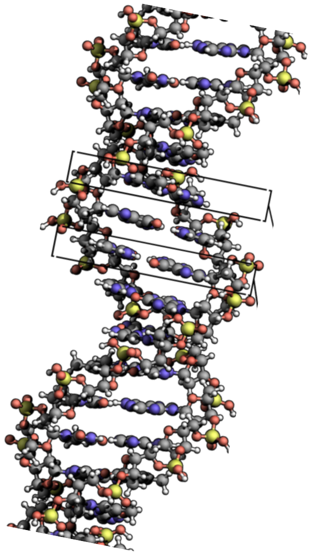
1. Observation and Formulation of a question
2. Hypothesis: conjecture that may explain the observed behavior
3. Prediction: to predict the outcomes of the hypothesis

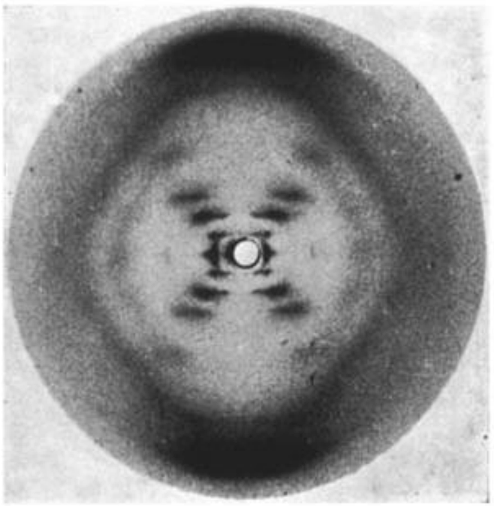
4. Testing: to test the predictions experimentally

- do the observations of the real world agree with the predictions?
- If they agree, confidence in the hypothesis increases; otherwise, it decreases. Agreement does not assure that the hypothesis is true; future experiments may reveal problems.

université de BORDEAUX

DNA Example





1. Question: What is the structure of DNA?

2. Hypothesis: Francis Crick and James D. Watson hypothesized that DNA had a helical structure.

3. Prediction: If DNA had a helical structure, its X-ray diffraction pattern would be X-shaped (derived from the mathematics of the helix transform).

4. Experiment: Rosalind Franklin crystallized pure DNA and performed X-ray diffraction to produce Photo 51. The results showed an X-shape.

Precession of Mercury

Hypothesis: Einstein's theory of General Relativity

Prediction: Mercury's orbit using relativistic calculations

Testing: Calculations matched observation much more closely than did Newtonian theory.

Logical Fallacies

Syllogisms

General form:

- Major premise
- Minor premise
- Conclusion

The premises and conclusion of a syllogism can be any of four types:

- All * are * (*All humans are mortal*);
- No * are * (*No humans are perfect*);
- Some * are * (*Some humans are healthy*);
- Some * are not * (*Some humans are not clever*).

Four possible figures for a syllogism:

- Major premise: middle term-predicate, minor premise: subject-middle term;
- Major premise: predicate-middle term, minor premise: subject-middle term;
- Major premise: middle term-predicate, minor premise: middle term-subject;
- Major premise: predicate-middle term, minor premise: middle term-subject.

Conclusion has always the form: subject-predicate

Syllogisms

General form:
Major premise
Minor premise
Conclusion

- Four types for the premises and conclusion of a syllogism.
- Four possible figures for a syllogism.

Syllogisms

General form:
Major premise
Minor premise
Conclusion

- Four types for the premises and conclusion of a syllogism.
- Four possible figures for a syllogism.

4 x 4 x 4 x 4 = 256 possible forms.

Syllogisms

General form:
Major premise
Minor premise
Conclusion

- Four types for the premises and conclusion of a syllogism.
- Four possible figures for a syllogism.

4 x 4 x 4 x 4 = 256 possible forms.

Only 24 are correct.

Hasty Generalization

Making assumptions about a whole group or range of cases based on a bad sampling.

Example: stereotypes.

Hasty Generalization

To not confound with inductive reasoning:

Premise. *Every horse that has ever been observed has had a heart*.

Conclusion. *Every horse has a heart*.

False Dilemma

Mentioning fewer alternative that actually exist (often only two):

A or else B; not A, therefore B.

Logical form is valid, but:
maybe A or else B is not true;
maybe A and B are not mutually exclusive

Example: *If there is any flaw at all in the theories of evolution, then creation science is the only other possible truth.*

False Dilemma: straw-man argument

A or else B; not A, therefore B.

