

Conceptual Breaks

Children's edition

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The Universe and Its Observers

This book is for readers roughly nine to twelve years old. Each short chapter introduces a change in how a scientific or mathematical question could be answered. Some ideas are demanding and can be discussed with an adult. The aim is to keep the important distinction clear, rather than to give every historical detail or calculation.

The chapters are adapted from the corresponding scientific chapters. They introduce no practical experiments. The notes for adults at the end provide the source references used by those chapters. A short explanation should still make clear what the evidence does, and does not, establish.

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Motion without a continuous mover

A stone keeps moving after it leaves someone's hand. Long ago, this raised a difficult question: if the hand is no longer pushing, what keeps the stone going?

Buridan proposed that the throw gave the stone something called "impetus." Resistance could reduce it. His idea helped change the explanation, but it was not the same as today's account of motion.

In modern mechanics, an object moving uniformly in a straight line does not need a continuing force simply to keep that motion. Forces explain changes in speed or direction. A stone falling and an object slowing on a table are experiencing interactions, so neither is an example of completely undisturbed motion.

The important change was in the question. Instead of always asking what sustains motion, scientists could ask what changes it. That made stopping and turning things to investigate, rather than signs that motion had simply run out.

Speed and direction are different parts of describing motion. Something can keep the same speed while turning. That is why a circular path and a straight path are not the same kind of continuation. The question is

not only whether an object keeps moving, but how its motion changes.

Think about it

Can an object change its motion without changing its speed?

Reasoning

Yes. It can turn. Changing direction changes its velocity, even when its speed stays the same.

Extinction becomes a fact of natural history

A fossil tells us that an animal once lived. But an unfamiliar fossil does not immediately tell us that every animal of its kind has disappeared. Some might still live somewhere people have not searched.

Cuvier compared fossil bones with bones of living animals. He had to ask whether differences meant a different kind of animal or ordinary variation. He also considered whether a surviving animal would probably have been noticed.

Not finding a large, conspicuous land animal can mean something different from not finding a tiny animal in little-explored water. The search matters.

Extinction means that a kind of living thing has disappeared completely. Establishing that loss does not, by itself, reveal its cause. The new idea allowed natural history to include animals that could no longer be found alive, while keeping the evidence for disappearance separate from the explanation of how it happened.

A collection of animals can be incomplete. Finding no match in that collection is therefore not enough to conclude that a fossil animal is extinct. Researchers also need to consider how much is known about living

animals and where an unknown survivor could remain. The confidence of the conclusion depends on that evidence.

Think about it

Does an empty search always show that nothing is there?

Reasoning

No. A search can miss something. We need to ask where and how the search was made and how likely it was to detect a survivor.

Life becomes open to physicochemical explanation

Yeast can make sugar undergo a chemical change called fermentation. Scientists asked whether this change required whole living yeast cells, or whether material from inside the cells could still do it.

Buchner described a preparation that fermented after the yeast cells had been broken apart. This did not mean that life had been made from nothing. The material still came from cells, and it was not just one perfectly separated ingredient.

The result made a smaller, important point: the chemical change could continue without whole cells remaining intact under those conditions. Researchers could now investigate which components were needed.

That did not explain everything a cell does. An extract that ferments does not necessarily grow or reproduce. Science advanced by separating one question from the much larger question of how an entire living thing works.

A failed preparation can also be informative, but it needs care. Perhaps the activity really cannot occur outside a cell. Or perhaps the preparation damaged a component that was needed. Researchers must

distinguish those explanations. The method used to investigate a process can accidentally stop the very process they want to understand.

Think about it

If an extract does not work, is there only one possible explanation?

Reasoning

No. Something necessary may be missing, damaged or too diluted. Failure by itself does not identify the reason.

Cells become units of living organization

Looking through a microscope can reveal tiny compartments. But seeing a compartment is not the same as knowing how a whole plant or animal is organized.

Scientists compared many tissues and developed the idea that cells are basic units of living organization. Some early explanations of how cells formed were wrong, even though the comparison between plant and animal cells was useful.

Another question needed evidence through time: where do new cells come from? Observing division helped establish that cells arise from existing cells. A picture of two neighboring cells would not have shown that by itself.

