Key Skills for Computer Science

Lecture 2: Scientific Thinking

Michael Wooldridge
(mjw@liv.ac.uk)

University of Liverpool

Science is the Answer?

- The scientific method is highly regarded!
  - "scientifically proven to reduce spots"
  - "scientifically proven to wash cleaner"
  - "Neutrogena clinical, powered by ion_2 complex (TM)"
- Of course, science is responsible for bad things as well:
  - the H bomb
  - global warming
  - ...

The Triumph of Science

- The scientific method is the reason we aren't all living in caves, fighting off sabre tooth tigers with our bare hands
- The adoption of the scientific method, *not just in science*, but throughout all aspects of work, society, and life has changed our world beyond all imagining
- But what *is* the scientific method?
- When *is* something "scientifically proven"?

Science as

Knowledge Derived from Observations

Science as Knowledge Derived from Observed Facts

- A commonsense view of science:
  - **Events** happen
  - **Observations** are made of these events
  - **Facts** result from these observations
  - **Reasoning** from these facts leads to **scientific knowledge**, in the form of a **theory**

An Example

- **Events**:
  - people eat the red plant
- **Observation**:
  - everyone who eats the plant dies
- **Facts**:
  - eating the red plant kills you
- **Scientific theory:**
  - the red plant is poisonous

Another Example: The Heliocentric Universe

- Until the 16th century and the work of Copernicus, it was pretty much universally believed that the Earth was at the centre of the Universe
- Copernicus made careful observations of the motion of the planets (not known to be planets at the time)
- It seemed clear that the planets were orbiting, but *retrograde motion* couldn't be easily reconciled with an Earth at the centre
- Copernicus realised that the observations could be explained if the Sun was at the centre of the rotation
- Copernicus's theory was a better explanation than the alternatives available

Yet Another Example

- It was observed that sick people convalescing in hospitals will recover more quickly if the hospital is in an attractive location
- The facts seem clear, but how do we interpret them?
- One possibility: attractive locations aid recovery (and so we should build hospitals in beauty spots)
- Is this theory reasonable, given the facts? What other theories might you posit?

Two Issues

- What does it mean to *observe an event* and *obtain a fact*?
  - A fact is something beyond question -- to what extent can we obtain such facts?
- What does it mean to *reason*?
  - Given a particular collection of facts, what constitutes a reasonable theory?

Three Assumptions

1. Facts are given to careful, unprejudiced observers
2. Facts are *prior to* and *independent of* theory
3. Facts constitute a firm and reliable foundation for scientific knowledge

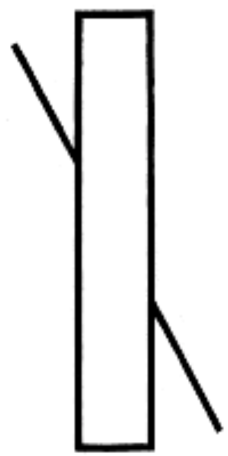
Are these assumptions reasonable?

(Chalmers, "What is this thing called science?")

The Problem with Perception

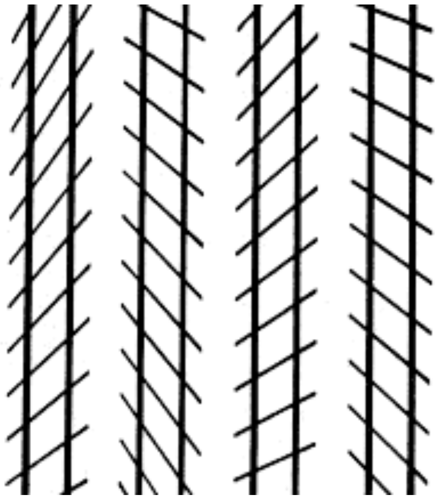
- We *perceive* the world through our senses:
  - sight, sound, smell, touch, taste
- But our perceptions of the world are:
  - incomplete, partial
  - imprecise
  - prejudiced by upbringing and culture
  - and, occasionally, just plain misleading....

The Poggendorf Illusion



It is in fact a straight line even though the emerging line looks parallel to the ingoing line.

The Zolner Illusion



The lines are
actually parallel...

The Müller-Lyer Illusion

The two arrow shafts
are actually the same length...

The Problem of Prior Knowledge

- Give a telescope to:
  - Patrick Moore
  - Isaac Newton

  and ask them to make observations of the sky.
- Who is more likely to make a useful contribution to astrophysics?
- Moore would readily admit Newton is cleverer! B
  - But Newton *lacks the conceptual framework to make useful observations*
- The search for observations and facts is necessarily guided by prior knowledge
- Does that knowledge prejudice us? If so, in what sense is science *impartial*?