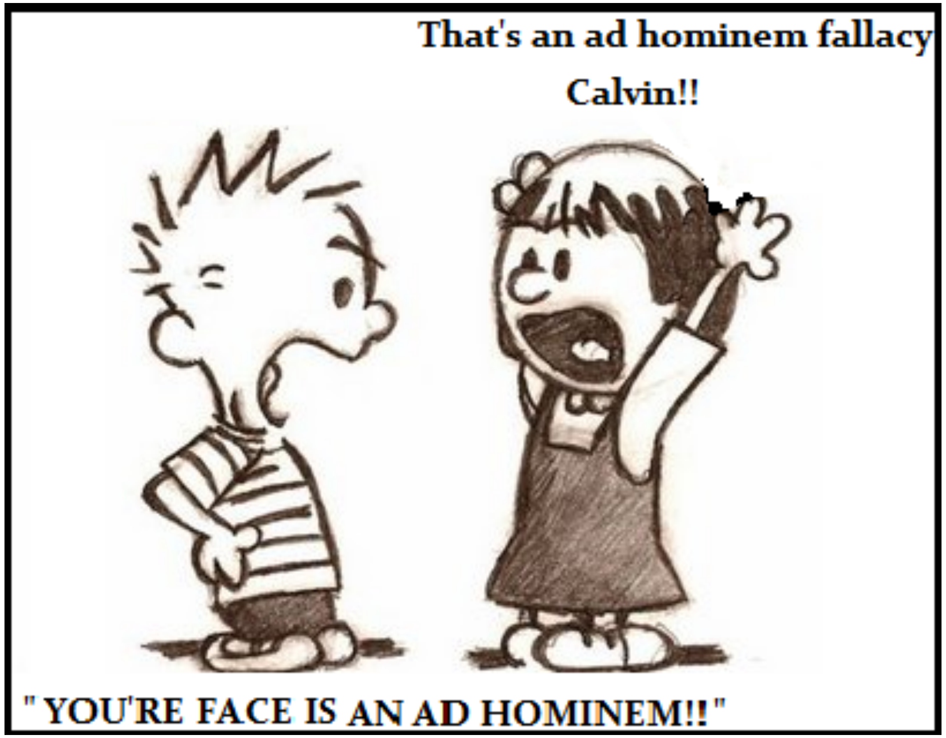
not A supported by attacking the opponent's weakest evidence or even or a straw-man representation of the opponent's reasons.

Example: *How come there are still monkeys?*

université de BORDEAUX

ad hominem Argument

Attacks the opponent rather than debating the issue.