Cells also work in relation to their surroundings and to other cells. An organism is more than a heap of separate pieces. Cell theory gave scientists a way to investigate those relationships; it did not explain every detail of life at once.

Imagine a theory that correctly recognizes a repeated structure but gives a mistaken story about how it forms. Correcting that story need not erase the useful

observation. Cell theory developed through this kind of separation: the claim about organization and the claim about origin needed their own support.

Think about it

Would a still picture of two cells show how they came into existence?

Reasoning

Not by itself. Evidence about change through time is needed to support the claim that one cell divided into two.

Geometry no longer has one inevitable form

In mathematics, a proof starts from assumptions and follows rules. What happens if a statement cannot be proved from the assumptions we chose?

For a long time, mathematicians tried to prove a particular rule about parallel lines from other geometrical rules. Eventually, alternative geometries were developed by changing that assumption and carefully following the consequences.

This did not mean that Euclidean geometry suddenly became useless or that any answer was acceptable. Different assumptions still require careful reasoning. A picture alone cannot decide whether every step is justified.

There is also a difference between a mathematical possibility and a description of the physical world. Measurements are needed to decide which description works in a particular setting. The important change was that geometry could have alternatives, and those alternatives could be compared precisely.

A drawing can make a rule look obvious because we are used to a particular kind of geometry. But what the drawing suggests and what the assumptions prove are

different questions. Mathematicians can use models to investigate an unfamiliar geometry without first claiming that it describes every physical measurement.

Think about it

Does changing an assumption mean that careful reasoning is no longer needed?

Reasoning

No. The consequences still have to follow from the chosen assumptions. An alternative geometry is a structured argument, not permission to draw any conclusion.

Infinity becomes an object of exact comparison

You can pair each positive whole number with an even number: one with two, two with four, three with six, and keep following the rule. Every number on either side gets exactly one partner.

That is surprising because the even numbers are only part of the whole-number collection. For infinite collections, pairing provides a precise way to ask whether they have the same size.

Not every infinite collection can be put into a complete list. Cantor's later diagonal idea starts with a proposed list and gives a rule for constructing something missing from it. The rule works against any proposed list of the specified kind.

This is a mathematical argument, not an experiment that counts infinitely many objects. Its lesson is that "endless" does not answer every question about size. We must say exactly what kind of comparison we mean.

A finite example can help us understand a rule, but cannot by itself prove what happens for an infinite collection. The diagonal argument explains why its construction differs from every entry at a specified

position. Its force comes from that reasoning, rather than from writing a very long table.

Think about it

Would checking a large number of examples replace the infinite-list argument?

Reasoning

No. Many examples can illustrate the idea. The proof must explain why it works for every position in any proposed complete list of the stated kind.

Giant molecules become a chemical possibility

A large particle can be a group of small molecules holding together, or it can be one giant molecule connected by chemical bonds. Those possibilities may look similar in some measurements.

Staudinger argued that ordinary chemical bonds could connect very long structures. Researchers needed evidence that the connections really extended through a large molecule, rather than only forming a loose group.

They compared chemical changes and different kinds of measurements. No single observation of a thick liquid could settle everything.

A material could also contain chains of different lengths. An average describes that mixture; it does not mean that every chain has the average length. The new idea gave chemistry more things to measure and explain, including chain length and shape. It did not make groups of small molecules disappear from nature.

Different measurements can describe a mixture in different ways. One average can give equal weight to each molecule, while another gives more weight to molecules contributing more mass. The answers can differ without either answer claiming that every

molecule is identical. Scientists need to say what their measurement means.

Think about it

Must a sample contain a molecule whose size is exactly the average?

Reasoning

No. An average can summarize different sizes without being the size of any one molecule in the sample.

Testing gravity: 1915 to 1975

One successful measurement may fit more than one explanation. To compare explanations of gravity, scientists needed different kinds of tests.

They studied planetary motion, changes in the apparent positions of stars, shifts in radiation frequency and the time taken by radar signals. Each test asked something different. A good result in one test did not automatically answer all the others.

The measurements also needed checks. An instrument can introduce an offset, and a photograph requires careful comparison. Scientists had to distinguish these influences from the effect being tested.