Observations, Public & Private

- Science is *shared* but observations are *private*

  I do not have access to your observations; you do not have access to mine... and this is a problem if we want to construct a shared theory

- How do we make an observation?
  - open our eyes and facts enter our heads... no
- *Observations are active things*
  - imagine seeing a tomato in front of view
  - how can you verify your perception?

Making Observation Active and Controllable

- It is not suprising that perceptual judgements can be fallible, for many reasons
- A key goal of science is to arrange the observation setting so that reliance on individual perceptual judgements is minimised -- to give confidence in the observations
- Example: Galileo’s observations of Jupiter’s moons
  - An objection to Copernican heliocentrism: if the earth goes round the sun, why isn’t the moon left behind? why does it stay with us?
  - Galileo observed moons orbiting Jupiter, which gives credence to the idea that our moon orbits the Earth
  - To do this, he required careful measurements of positions of Jupiter’s moons, and he augmented his telescope with apparatus allowing systematic measurements
  - anybody who wanted to could repeat Galileo’s observations, using his apparatus

Testable Observations can be Fallible

- A key criteria for science is the notion of *testability*
- An observation that is *testable* is of much more value than one that is not
- But apparently testable observations are often much more difficult to pin down than they might seem...
  - Observation: *the earth is stationary*
  - Can you think of any reasonable tests available in Galileo's time that might refute this?

The Role of Experiment

- In the real world, huge numbers of processes and influences bear on any physical phenomenon.
- This limits the value of simple human observations for the basis of scientific theory formation
- To properly observe such phenomena, it is necessary to *isolate* the phenomena from influences that are believed to be irrelevant
- We do this with *experiments*

The Role of Experiments

- An experiment provides a setting for making observations in which the phenomenon/event of interest is isolated from influences that are considered irrelevant, so that we can have more confidence about
- Usually an experiment will be designed so that observations (measurements,...) can be made easily and transparently
- Experiments must be
  - *appropriate,* in the sense that you *observe what is relevant*
  - *adequate*, in the sense that we are capable of actually recording the phenomena of interest

Theory Change

- In 1687, Newton published his *Principia Mathematica*, which contained (amongst other things) his 3 *laws of motion.*
- For 200 years Newton's book provided the basis for understand the dynamics of our world. And it explains the macro-world of our everyday senses pretty bloody well!
- It is unlikely that any experiment that could be constructed in 1687 would have provided results disagreeing with *Principia*.
- But Newton's laws don't hold for objects that move *very fast*... and in 1905, everything changed
- (We will discuss the role of theory change in more detail later)

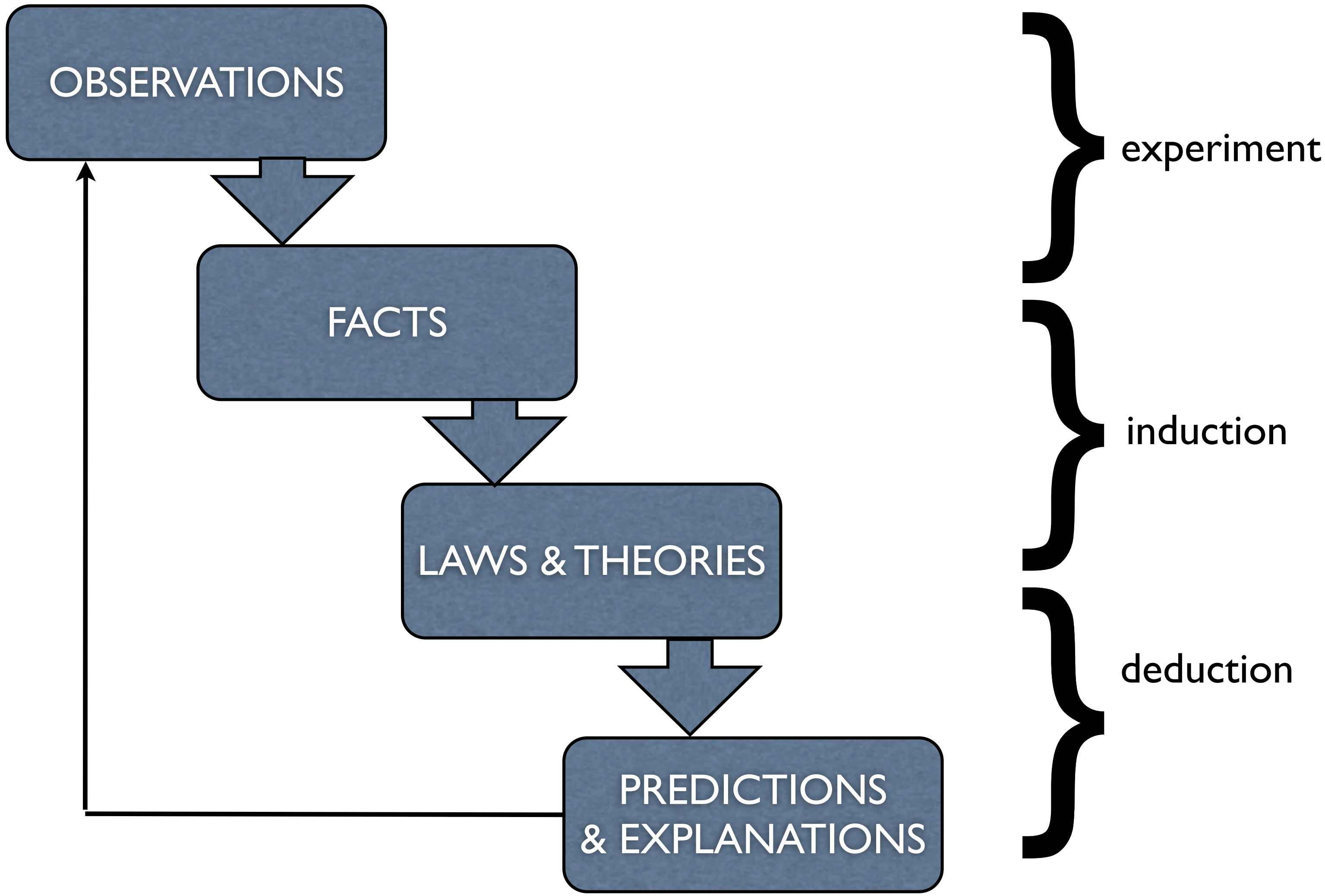
From Individual Facts to Theories: *Induction*