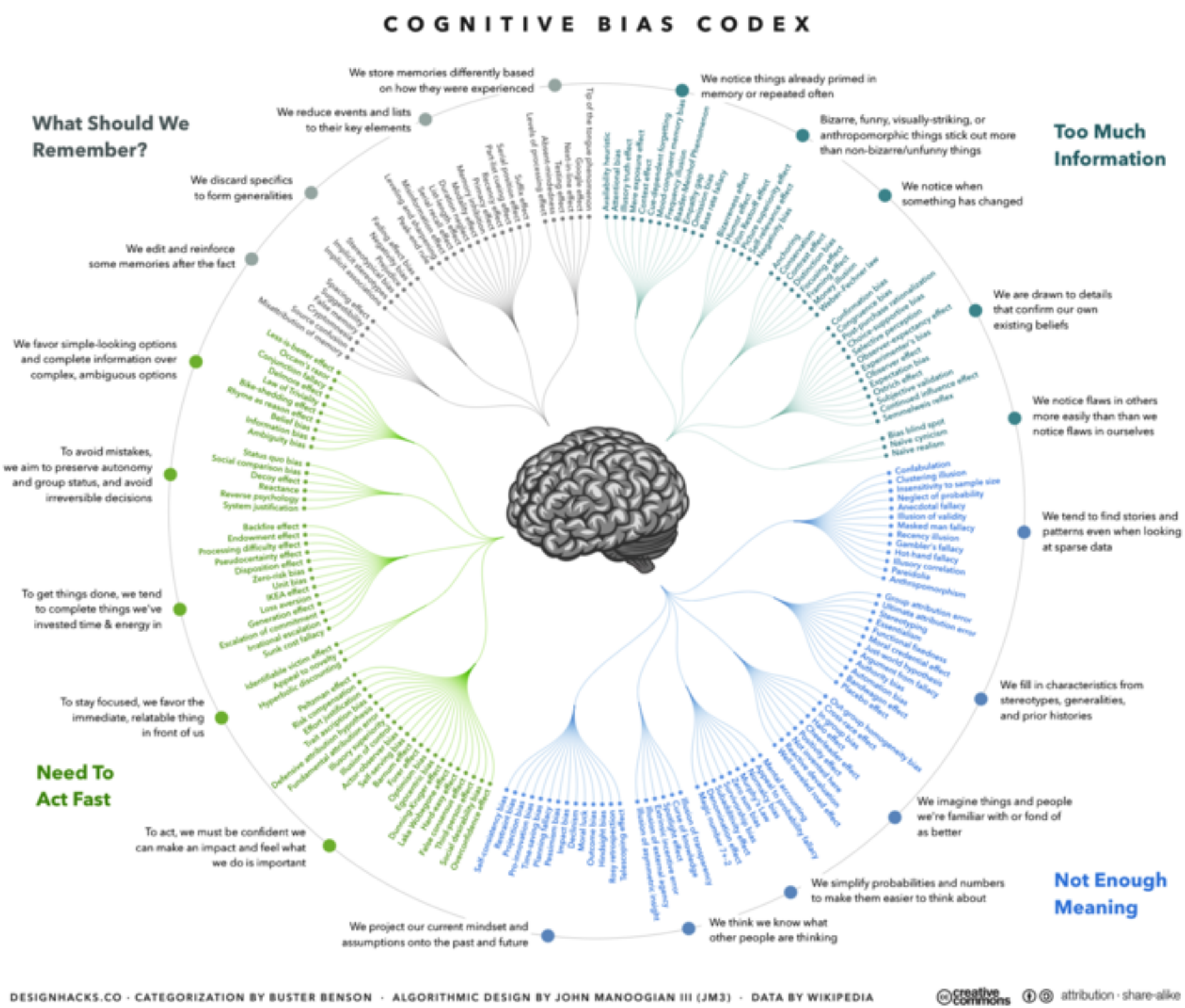


Cognitive Biases

Introduced in 1972;

When human judgments differ from rational choices.

Explained as heuristics that are simple for the brain, but with a systematic error.



Wikipedia's complete (as of 2016) list of cognitive biases, beautifully arranged and designed by John Manoogian III (jm3). Categories and descriptions originally by Buster Benson.

Cognitive Biases

From Ambiguity effect:

The tendency to avoid options for which missing information makes the probability seem "unknown".

…to Zero-risk bias:

Preference for reducing a small risk to zero over a greater reduction in a larger risk.

Post-purchase rationalization:

The tendency to persuade oneself through rational argument that a purchase was good value.

Not invented here:

Aversion to contact with or use of products, research, standards, or knowledge developed outside a group.

Experimenter's or expectation bias:

The tendency for experimenters to believe, certify, and publish data that agree with their expectations for the outcome of an experiment, and to disbelieve, discard, or downgrade the corresponding weightings for data that appear to conflict with those expectations.

Scientific Reasoning

Classical deduction rule:

1. Theory (when I throw a ball upwards, it falls down);
2. Fact (I throw a ball upwards);
3. Conclusion (*the ball will fall down*).

Modus Ponens: From A and $A \Rightarrow B$, B

Not all inferences are deductive: Inductive reasoning

- The first 5 eggs in the box were rotten;
- All the eggs in the box have the same best-before date stamped on them;
- Conclusion: The 6th egg will be rotten.

Induction is Not Safe

The 6th egg may not be rotten. The conclusion could be wrong.

Deduction should be preferred in scientific reasoning BUT…

Research Method

1. Observation and Formulation of a question
2. Hypothesis: conjecture that may explain the observed behavior
3. Prediction: predicting the outcomes of the hypothesis
4. Testing: testing the predictions experimentally

université de BORDEAUX

Example

1. Observe swans:






2. Observations: Swan #1 is white, swan #2 is white, etc.

3. Generalized theory: *All swans are white*

Example (cont.)

There are also black swans!

université de BORDEAUX

Conclusions from the Example

The set of observations is important.

We cannot prove a general theory, there is only evidence.

However, we can prove that a theory is wrong.

Popper's Falsificationism

Because truth cannot be proven, a theory must be at least falsifiable;

Scientists should try to falsify their theories;

A theory is more evident when passing more falsification trials.

