PROGRESS IN SCIENCE: AN EPISTEMOLOGICAL PERSPECTIVE

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"DWARF GALAXIES ON THE SHOULDERS OF GIANTS"

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The "Problem of Induction"

Q: How do scientists arrive at *(seemingly correct)* theories?

A: *(I. Newton, F. Bacon, …)* **From experience!**

i.e. By generalization from observed facts.

⇒ By ***induction***.

(*Def*: "The derivation of general principles from specific observations.")

The "Problem of Induction"

But **induction is a fallacy**.

- "We have no reason to draw any inference concerning any object beyond those of which we have had experience" *(D. Hume)*

- Discrete instances do not imply universal laws

- Mistaken principles may entail truthful consequences

- **Any finite data set is consistent with an infinite number of different theories**

The "Problem of Induction"

But **induction is a fallacy**.

- "We have no reason to draw any inference concerning any object beyond those of which we have experience" *(D. Hume)*

- Discrete instances do not imply universal laws

- An infinite number of theories is always consistent with any finite data set

- Mistaken principles may entail truthful empirical consequences

So: How do scientists do it?

Logik der Forschung

Karl Popper (1929):
Observed facts can not ***prove*** theories; but they can ***disprove*** them. And that is all you need!

Suppose $A \Rightarrow B$ *(and* $B_1, B_2, B_3, \ldots$*)*

(hypothesis⇒consequence)

$\therefore \quad \neg B \Rightarrow \neg A$ *("modus tollens")*

Conjectures and Refutations

i) Postulate a theory
ii) Generate testable predictions
iii) Test the predictions

If the observations ***confirm*** the predictions, then you are doing OK *(so far)*.

If the observations ***refute*** *(just one)* prediction, you have learned something!

Your theory is ***false*** — reject it, and find another.

Conjectures and Refutations

In order for this to work, ***predictions must be refutable.***

∴ Progress in knowledge requires that theories be ***falsifiable***.

Popper proposed falsifiability as a "demarcation criterion":

Falsifiable theories are scientific.
Non-falsifiable theories* are non-scientific.

*Freudianism, Marxism, …

Corroboration

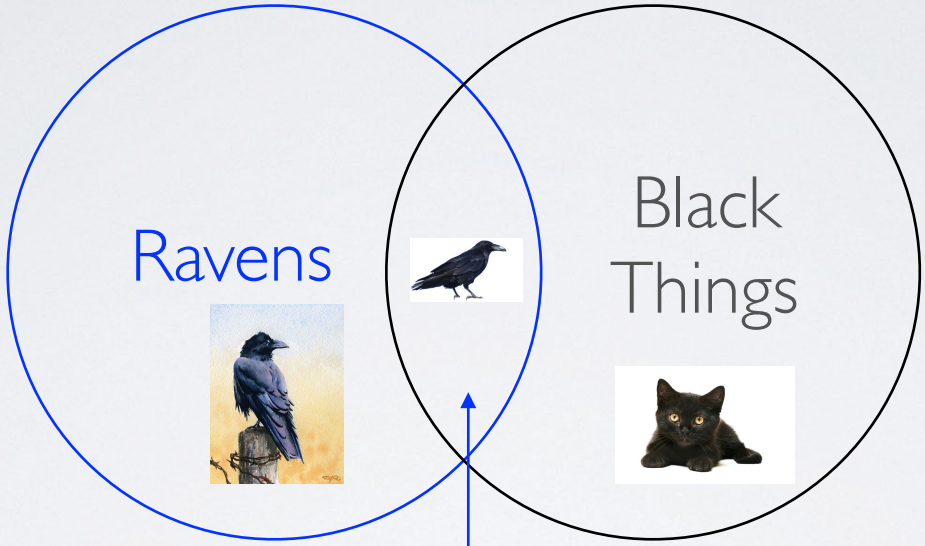
Suppose you have *two* theories, neither of which has been (conclusively) falsified.

Is there *any way* in which *observations* can decide between them? *(Remember: induction doesn't work!)*

Carl Hempel (1945): *Assume* that observations of black ravens support the hypothesis "All ravens are black".