- Our model of science:
  - events -> observations -> facts -> theories
  - so far we have been concerned with events, observations, facts
  - But how do we go from *facts* to *theories*?
- This is achieved via *inductive reasoning*

From Theories to Predictions: *Deduction*

- The process of going from theories to predictions is known as *deduction*
- A standard example...
  - *Theory*: All men are mortal; Michael is a man
  - *Prediction*: Michael will die
-

A Model of Science



Deductive Logical Reasoning

- *Deductive logical reasoning* starts with some *premises* and on the basis of these, derives some *conclusions*
- *Logic* is concerned with what conclusions you can derive from the premises
- We say the reasoning is *sound* or *valid* if it is acceptable to draw the conclusions from the premises
- Soundness/validity usually means

if the premises are true

then the conclusion must also be true

(We will hear lots more about logical reasoning in coming weeks...)

Sound Reasoning doesn't imply Correctness

- Consider the following reasoning:
  - Premises:
    - if something has wings, it can fly
    - Pigs have wings
  - Conclusion:
    - Pigs can fly
- Logically, this argument is impeccable. The conclusion follows from the premises. But *both* premises are false.
- So, reasoning *has nothing to say about whether the premises are true or not*.

Induction

- Induction is the process of deriving *general laws or* theories from a number of *individual facts*
- This is *generalisation*
- (Closely related to, but not quite the same thing as the proof technique known as mathematical induction.)

An Example of Induction

- Premises:
  - Metal M1 expands when heated
  - Metal M2 expands when heated
  - Metal M3 expands when heated
- Conclusion:
  - All metals expand when heated.

Induction is *NOT* Sound Reasoning

- The problem with this type of induction is that it is *not* sound logical reasoning.
- Logically, the conclusion *does not* follow from the premises

When is Induction Justifiable?

1. The number of observations forming the basis of a generalisation must be sufficiently large.
2. The observations must be repeated in a wide range of circumstances
3. All observations must be consistent with the stated general law.

Over Generalisation

- Going for dinner in Pittsburgh with an American family.
- Their son Alex (7) observes that I am vegetarian, as is his British nanny.
- “All British people are vegetarians!” he exclaims.
- “No Alex”, says his father, (a Professor), “you’re overgeneralising”.

An Insufficient Range of Observational Circumstances

- We observe that Michael is grumpy on Saturday 1st, Saturday 8th, and Saturday 15th
- We conclude that Michael is always grumpy on Saturdays
- We omitted to note that the observations follow a night out on the town...

Karl Popper and Falsificationalism

- Popper made a crucial distinction between theories that are *falsifiable* and those that are not
- A theory is falsifiable if there is a test that can be applied which could refute the theory
- If no such test exists, then the theory has no value: there is no practical way it could ever be judged right or wrong

The Flying Spaghetti Monster

WWFSMD?