Falsifiable?

A valuable theory predicts observations.

If a prediction is in conflict with the real observation, then the theory fails.

Hence, the theory cannot be true anymore.

In Practice…

- Most scientists are not interested in showing that a certain theory is false;
- They want to convince people about their theory;
- Falsifying theories does not seem a constructive task.

Other Problems with Falsificationism

Some statements, like:

"For every metal, there is a temperature at which it will melt"

cannot be falsified.

Let's Go Back to Induction

Induction has problems;

HOWEVER, it is very successful (in science and daily life);

Just be careful;

université de BORDEAUX

Other Problems with Induction

Philosopher David Hume (1711-1776) noted that:

Use of induction cannot be rationally justified;

Induction relies on the "Uniformity of Nature" assumption: "The nature today is the same as in the past", but

this assumption cannot be proven.

Nelson Goodman: The New Riddle of Induction

Defines "grue": Something is *grue* if and only if it has been observed to be green before a certain time *t* and blue after that time.

All emeralds we have ever seen are green, but also "grue".

– Given the observations of a lot of green emeralds, one would inductively infer that all emeralds are green.

– Given the same set of observations of green emeralds, someone using the predicate "grue" will inductively infer that all emeralds, which will be observed after *t*, will be blue.

Inference to the Best Explanation

Example:

- The cheese has disappeared from the larder, apart from a few crumbs;
- Noises were heard coming from the larder last night.

Who ate the cheese?

université de BORDEAUX

Possible Explanations

Mouse hypothesis:

Mice love cheese;

Mice make scratching noises.

Maid hypothesis:

Maid likes cheese;

Maid left crumbs to accuse the mice;

The heater made the noises.

Occam's Razor

The mouse hypothesis is better because it requires only one cause.

Also often used in science.

How do we know that the universe can be described using simple models?

université de BORDEAUX

Probabilities and Induction

A probability is a function that assigns a number between zero and one to each sentence in a language.

If A is a sentence then:

- $0 \leq P(A) \leq 1$;
- If A and B are logically incompatible then
$$P(A \text{ or } B) = P(A) + P(B)$$
- If A is logically necessary then $P(A) = 1$.

université de BORDEAUX

Conditional Probability

Conditional probability $P(B \mid A)$ for pairs A, B of sentences:

If $P(A) > 0$ then $P(B \mid A) = P(A \text{ and } B) \,/\, P(A)$.

université de BORDEAUX

Independence

Sentences A, B are said to be independent if

$$P(A \text{ and } B) = P(A)\, P(B)\ .$$

Bayes Theorem (simplified)