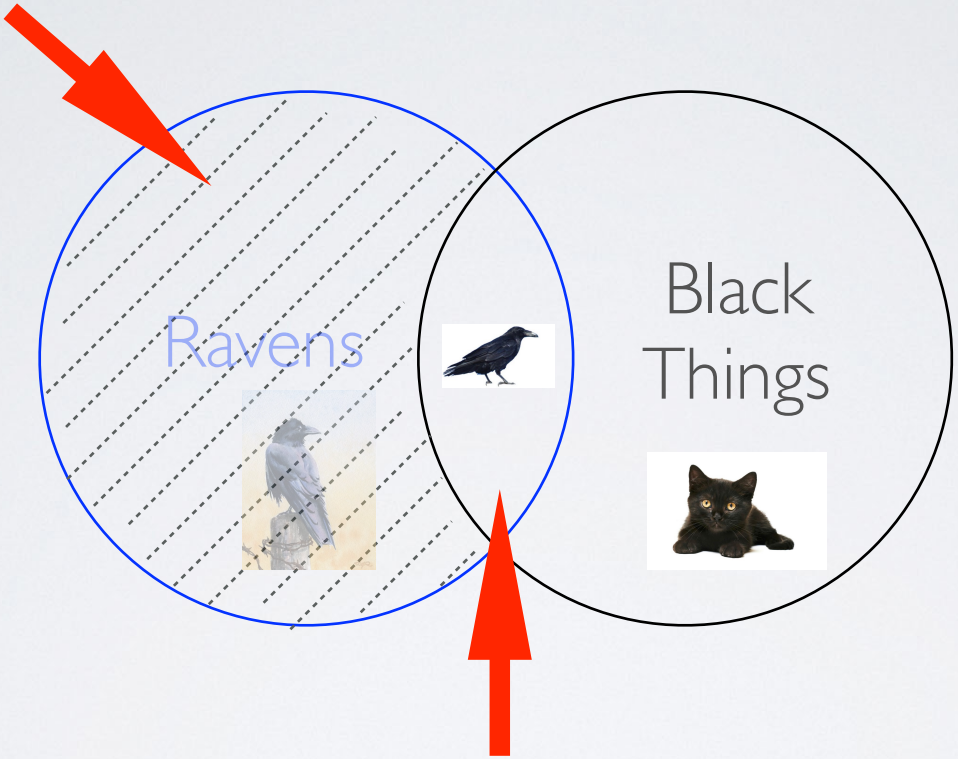
What does this imply, logically?

Non-Black Non-Ravens



Non-Black Non-Ravens

"All ravens are black" means:
this region is empty.



Now *assume* that observations of black ravens corroborates the assumption that all ravens are black…

$\mathcal{H}$: All ravens are black

= If raven, then black

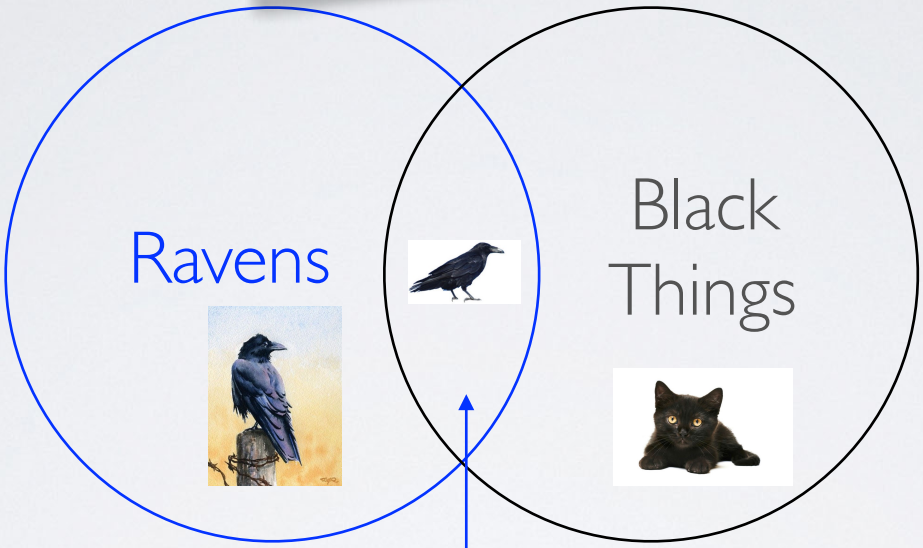
= If ***not*** black, then ***not*** raven ("*modus tollens*")

$\mathcal{H}'$: All non-black things are non-ravens.

If observations of black ravens confirms $\mathcal{H}$, then observations of non-black non-ravens confirms $\mathcal{H}'$.

But $\mathcal{H} \Leftrightarrow \mathcal{H}'$!

∴ Observation of these things confirms "All ravens are black"



Non-Black Non-Ravens

Karl Popper: Hempel is right! Logically, confirming a theory's predictions does not confirm the theory.

But *(he said)*: Consider a different situation. Suppose that prior to your new theory, there was an older theory that did not say as much about the world. *(E. g. "Ravens can be black or brown".)*

When you then set about testing your new theory ("All ravens are black"), *you expect it to fail*, since nothing in your background knowledge would lead you to expect that it is correct.

If you then confirm its new predictions, that is impressive, from a ***probabilistic*** (not logical) point of view.

Corroboration *(Popper)*

Does evidence (e) support hypothesis (h)?

Yes, if:

i) e is ***implied*** by h;
ii) e is ***improbable*** based on background knowledge alone

Condition (ii) is *essential* to avoid Hempel's paradox.

Best possible case: evidence e *falsifies* the earlier theory.
This is what Popper called a "crucial experiment".