- Where did the universe come from?
- My theory: an omnipotent but undetectable entity -- the flying spaghetti monster -- created the universe, and on creation, vanished (leaving no trace of itself)
- There is lots wrong with this theory, but crucially, it is constructed in such a way that *there is no possible test for it*
- The theory makes *no predictions*
- Popper claims such theories have no useful status in science

Science as Falsificationalism

- Popper's view of science (crudely) is to...
  1. construct a speculative predictive theory
  2. rigorously test the theory
  3. if the theory fails, then construct a new speculative theory that better fits the observed facts, and goto 2
- Clearly, if a theory cannot be tested, then we cannot carry out (2)...

Examples of Falsifiable Claims

- It never rains on Wednesdays
- All substances heat when expanded
- When a ray of light is reflected from a mirror, the angle of incidence is equal to the angle of reflection

Claims that Cannot be Falsified

- Either it is raining or it is not raining
- All points on a Euclidean circle are equidistant from the centre
- Luck is possible in sporting competitions

Degrees of Falsifiability

- A theory is more useful the more predictions it makes
- Which of the following theories is more useful?

1. Mars orbits the sun in an ellipse
2. All planets orbit their stars in an ellipse

- We say that (2) is *more general* than (1)
- While there is a limit to how general useful theories can be, in general, general theories are better...

Inductivism *versus* Falsificationalism

- Inductivism is inherently *cautious*:
  - Encourages us to posit theories only in highly constrained settings, after many careful observations
- Falsificationalism is inherently *bold*:
  - Encourages us to posit speculative theories, and not be afraid of those theories being wrong

Degrees of Falsifiability

- What makes one theory "better" than another
- Intuitively, a theory is better if it is *more falsifiable*
- A theory T1 is more falsifiable than a theory T2 if it makes more predictions that can be verified/falsified

Degrees of Falsifiability: An Example

- Consider two theories T1 and T2
- T1 = *all pairs of bodies attract with a force that varies as the inverse square of their separation*
- T2 = *the planets of the solar system attract with a force that varies as the inverse square of their separation*
- We say that T1 *implies T2.*
- T1 gives us many more opportunities for falsification

Ad Hoc Extensions to Theories

- When a theory becomes falsified by some observation, it is tempting to try to "fix" it as one fixes a bug in a program, by modifying it in some way
- The danger is to modify it the theory in an *ad hoc* way
- Extensions must be useful, in the sense that:
  - they make predictions that were not already made, and
  - they must be falsifiable.

An Example of *ad hoc* Theory Modification

- Galileo observed mountains on the moon through his telescope, which disagreed with the accepted theory that all celestial bodies were perfect spheres
- An adversary postulated an invisible substance filling the valleys so that the moon was indeed a perfect sphere (and there was no way that the substance could be detected)

Scientific Progress and Falsificationalism

- Is it a breakthrough to falsify a theory? It depends.
- If the theory is *cautious*, then it may be a breakthrough
  - "the earth is at the centre of the universe" was a very cautious theory -- falsifying it was significant
- If the theory is *bold* and *very risky*, then probably not...
  - theory: the flying spaghetti monster will return to earth tomorrow and all non-pastafarians will be cast into hell
  - "another crazy idea proved wrong"

Kuhns

- Historically, science seems neither inductive nor falsificationalist -- its a bit of both, with lots of other stuff going on...
- Kuhns argued that neither view captures what goes on in “real” science
- His model:

  pre-science - normal science - crisis - revolution - new normal science - new crisis ...

Normal Science

- Normal science is the process of *working within a paradigm* to flesh out an existing theoretical framework
- The notion of *paradigm* is central:
  - a set of background assumptions, problems, objectives, models, experimental settings and standards that guide "normal scientific progress"

Crisis

- Kuhns argued that crises occur when the weight of evidence accumulates against an existing theory and paradigm, to the point where modifications can no longer reasonably be made
- At this point, a crisis occurs, which can only be resolved by a new theoretical framework and paradigm

Paradigms: An Aside

- We are familiar with the notion of paradigms in computing, in the sense of *programming paradigms*:
  - object-oriented programming (Java, C++)
  - procedural programming (C, Pascal)
  - functional programming (LISP, ML, Miranda)
  - logic programming (Prolog)
- Each paradigm comes with its own notion of “what makes a good program”, and its own *mindset* -- way of thinking about programming and software development

Paradigms are Inherently Conservative

- Those working within a paradigm will be reluctant to acknowledge crisis
- A paradigm will tend to set up criteria that confirm itself
- By definition, other paradigms will be judged less attractive!