$$P(H \mid D) \propto P(D \mid H)P(H)$$

posterior: new probability for the hypothesis

prior: probability before collecting data

likelihood: impact of the data on the hypothesis

université de BORDEAUX

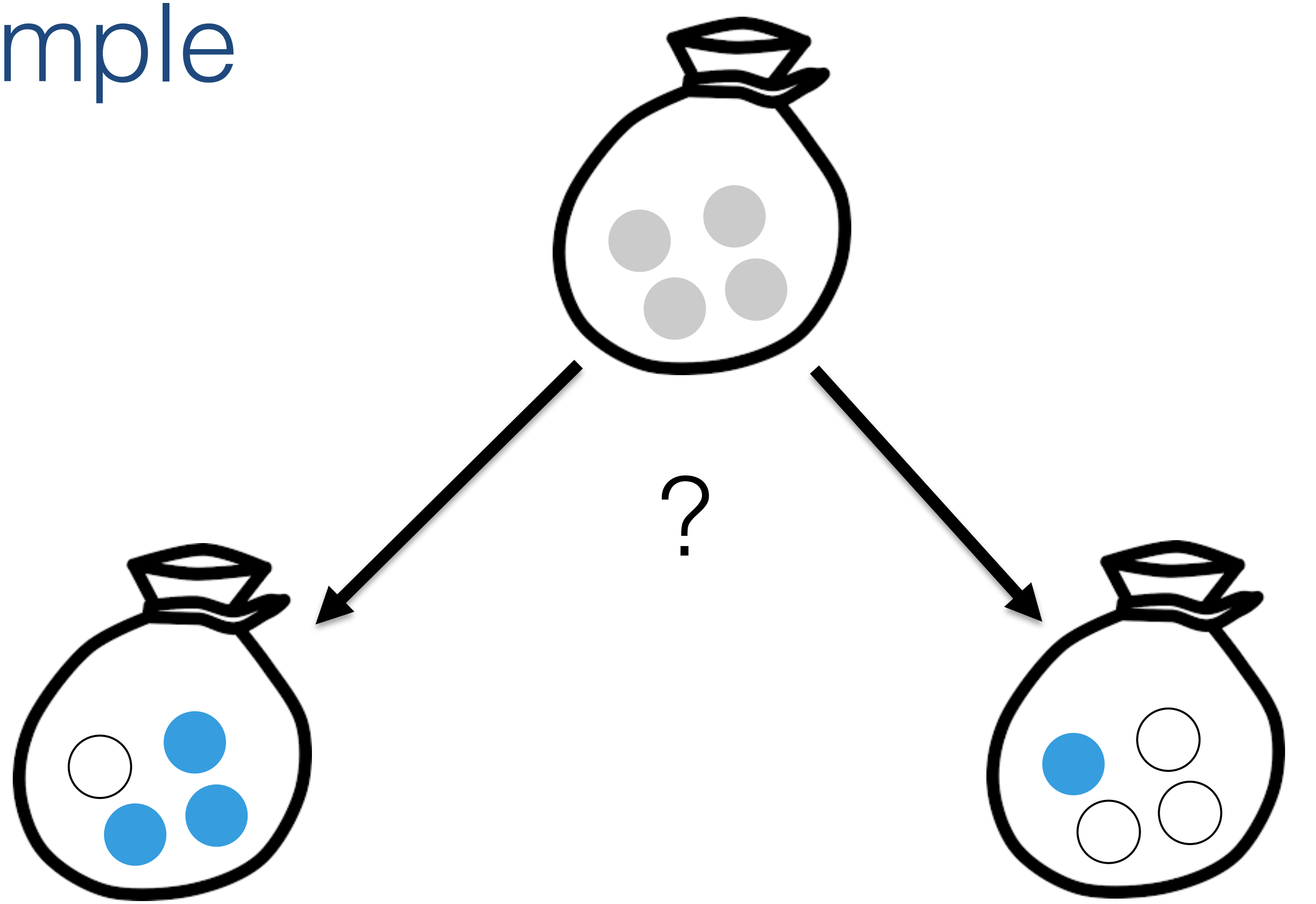
Bayes Theorem

$$P(H \mid D) = \frac{P(D \mid H)P(H)}{P(D)}$$

$$P(D) = \sum_i P(D \mid H_i)P(H_i)$$

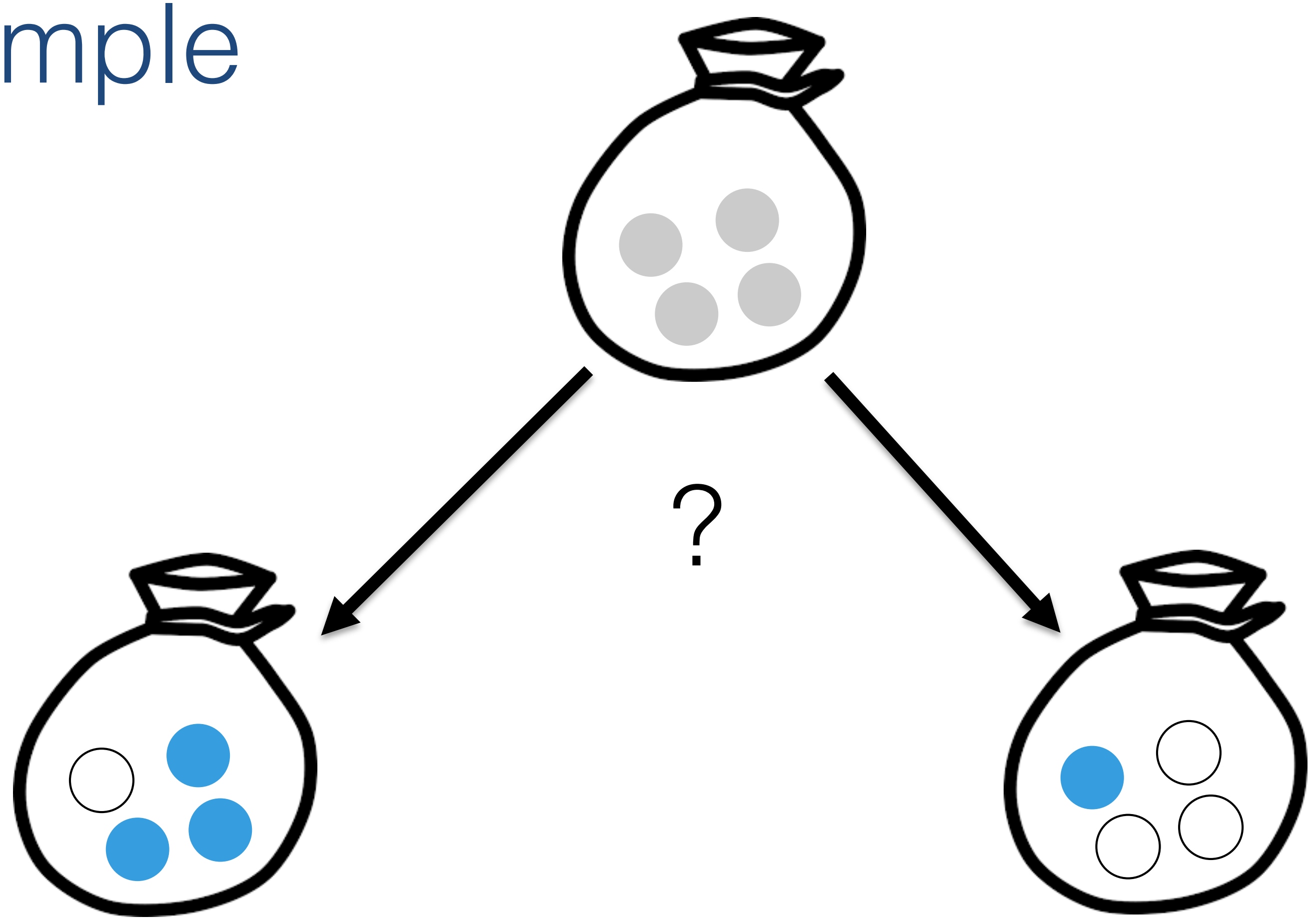
université de BORDEAUX

Example



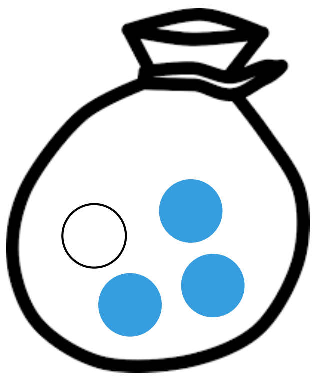
Hypothesis H_B Hypothesis H_W

Example

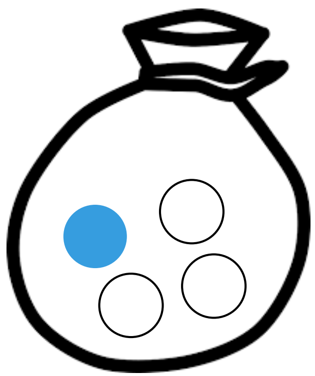