Combining tests can be stronger than repeating one kind of success. An explanation that survives one measurement may fail another. The change was toward asking a more precise question: which part of an explanation of gravity does this experiment support, and which alternatives still remain?

The history also distinguishes explaining an already known problem from testing a newly proposed effect. Both can be useful, but they play different roles. A strong account asks what alternatives could also fit, rather than treating every agreement as proof that no other explanation remains possible.

Think about it

Why might two different tests be more useful than one?

Reasoning

One test may leave several explanations possible.

Another can examine a different consequence and help distinguish explanations that survived the first.

Quantum foundations become experimentally discriminable

If two envelopes contain opposite answers, opening one tells you what the other contains. That ordinary correlation does not show that a message traveled between them.

Quantum experiments compare more complicated patterns. The experimenters can choose different measurements, and a proposed explanation must account for the results across those choices.

Bell showed that certain assumptions place a limit on the resulting correlations. Quantum theory predicts patterns that can exceed that limit, and experiments test those predictions.

The choices, the detection of results and the way trials are counted all matter. A result has to be interpreted with those conditions in view. It does not mean we can send any message we choose faster than light. The advance was to turn a particular disagreement about explanations into a precise experimental question.

Collecting the results fairly is part of the experiment. If only some events are detected, researchers need to understand whether that selection could change the pattern. Testing an idea therefore involves more than

comparing an attractive number with a prediction. It also involves checking how the number was obtained.

Think about it

Can a striking pattern be understood without checking how the results were selected?

Reasoning

Not safely. The selection process might favor some outcomes. An experiment must address that possibility before making its intended inference.

Deterministic laws cease to guarantee practical prediction

A rule can be exact while a forecast remains uncertain. To use the rule, we also need to know where the system starts.

In some systems, a tiny starting difference becomes much larger later. Two calculations that begin almost alike can then give very different detailed forecasts. Lorenz studied this in a simplified mathematical model connected with atmospheric motion.

That does not mean that every complicated pattern is chaos, or that no predictions are useful. Noise can make a record look irregular, and a broad statistical description may remain useful when a detailed path does not.

The important distinction is between having a rule and knowing enough to make a particular forecast. Better measurements help, but the way uncertainty grows also matters. A scientific explanation can tell us why a forecast has limits.

The useful length of a forecast also depends on the question. Predicting one exact path can be harder than describing a broader statistical pattern. Losing one kind of prediction does not automatically remove every kind

of knowledge. Scientists have to identify which feature they are trying to forecast.

Think about it

Does an uncertain detailed path mean that nothing useful can be predicted?

Reasoning

No. Some broader properties may still have useful statistical descriptions. Those regularities must also be established rather than simply assumed.

From electrodynamic infinities to Wilson's scales

Sometimes a calculation produces an infinite answer where scientists need a finite prediction to compare with a measurement. Writing “infinity” does not mean an instrument has found an infinitely large result.

Physicists developed careful ways to connect quantities in their equations with quantities they measured. The method had to make several predictions consistently, rather than invent a separate adjustment for every result.

Later, researchers asked how a description changes when it examines different scales. Wilson connected work on particles and their interactions with problems in which variations at many different scales have to be considered together. He built on earlier mathematical developments.

The result was a new kind of question: when the resolution, or level of detail being considered, changes, what must change in the description? This did not solve every difficulty in physics. It made a difficult dependence something that could itself be studied.

A small mismatch between a simple prediction and a careful measurement can matter. It gives a calculation

something definite to explain. But a successful correction is useful only if it is defined consistently. A new adjustment invented for every result would not place the same demands on a theory.

Think about it

Why should the same definitions work across several predictions?

Reasoning

Because they let the theory face more than one test. A separate adjustment for each result could hide a failure instead of explaining it.

Discrete genes and continuous variation: a statistical reconciliation

People can differ in height by small amounts. Does that mean inheritance must blend like paints? Not necessarily.

Many separate inherited contributions can combine. There are often more ways to make a middle total than a very low or very high total. Conditions in the environment can add further differences.

Fisher developed a statistical account connecting Mendelian inheritance with variation and resemblance among relatives. In Mendelian inheritance, inherited factors pass between generations as separate alternatives rather than blending together. The explanation needed assumptions about both inheritance and the population being studied.