Conditions for Progress *(Popper)*

A new theory represents progress if:

1. It is **falsifiable** (but not yet falsified);

2. It contains **more content** than the old theory
   (= more potential for falsification)

3. Some of its **novel predictions** have been verified.
   (NB ***only*** the novel predictions matter!)

What is a "novel" prediction?

People disagree; various criteria have been proposed.

But everyone seems to agree on the following:

Observed data do ***not*** support a theory, if those data were used in ***constructing*** the theory.

"You can't use the data twice"

If you adjust the parameters of your model to fit the data, you can not claim that those data support your model!

ΛCDM theorists violate this methodological rule ***all the time***

(e.g. the "concordance" model; cosmological simulation codes, which contain parameters for sub-grid physics; etc.)

(*w/* Thomas Kuhn)

Imre Lakatos

Lakatos noticed the following things:

1. Theories are *always* embedded in an "ocean of anomalies".

2. Scientists respond to anomalies by invoking ***auxiliary hypotheses*** — ***not*** by changing the "hard core" of their theory.*

3. Therefore, the proper unit of appraisal is not "the theory," but rather ***"the research program"***: a ***sequence*** of related theories.

*Lakatos *observed* this; he did not *endorse* it.

Research Programs

Lakatos claimed that research programs* have **three elements**:

- The **hard core**: those assumptions or hypotheses that a theorist will never abandon, regardless of the evidence.
- The **positive heuristic**: guidelines for developing the theory, for dealing with anomalies etc.
- **Auxiliary hypotheses**, which are invoked in order to "protect" the hard core from falsification.

*Both good ("progessive") and bad ("degenerating") programs have these elements.

Examples of "Hard Core" postulates

- The **Newtonian Research Program:**

  — Newton's law of gravity and his laws of motion are correct

- The **Phlogiston Research Program:**

  — Combustibles contain an inflammable principle which they release upon burning

- **Bohr's Research Program:**

  — The angular momentum of every electron is an integer multiple of $h/2\pi$

  — The relation between the frequency and the energy emitted in is $E = h\,\nu$

- The **ΛCDM Research Program:**

— Einstein's theory of gravity and motion is correct

— Dark matter exists and behaves like a collisionless fluid in response to gravity

The "Methodology of Scientific Research Programs"

A research program is **progressive** if:

1. Each new theory in the sequence:
   (i) accounts for previous successes, and
   (ii) predicts some novel facts.

2. (At least) Some of the novel predictions should be verified.

3. Changes, whenever possible, should conform to the "positive heuristic"
   i.e. they should not be "forced moves"

It is *very hard* to argue that the ΛCDM Research Program is progressive.

— Dark matter, dark energy, inflation were all "forced moves": *ad hoc* hypotheses invoked in response to falsifying observations

— At least two of these hypotheses add no content in the sense understood by Popper or Lakatos: i.e. they make no falsifiable predictions

E.g. the properties of "dark energy" are freely adjusted in response to data, *in whatever way is required* to maintain the inviolability of the hard core *(cf. phlogiston; aether; …)*

— Few (if any) examples exist of confirmed, novel predictions

The Milgromian Research Program: The Hard Core

"(a) Standard dynamics breaks down in the limit of small accelerations.

(b) In the limit of small accelerations, the acceleration of a test particle is given by $(a/a_0)a \approx g_N$, where g_N is the conventional gravitational acceleration and a_0 is a constant with the dimensions of acceleration.

(c) The transition from the Newtonian regime to the low acceleration asymptotic regime is determined by the acceleration constant a_0 (in the sense that the transition occurs within a range of accelerations of order a_0 around a_0)."

(Milgrom 1983b, p. 371)

The Milgromian Research Program

Theory	Novel elements	Novel predictions	Corroborated?
T_0 (core)	$\mu(a/a_0)\boldsymbol{a} = -\boldsymbol{\nabla}\phi_{\rm N}$, $\mu(x \gg 1) \approx 1$, $\mu(x \ll 1) \approx x$	Asymptotic constancy of orbital velocity around isolated mass ($V \Rightarrow V_\infty$, $r \Rightarrow \infty$) $V_\infty^4 = a_0 GM$ External-field effect	— yes maybe
T_1	$\mu(x) = x/(1+x^n)^{1/n}$	Detailed prediction of galaxy rotation curves Radial acceleration relation	yes yes
T_2	Non-relativistic action (e.g. QUMOND)	Dynamics of polar rings Dynamics of tidal streams	yes maybe
T_3	…	…	…

The Milgromian Research Program has made novel predictions at every stage, and many of its novel predictions have been confirmed:

- The baryonic Tully-Fisher relation
- Detailed prediction of galaxy rotation curves
- The radial-acceleration relation

∴ The Milgromian Research Program is "progressive".

Comparing *different* research programs*

Hard! because:

1. Theories can be *incommensurate*.

2. One research program may be "mature"; another not so much.

3. In their early phases, theories may make predictions in different, limited regimes.

*E.g. ΛCDM vs. Milgromian dynamics