Hypothesis H_B Hypothesis H_W

$$P(H_B \mid D) = \frac{P(D \mid H_B)P(H_B)}{P(D \mid H_B)P(H_B) + P(D \mid H_W)P(H_W)}$$

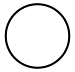


Hypothesis H_B



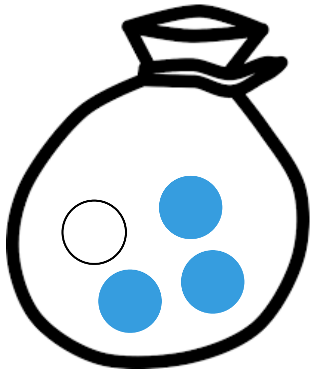
Hypothesis H_W

$$P(H_B) = P(H_W) = 0.5$$

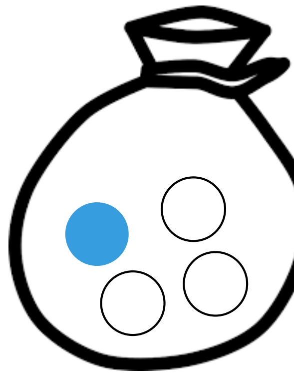
Draw #1: White 

$$P(H_B \mid D) = \frac{P(D \mid H_B)P(H_B)}{P(D \mid H_B)P(H_B) + P(D \mid H_W)P(H_W)}$$

$$P(H_B \mid \text{White}) = \frac{P(\text{White} \mid H_B)P(H_B)}{P(\text{White} \mid H_B)P(H_B) + P(\text{White} \mid H_W)P(H_W)}$$