A statement about differences across a population is not a recipe saying how much of one person was made by genes. Relatives can also share environments. The new idea connected separate contributions with a smooth-looking pattern, while making the conditions of that connection something to investigate.

Think about a total built from many small contributions. An extreme total may require all the

contributions to point the same way, while a middle total can arise from many combinations. This illustrates how separate contributions can make a broad pattern. It is not a count of the actual causes of one person's height.

Think about it

Does a smooth-looking pattern prove that its causes blend continuously?

Reasoning

No. Many separate contributions can combine into such a pattern. The appearance of the total does not settle how the contributions are inherited.

Deciphering the genetic code: 1954 to 1966

A written message needs more than enough symbols. Someone must know how to group them and what the groups mean. Scientists faced a related problem when investigating how nucleotide sequences, ordered strings of chemical building blocks, specify proteins.

Counting combinations suggested possibilities, but did not reveal the actual assignments. Mutations helped investigate how the sequence was grouped. Researchers prepared sequences of RNA, a molecule built from nucleotides, to use as experimental inputs. This prepared material is called synthetic RNA. They tested it in cell-free preparations: systems using components from cells rather than whole, intact cells. These tests helped connect particular patterns with products.

Different experiments supplied different pieces of the answer. A result about grouping was not yet a complete dictionary, and one successful assignment did not explain all the others.

The genetic code became something that could be tested relation by relation. The code table describes those assignments, but does not do the physical work itself. Cellular machinery is needed to make the mapping operate.

Grouping matters. If symbols are read in groups, adding one symbol near the beginning can change the groups that follow. A later compensating change can restore the grouping farther along. Such examples help explain a reading frame, but the biological claim still needs evidence from actual experiments.

Think about it

Is knowing how symbols are grouped the same as knowing every assignment?

Reasoning

No. Grouping describes how a sequence is read. A dictionary must also connect particular groups with their outputs.

Evolution without an adaptive explanation for every change

A change in a biological sequence can appear without becoming common throughout a population. A new change and a change that eventually replaces an earlier variant are not the same count.

Kimura compared an estimated rate of molecular replacement with an earlier model of the cost of selection. Under those assumptions, the replacement seemed too fast for every change to require its own advantageous selective process.

He proposed that many replacements could instead involve neutral or nearly neutral changes. Neutral changes give no advantage or disadvantage in reproduction; nearly neutral changes have only a very small such effect in the population concerned. The calculation and its assumptions were debated. It did not prove that every molecular change was neutral.

The important step was to compare a proposed explanation with how much change it would need to produce. A useful scientific disagreement can ask whether the measurements, the estimates or the model need revision, rather than simply choose a slogan.

The neutral model distinguishes the number of new variants from the chance that any one becomes fixed, meaning that it replaces the other alternatives at the relevant genetic position throughout the population. A larger population can supply more new variants while each new neutral copy has a smaller chance of eventually reaching that state. Those are two different contributions to the expected replacement rate, not a promise about one particular variant.

Think about it

Can a correct calculation prove that all its starting assumptions fit nature?

Reasoning

No. It tells us what follows if the assumptions apply. The evidence for those assumptions needs examination as well.

Immunity becomes selection among biological variants

How can the immune system respond specifically to something it has not encountered before? One idea is that the unfamiliar substance instructs the system to make a matching response. Another is that it selects from possibilities already present.

Clonal selection places those possibilities in different cells. A suitable cell can multiply, producing descendants with a related specificity: a similar ability to recognize particular molecular features. The response can grow without each new cell receiving a separate design from the foreign substance.

Measurements of individual cells helped distinguish this account from alternatives that could look similar when all their products were mixed together.

The idea did not answer every question about immunity. Scientists still needed to explain how diversity arose, how responses were controlled and how changed populations persisted. This is an explanation of a biological principle, not advice about treating illness.

A mixture can hide differences between the things producing it. If a sample contains two antibody products, perhaps different cells supplied them, or

perhaps the same cells supplied both. Looking at the mixture alone cannot distinguish those accounts. Measuring individual cells can make the difference testable.

Think about it

Does finding two products in a mixture show that each cell makes both?