Hypothesis H_B



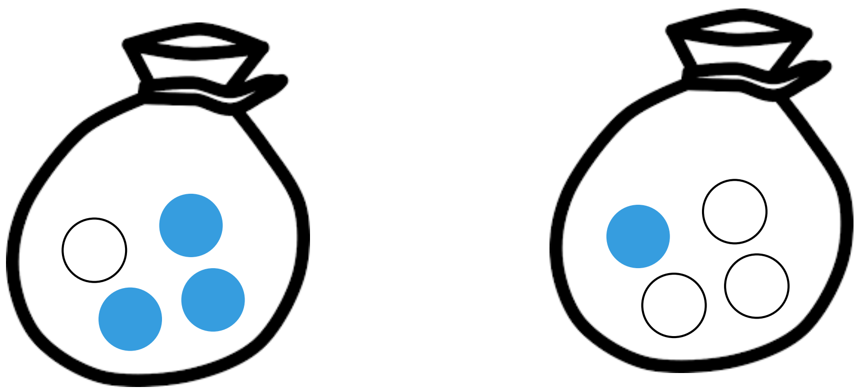
Hypothesis H_W

$$P(H_B) = P(H_W) = 0.5$$

$$P(H_B \mid \text{White}) = \frac{P(\text{White} \mid H_B)P(H_B)}{P(\text{White} \mid H_B)P(H_B) + P(\text{White} \mid H_W)P(H_W)}$$

$$P(\text{White} \mid H_B) = ?$$

université de BORDEAUX



Hypothesis H_B Hypothesis H_W

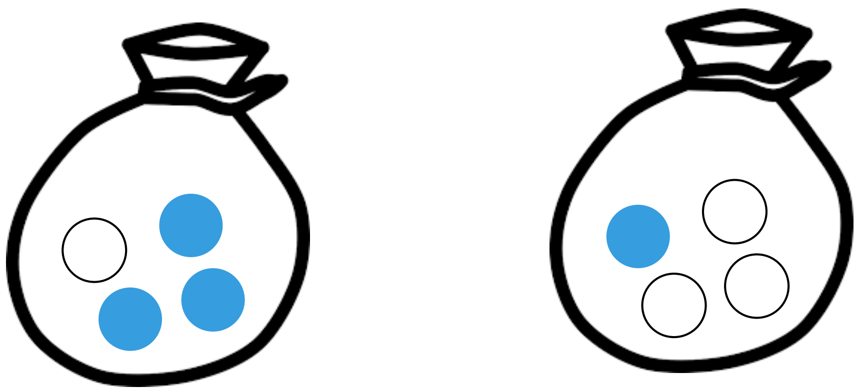
$$P(H_B) = P(H_W) = 0.5$$

$$P(H_B \mid \text{White}) = \frac{P(\text{White} \mid H_B)P(H_B)}{P(\text{White} \mid H_B)P(H_B) + P(\text{White} \mid H_W)P(H_W)}$$

$$P(\text{White} \mid H_B) = \frac{1}{4} = 0.25$$

$$P(\text{White} \mid H_W) = \frac{3}{4} = 0.75$$

$$P(H_B \mid \text{White}) = \frac{0.25 \times 0.5}{0.25 \times 0.5 + 0.75 \times 0.5} = 0.25$$



Hypothesis H_B Hypothesis H_W

$$P(H_B) = 0.25,\ P(H_W) = 0.75$$

Draw #2: Blue

$$P(H_B \mid \text{Blue}) = \frac{P(\text{Blue} \mid H_B)P(H_B)}{P(\text{Blue} \mid H_B)P(H_B) + P(\text{Blue} \mid H_W)P(H_W)}$$

$$P(H_B \mid \text{Blue}) = \frac{0.75 \times 0.25}{0.75 \times 0.25 + 0.25 \times 0.75} = 0.50$$

université de BORDEAUX

draw	outcome	$P(H_B \mid D)$
1	White	0.25
2	Blue	0.5
3	White	0.25
4	Blue	0.5
5	Blue	0.75
6	Blue	0.9
7	Blue	0.964..

Let say we have a blood test for some rare disease which occurs by chance in 1 in every 100 000 people.

if a patient has the disease, it will correctly say so with probability 0.95;
if a patient does not have the disease, the test will wrongly say that he does with probability 0.005

If the test says a patient has the disease, what is the probability that this is a correct diagnosis?

Let say we have a blood test for some rare disease which occurs by chance in 1 in every 100 000 people.

- if a patient has the disease, it will correctly say so with probability 0.95;
- if a patient does not have the disease, the test will wrongly say that he does with probability 0.005

If the test says a patient has the disease, what is the probability that this is a correct diagnosis?

$$P(H_B \mid D) = \frac{P(D \mid H_B)P(H_B)}{P(D \mid H_B)P(H_B) + P(D \mid H_W)P(H_W)}$$

$$P(\text{Disease} \mid \text{Positive}) = \frac{P(\text{Positive} \mid \text{Disease})P(\text{Disease})}{P(\text{Positive} \mid \text{Disease})P(\text{Disease}) + P(\text{Positive} \mid \text{No Disease})P(\text{No Disease})}$$

- Disease occurs in 1 in every 100 000 people;
- if a patient has the disease, it will correctly say so with probability 0.95;
- if a patient does not have the disease, the test will wrongly say that he does with probability 0.005

$$P(\text{Disease} \mid \text{Positive}) = \frac{P(\text{Positive} \mid \text{Disease})P(\text{Disease})}{P(\text{Positive} \mid \text{Disease})P(\text{Disease}) + P(\text{Positive} \mid \text{No Disease})P(\text{No Disease})}$$

- Disease occurs in 1 in every 100 000 people;
- if a patient has the disease, it will correctly say so with probability 0.95;
- if a patient does not have the disease, the test will wrongly say that he does with probability 0.005

$$P(\text{Disease} \mid \text{Positive}) = \frac{P(\text{Positive} \mid \text{Disease})P(\text{Disease})}{P(\text{Positive} \mid \text{Disease})P(\text{Disease}) + P(\text{Positive} \mid \text{No Disease})P(\text{No Disease})}$$

$$P(\text{Disease}) = 0.00001$$

$$P(\text{Positive} \mid \text{Disease}) = 0.95$$

$$P(\text{Positive} \mid \text{No Disease}) = 0.005$$

$$P(\text{Disease} \mid \text{Positive}) = \frac{0.95 \times 0.00001}{0.95 \times 0.00001 + 0.005 \times 0.99999} = 0.002$$

Let's assume that
the probabilities of boys and girls are equal, and
the gender of each child is an independent factor.

Suppose Mr and Mrs Smith have two children, one of whom is a girl. What is the probability that the other child is a girl?

Let's assume that

- the probabilities of boys and girls are equal, and
- the gender of each child is an independent factor.

Suppose Mr and Mrs Smith have two children, one of whom is a girl. What is the probability that the other is a girl?

Four possibilities for the 2 children:

boy&boy, boy&girl, girl&boy, girl&girl

Let's assume that

- the probabilities of boys and girls are equal, and
- the gender of each child is an independent factor.

Suppose Mr and Mrs Smith have two children, one of whom is a girl. What is the probability that the other is a girl?

Four possibilities for the 2 children:

~~boy&boy~~, boy&girl, girl&boy, girl&girl

université de BORDEAUX

Let's assume that

- the probabilities of boys and girls are equal, and
- the gender of each child is an independent factor.

Suppose Mr and Mrs Smith have two children, one of whom is a girl. What is the probability that the other is a girl?

Four possibilities for the 2 children:

~~boy&boy~~, boy&girl, girl&boy, girl&girl

Probability that the other child is a girl: 1/3

université de BORDEAUX

Why Our Intuition Is So Bad?

The question could also be written as:

For a family with two children, what is the probability that the other child is a girl, when *one is a girl?*

P(X when Y) is not defined;
Does it correspond to P(X | Y), P(Y | X), or P(Y and X)?

université de BORDEAUX

DNA Profiles

The 'match probability' is the probability is the probability that an individual's DNA will match the crime sample, given that he or she is innocent.

What really matters is:

What is the probability that the suspect is innocent, given a DNA match?

Why We Make Bad Decisions

Expected Value = (Odd of Gain)x(Value of Gain)

Why We Make Bad Decisions, Dan Gilbert, TED talk.

université de BORDEAUX

http://win.ua.ac.be/~sdemey/Tutorial_ResearchMethods/