Reasoning

No. Different cells may contribute different products. The organization of the producers needs its own evidence.

Formal proof encounters internal limits

A set of rules can let us check whether someone has followed a proof correctly. That does not mean the rules can answer every question we might ask.

Mathematicians found ways to study proofs as mathematical objects. Gödel showed limits for certain sufficiently strong formal systems, under important conditions. A statement that cannot be settled inside one system may be settled in a stronger one.

Related work on computation established that no single always-correct procedure can decide every instance of a particular unrestricted task, such as whether arbitrary programs halt.

These results do not mean that all proofs fail or that nothing can be known. Many questions can still be answered rigorously. The new achievement was to prove why some universal promises were impossible, while keeping the conditions of that conclusion clear.

The conditions of a mathematical result matter. A limit for a certain powerful system does not automatically apply in the same way to every simpler system. And proving that a universal method cannot work does not prevent useful methods from solving more restricted

problems. A limit becomes informative when we say what it limits.

Think about it

Does a limit on a universal method make every individual proof unreliable?

Reasoning

No. A particular proof can still follow its rules correctly. The limit concerns the reach of the whole method, not an error inserted into each argument.

Making sensation measurable: psychophysics and mental chronometry

You cannot see another person's sensation directly. But you can control a stimulus and observe a response, such as whether the person notices a difference.

Scientists studied how noticeable changes depend on the starting level of a stimulus. They also compared how long different response tasks took.

A measured difference still needs interpretation. If a choice task takes longer, the extra time might reflect the choice itself, changes in preparation, or several processes together. Subtracting the times does not automatically reveal which explanation is right.

The new approach made parts of mental activity open to quantitative investigation. Its strength came from connecting public measurements with clearly stated assumptions, rather than pretending that every number was a direct reading of someone's private experience.

Noticing a difference and measuring how large a sensation feels are also different tasks. Fechner connected them through an extra assumption about equal steps of sensation. A calculation can show what

follows from such an assumption, while leaving scientists to ask whether that assumption is suitable.

Think about it

If two measured times differ, do we immediately know why?

Reasoning

No. Several parts of the tasks may have changed. A model of those parts is needed before assigning the difference to one mental operation.

Remembering becomes reconstruction

Remembering can keep real information while changing how it is put together. It is not always like replaying a film.

Ebbinghaus showed that something difficult to recall could still be easier to learn again. Bartlett studied how meaningful material was organized in remembering. Later experiments showed that question wording and associations among words could affect reports.

That does not mean every memory is wrong. Accurate information and mistakes can appear together. Leaving out a detail, changing a detail and adding something that was not there may also involve different processes.

The important change was to study both what survives and how a present recollection is formed. Confidence alone cannot settle accuracy, and a laboratory result does not decide whether any particular person's account is true or false.

A good experiment needs a reliable record of what was presented. Without that reference, two different recollections do not by themselves show which one changed. Researchers can control the original material and later questions, then compare the reports. This

helps turn a broad idea about memory into a testable question.

Think about it

Is leaving out a detail necessarily the same process as adding an absent detail?

Reasoning

No. The discrepancies are different. An explanation should investigate them rather than give every change the same name and stop there.

The adult brain becomes a changing system

An adult brain can change, but “change” can mean several things. A response can become stronger, or a region can respond differently to sensory information. That does not automatically mean new neurons have been made.

Experiments helped distinguish these possibilities. Researchers measured lasting changes in neural responses and changes in the way sensory responses were mapped. The exact measurement mattered: a bigger signal was not a direct measurement of more knowledge.

Plasticity is the name for a family of changes, not a promise of unlimited improvement. Some changes may not last or may not help.

The important questions are precise: what changed, what produced it, how long did it last, and what difference did it make? A brain can have a stable organization while still being affected by its history.

A map of responses shows how places in the nervous system respond under particular conditions. If the responses change, the map can change without brain tissue physically sliding into a new place. Functional

measurements and anatomical measurements address connected but different questions, so one should not silently replace the other.

Think about it

Does a stronger recorded neural response directly mean more knowledge?

Reasoning

No. It is a change in the measured response. Connecting that change to learning or a particular memory requires further evidence.

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Motion without a continuous mover

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